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Lithium Extraction Methodology and Recovery from Conventional Resources: A Critical Review

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Abstract Lithium recovery from various primary sources, such as brine, ores, seawater, and clay, or secondary resources that include lithium-ion batteries (LIB) and lithium-ion metal oxide batteries (LIMOB) poses a challenge due to the complexity of the extraction processes. This review aims to examine recent advancements in lithium extraction and recovery from both primary and secondary sources. It provides an overview of the established recovery and separation techniques for primary sources, including precipitation, chromatography, ion exchange, and membrane technologies, alongside the chemical agents used in these processes. Additionally, lithium recovery from secondary sources through methods such as hydrometallurgy, pyrometallurgy, and bioleaching, highlighting the use of various organic and inorganic sorbents, is also addressed. Some of the advantages and disadvantages of the recovery techniques, as well as economic, environmental, and technical data analysis, are also discussed. While the recovery of lithium from primary sources has been extensively studied, secondary sources—particularly spent LIBs and LIMOBs—have received relatively less attention, mainly due to challenges such as the hazardous nature of recycling processes, stringent environmental regulations, high operational costs, and significant energy requirements. Nevertheless, the emergence of bioleaching technologies offers a promising alternative technique for lithium recovery from secondary sources, owing to their potential for environmentally sustainable operations, cost-effectiveness, and lower energy consumption, availability of materials and bio-organisms, despite the new emergence for lithium recovery from secondary resources. The major highlight of this review paper is the comparison of each recovery technique. Among the primary resources

Highlights

- Recent advancements in lithium extraction and recovery from different (primary and secondary) resources.
- Examine different separation techniques (precipitation, ion-exchange, chromatography, membrane, hydrometallurgy, pyrometallurgy, and bioleaching) for lithium salts.
- Overview of the advantages, disadvantages, limitations, and potential improvements for each lithium recovery technique.
- Economic analysis, and environmental impacts, of each lithium recovery process.

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-brine, ore, clay- recovery techniques, precipitation techniques were found to recover ~ 99.5% of lithium in the form of lithium chloride (LiCL), while membrane and chromatography managed to recover ~ 98%, and lastly, 78% using liquid–liquid extraction techniques. However, by implementing the hydrometallurgy technique to recover lithium from secondary resources in the form of lithium fluoride (LiF), lithium phosphate (Li_3PO_4, and lithium carbonate (Li_2CO_3), only ~ 88% of lithium salts were recovered, while in pyrometallurgy similar recovery percentage was noticed, 87%. Additionally, a 70 ~ 96% recovery rate is reached using bioleaching and microorganisms.

Keywords Lithium recovery · Primary resources · Secondary resources · Brine water · Seawater · Ore · Clay · Precipitation · Chromatography · Ion-exchange · Membranes · LIB · LIMOB

1 Introduction

The global shift toward low-carbon energy has significantly increased the demand for lithium, which is essential for electric vehicles and renewable energy storage (Butylskii et al., 2024; Scarlat et al., 2018; Wang et al., 2022a). While lithium is utilized in industries like medicine, ceramics, and glass, its limited natural abundance and uneven geographic distribution pose supply challenges (Child et al., 2019). Lithium is typically extracted from hard rock (like spodumene), clays, and brine sources using high energy and intensive resource processes which includes acid leaching and solar evaporation. Though salt-lake brines account for the majority of current lithium production, unconventional sources like geothermal brines, seawater, lithium ion batteries (LIB), and lithium ion metal oxides batteries (LIMOB) are gaining interest due to their vast potential and environmental concerns that is linked to traditional extraction methods (Liu et al., 2019). However, extraction from these sources remains technologically and economically challenging. Ongoing improvements aim to enhance yield and reduce the environmental footprint of global lithium production (Wilson, 2019). While critical to decarbonization, current lithium extraction methods using techniques such as brine evaporation and hard rock mining pose severe environmental, water, and energy challenges. Moreover, lithium supply is concentrated in a few countries, raising geopolitical and supply chain risks. In response, there is growing interest in alternative lithium sources and battery recycling to build a more sustainable, diversified, and secure lithium supply chain essential for clean energy systems (Marinova et al., 2025; Mousavinezhad et al., 2024). Innovative technologies like Direct Lithium Extraction (DLE) and Lithium Brine Concentration (LBC) have emerged to overcome the inefficiencies and environmental impacts of traditional evaporation pond methods and rock mining (Brown & Peake, 2006; Ihsanullah et al., 2016; Kanagasundaram et al., 2024). These advanced approaches offer continuous, selective lithium recovery with improved water efficiency. Techniques such as ion exchange, selective adsorption, and membrane processes enhance extraction performance. However, despite their promise, high implementation costs and technical hurdles have limited their widespread industrial adoption, with conventional methods still prevailing due to their lower expenses.

Around 24 heavy metals and metalloids are known to possess high risk and toxicity on human health upon consumption. These metals are (Al, As, B, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Mo, Na, Ni, Pb, Sb, Se, Ti, V, and Zn) are becoming critical topic due to their prevalence occurring in the environment, poisonousness, toxicity to living organisms and other life forms. One major source of these metals are motors and vehicle emissions, tires, roads, and asphalt, all considered a primary source of metal pollution, especially during rainy seasons when rainfalls aid in chemical diffusion and contamination of water resources during the wash-off. Most of these contaminants are washed off roofs, roads, and other metal-containing surfaces into streams of running water that usually pour into seas, lakes, or rivers. These phenomena can be seen widely in urban countries (Brown & Peake, 2006) and yet, in gulf regions, other diffusion resources of PAHs and heavy metals contamination scenarios are observed. These contamination processes include local fire emissions, industries un/deliberate discharge or burial or drainage of by-products (oil waste and corroded materials) in land or water sources (Brown & Peake, 2003). Oil refinery processes and industries are considered one of the topmost water/heavy metals contamination sources. Moreover, the release of heavy metal ions in the aqueous by-products of the industry was confirmed to leak into the environment, based on some research that revealed the pollution of soil and water bodies with heavy metals poses a great risk to agriculture and human health (Sarma et al., 2016; Zhang et al., 2015). High-density oils contain large groups of heavy metals with a wide concentration ranging from trace ~ 0.1wt% (Welter et al., 2009). Most of these metals include sodium (Na), potassium (K), calcium (Ca), copper (Cu), manganese (Mn), tin (Sn), lead (Pb), chromium (Cr), iron (Fe), nickel (Ni), vanadium (V), etc. (Ali & Abbas, 2006). To demetallize heavy oil, several technologies have been developed, such as chemical treatments (Geng et al., 2021), microwave (Shang et al., 2016), photochemical (Shiraishi et al., 2000), electrochemical (Welter et al., 2009), and microbial (Dedeles et al., 2000), which have shown promising metal removal efficiency.

Global investment and demand for clean energy and technologies have increased the requirement for essential minerals. Novel inventions and devices have influenced the minerals market and expanded its parameters for new mineral uses in the past years as well as in the upcoming future. The mineral market technologies will account for more than two-thirds of total clean energy demand in the next two or three decades. Accordingly, the global market and the international energy agency have reported an increase of up to 90% growth in lithium technologies, including sectors such as medical, lubricants, ceramics, glass, and alloying industries (Mends & Chu, 2023). In 2021, global lithium demand expressed in lithium carbonate equivalent (LCE) was anticipated at approximately 600,000 metric tons, distributed as follows: power batteries accounted for ~ 320,000 tons, consumer electronics batteries for 100,000 tons, energy storage systems for 60,000 tons, and traditional industrial applications for 120,000 tons. up until the year 2021, the battery industry has represented over 78% of total lithium usage, underscoring its dominant role as the primary application domain. The widespread application of lithium in battery technologies is largely attributed to its high electrochemical reactivity and favorable redox potential, properties that are integral to the performance of lithium-based energy storage systems. These characteristics have been instrumental in advancing lithium battery technologies, thereby accelerating the growth of the electric vehicle (EV) sector. Furthermore, in the context of global cumulative installations of new energy storage systems, lithium-ion batteries command a market share exceeding 90%, highlighting their preeminent and unmatched status in the field (Gu et al., 2024).

Concurrently, advancements in science and technology have catalyzed a widespread shift toward electrification and renewable energy solutions, with lithium-ion batteries (LIBs) emerging as a cornerstone technology across multiple industries, including electric vehicles and grid-scale energy storage systems (Barra & Falcone, 2024). The rapid expansion of these sectors is driving a substantial surge in LIB production, projected to triple within the next five years. This escalating demand necessitates a significant increase in lithium extraction, primarily from brine- and ore-based sources, thereby intensifying the environmental pressures associated with lithium resource development (Berger et al., 2025). Lithium (Li^+) the 25th most abundant metal on earth is considered one of the essential uncommon, rare metals, that have been intensively used in numerous industrial applications due to its paramount benefits in energy storage devices, including mobile phones, laptops, electric vehicles (EVs) and tablets. Moreover, more than one-third of global (Li^+) consumption is in glass manufacturing and ceramics (He et al., 2021; Zhang et al., 2023a). Yet, lithium does not occur naturally in the earth's crust or in large quantities, it is presented in the forms of phosphate, aluminum silicate, and mica-type minerals. Lithium compounds are used primarily in aluminum production industries, propellants of rockets industries, nuclear industries, pharmaceutical industries, lubricants and grease manufacturing, synthesis of vitamin A, batteries, and synthesis of organic compounds. Besides, Lithium/Aluminum or Lithium/Magnesium alloys are used to form stronger and lightweight alloys. Lithium is used extensively in thermonuclear plants to control the fusion of thermonuclear reactors (Mends & Chu, 2023). At the same time, lithium chloride (LiCl) is one of the most hygroscopic materials and is employed in industrial drying and air conditioning devices. Lithium is employed in the process of making synthetic rubber, greases, and other lubricants (Swain, 2017). Additionally, the fast breakthrough in lithium-ion batteries (LIB) market size and its usage in plug-in electric vehicles (PEV) is expected to reach 77.42 billion by the year 2024, due to its small atomic

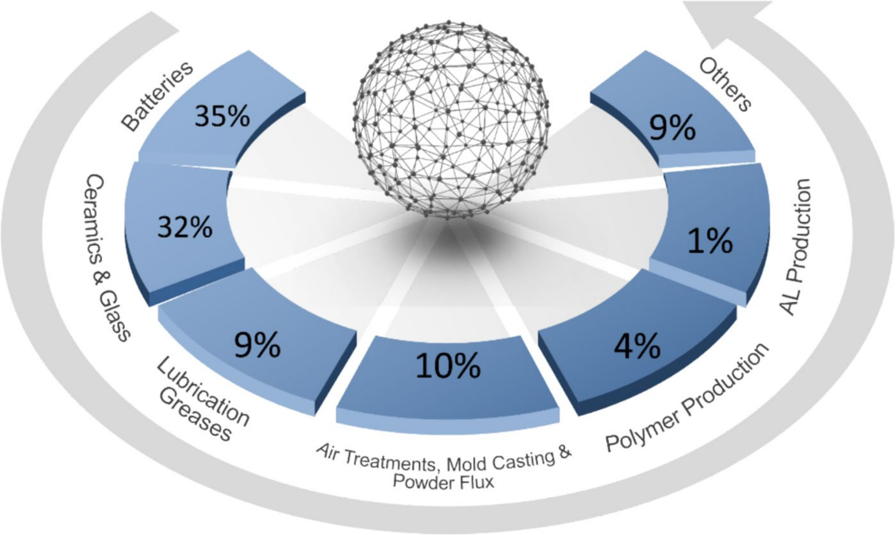


Fig. 1 The global usage of lithium (Li^+) and its end-use application percentages

radius, high operation voltage, energy density, long life cycle, and environmental friendliness. Figure 1 shows global Lithium distribution end-use and its applications, including battery recycling, ceramics and glass production, lubrication and greases, air treatments, casting, molding flux powders, polymer production, aluminum production, and some other uses.

Ultra-pure lithium compounds such as lithium carbonate (Li_2CO_3) are used in biomedical applications including chemotherapy treatment of joint inflammations, severe depression cases, and mental illness (Spase, 1995). Lithium is produced industrially in the form of compounds (Li_2CO_3, LiOH, LiBr, and C_4H_9Li). Therefore, it is crucial to regulate and choose the most efficient separation, purification, and recovery procedures for lithium to emphasize the importance of recycling such a rare metal and minimizing its environmental effects (Yun et al., 2023). Furthermore, regardless of the lithium sources -primary or secondary- each extraction process has its own advantages, disadvantages, limitations, and ways of improvement. These critical analysis points are mentioned for each process in this review for each section. An economic analysis: stating the financial burden of each recovery source, the environmental assessment of each extraction process, and its future impact.

2 Methodology of the Review Paper

Figure 2 presents the methodology of the review paper.

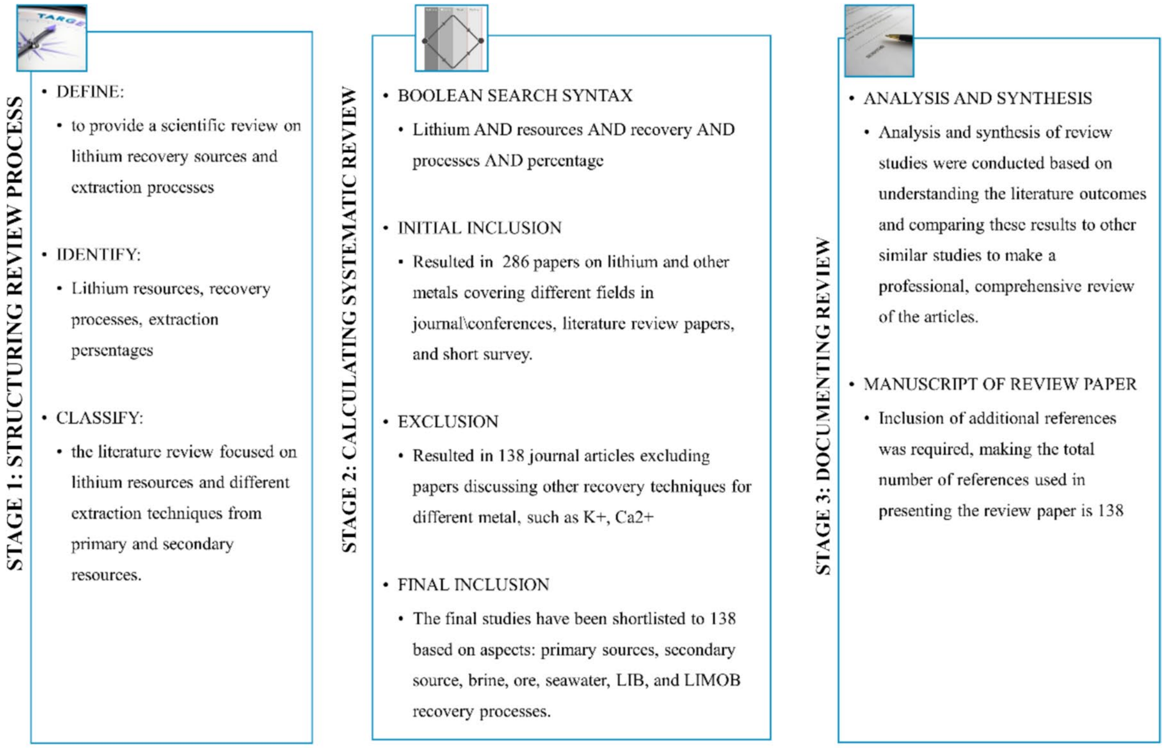
3 Lithium Recovery from Seawater and Brine

Seawater and ocean are considered one of the most abundant and crucial alternative resources of minerals. It is one of the most promising resources for lithium recovery. The amount of lithium in seawater was estimated to be approximately 2.6×10^{11} tone which is larger than the amount of lithium present in ores or clays (Roobavannan et al., 2023). Currently, around 60% of lithium recovery residential in minerals deposited in Australia, and 30% comes from brines in South America (Fan et al., 2020). Russia, Germany, and Korea investigated the recovery of lithium in the past years from salt lakes near the USA, the Dead Sea, thermal water, and hydromineral sources such as brine and geothermal locations (Zheng et al., 2023). In the beginning, the lithium recovery process from seawater was done through two techniques at different stages: (i) Co-precipitation and Extraction process and (ii) Ion-Exchange and sorption process, and (iii) the precipitation of Li_2CO_3 as summarized in Fig. 3. The highly concentrated seawater usually undergoes several purification steps depending on the metal impurities and concentration. Furthermore, these steps are bound to extra parameters depending on (i) solution PH, (ii) ionic size, (iii) surface charge, (iv) molecular structure, (v) basicity of ligand, and (vi) physicochemical properties (Mends & Chu, 2023) (Fig. 3).

However, With the increasing global demands for lithium and the discovery of novel extraction technologies, such as liquid–liquid extraction, membrane, ion exchange, and sorption, is essential (Alsabbagh et al., 2021). In particular, Column and gel permeation chromatography are quantitative separation techniques used for lithium recovery from brine sources, that allow the separation of lithium from other alkali and alkaline earth metals. Both chromatography techniques use polyacrylamide gel, blue dextran 2000, and bio-gel P-2 for separation. For instance, the distribution coefficients of Li^+ ions, eluted with water, were found to be 0.59 and 0.49 in dead sea water and in brines chromatographed on a column of Bio-Gel P-2 respectively. The order of eluted metals fraction was reported as follows: K^+, Na^+, Li^+, Mg^+, and Ca^{2+}, demonstrating the possibility of Li extraction (Rona & Schmuckler, 1973). In another study done by Abe et al. using the phase column chromatographic separation method, lithium recovery extraction using titanium (IV) antimonate cation exchanger (TiSbA) and HNO_3 to be eluted at 20 cycles have proven to recover up to 98% of lithium (Lee, 1967). In contrast, lithium recovery from brine does not follow any specific process or technique, due to different compositions of lithium compounds in each source. Numerous studies have reported different techniques to separate, recover, and purify lithium from brine among other sources as displayed in Fig. 4 (Christmann et al., 2015).

3.1 Co-precipitation Process

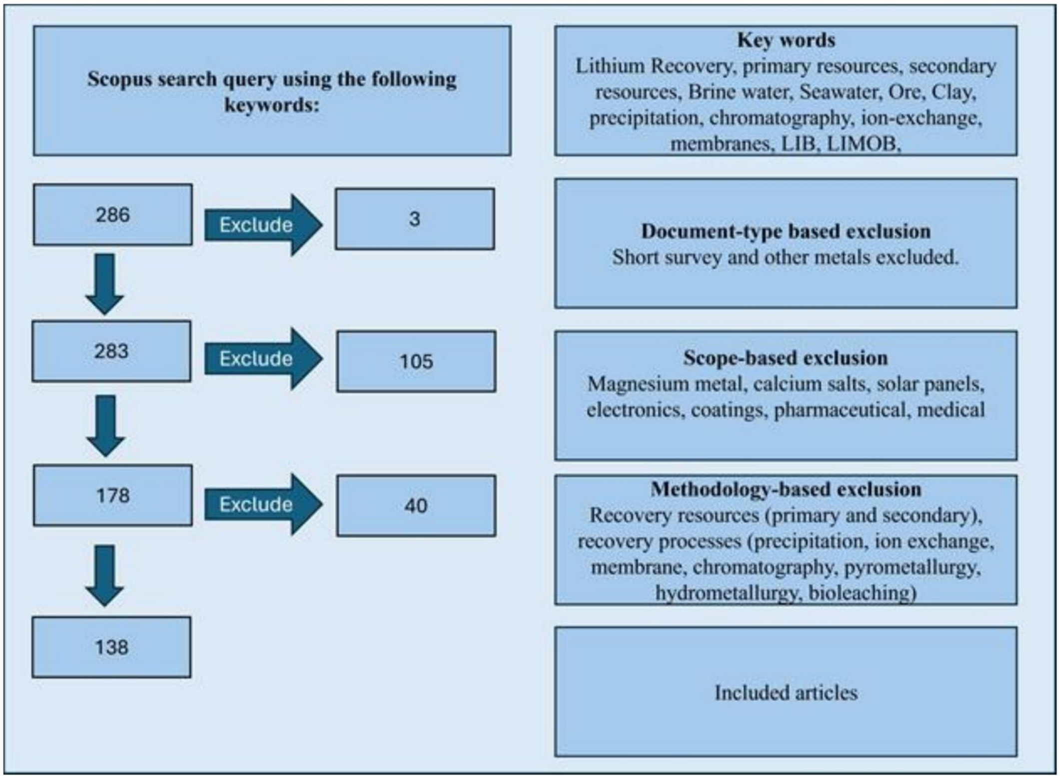
This process has not been widely used for lithium extraction due to some challenges including the high concentration of alkaline and alkali metals in seawater and brine, as well as the similar characteristics of some metals including Mg^+ to lithium, and extra required steps to recover lithium after separation, the loss of lithium during separation due to diffusion between the formed liquid layers. The same issues are also encountered when recovering lithium from land-based resources (Bhagyaraj et al., 2021). As for lithium recovery from liquid resources, several reagents such as aluminum hydroxide ($AL(OH)_3$), sodium carbonate (Na_2CO_3), calcium carbonate ($Ca(OH)_2$), magnesium hydroxide ($Mg(OH)_2$), and manganese hydroxide ($Mn(OH)_2$) are used to precipitate lithium into lithium carbonate (Um & Hirato, 2014). The recovery of lithium from such resources using the precipitation process can be challenging, as reported in other studies (Alsabbagh et al., 2021; Epstein et al., 1981; Liu et al., 2019). Chi Ma et. al. used ammonium sulfate $(NH_3)_2SO_4$ as a precipitation agent for Mg, Butyl Ethyl Propanediol (BEPD) to bind with boron, and polyethylene glycol PEG2000 to extract lithium from the brine sample, the schematic diagram of the precipitation process is shown in Fig. 5. In their process $(NH_3)_2SO_4$ was used to precipitate the majority of Mg from the brine solution, followed by a mixture of BEPD and PEG2000. The purpose of using these agents is their ability to bind with boron and lithium by creating three liquid phase solutions that can be later separated using route separation techniques. It was reported that boron was actively binding with the polyhydroxy compound which has a lower density (top layer) than the rest of the agents. Lithium separation was due to the electrostatic interaction of the active oxygen atoms in PEG2000 (middle layer), where Mg^{2+} due to its hydrophilicity to attract water molecules remains in the bottoms. The precipitation method achieved extraction rates of up to 87.2% for B^{3+}, 73.5% for Li^+, and 91.9% for Mg^{2+}. However, the low lithium extraction in the three-liquid phase precipitation method can be attributed to the diffusion of metal ions between the three layers, hindering higher extraction rates (Ma et al., 2024). It is important to note that lithium extraction through precipitation is usually followed by an extra liquid–liquid extraction step to separate lithium from other metals or compounds, especially in cases where aluminum salts and ammonia are used to precipitate lithium chloride at room temperature (An et al., 2012; Chen et al., 2023). What gives this technique its strength is the versatility of its reagents (e.g., $Al(OH)_3$, Na_2CO_3, $(NH_4)_2SO_4$, PEG2000) that can selectively target and precipitate different ions, making it chemically adaptable for various brine compositions. Another advantage is the phase separation potential. For instance, the innovative three-liquid phase separation method (e.g., PEG2000 for lithium, BEPD for boron) allows for simultaneous separation of multiple metals, which can be advantageous for comprehensive resource



- DEFINE:
  - to provide a scientific review on lithium recovery sources and extraction processes
- IDENTIFY:
  - Lithium resources, recovery processes, extraction persentages
- CLASSIFY:
  - the literature review focused on lithium resources and different extraction techniques from primary and secondary resources.

- BOOLEAN SEARCH SYNTAX
  - Lithium AND resources AND recovery AND processes AND percentage
- INITIAL INCLUSION
  - Resulted in 286 papers on lithium and other metals covering different fields in journal\conferences, literature review papers, and short survey.
- EXCLUSION
  - Resulted in 138 journal articles excluding papers discussing other recovery techniques for different metal, such as K+, Ca2+
- FINAL INCLUSION
  - The final studies have been shortlisted to 138 based on aspects: primary sources, secondary source, brine, ore, seawater, LIB, and LIMOB recovery processes.

- ANALYSIS AND SYNTHESIS
  - Analysis and synthesis of review studies were conducted based on understanding the literature outcomes and comparing these results to other similar studies to make a professional, comprehensive review of the articles.
- MANUSCRIPT OF REVIEW PAPER
  - Inclusion of additional references was required, making the total number of references used in presenting the review paper is 138



Key words
Lithium Recovery, primary resources, secondary resources, Brine water, Seawater, Ore, Clay, precipitation, chromatography, ion-exchange, membranes, LIB, LIMOB,

Document-type based exclusion
Short survey and other metals excluded.

Scope-based exclusion
Magnesium metal, calcium salts, solar panels, electronics, coatings, pharmaceutical, medical

Methodology-based exclusion
Recovery resources (primary and secondary), recovery processes (precipitation, ion exchange, membrane, chromatography, pyrometallurgy, hydrometallurgy, bioleaching)

Included articles

◂**Fig. 2** The methodology process along with inclusion/exclusion analysis of the review study

recovery. Achieving 73.5% lithium recovery from a complex matrix like brine. Indicates practical feasibility, particularly when combined with other separation steps. Some processes (e.g., using aluminum salts and ammonia) can be conducted at room temperature, which in turn reduces energy consumption. As for the limitation, the high ionic competition of brine and seawater contain high concentrations of alkali and alkaline earth metals (e.g., Mg^{2+}, Ca^{2+}) with similar ionic properties to Li^+, complicating selective extraction. Leading to ion diffusion between phases, such as in a three-phase system; metal ion diffuses across liquid layers, significantly reducing the effective separation and limit lithium recovery yield. The multi-step requirement of lithium precipitation is often incomplete and followed by liquid–liquid extraction or other purification steps to isolate the lithium salts Fig. 6. As well as the low selectivity of lithium despite creative chemistry; the process extraction process still suffers from lower selectivity for lithium in the presence of boron (B^{3+}) and magnesium (Mg^{2+}), requiring additional purification steps. One way of improving this technique is by optimizing the phase stability, and enhancing interfacial stability of the three liquid system, which in turn will minimize the ion diffusion and increase the purity and recovery rate of lithium salts. Other enhancement methods involve the development of selective ligand or chelating agent with higher lithium affinity over Mg^{2+} or B^{3+}. The third method is integrating precipitation with membrane separation or ion-exchange resins which provide continuous extraction and minimizing post treatment. Finally, fine tuning the temperature, pH and reagent concentration can help improve the precipitation kinetics and target lithium recovery more precisely.

3.2 Ion Exchange and Liquid–liquid Extraction

Complementary procedures were also proposed to recover lithium from aqueous sources using solar evaporation and crystallization followed by ion exchange used in/Organic sorbents such as NaCl, KCl, and $CaSO_4$. Among the widely used sorbents, only cations-based exchangers such as manganese oxides (MnO) show efficient lithium recovery. Other ion exchangers are H_2TiO_3 and titanium (IV) antimonate cation exchangers (TiSbA), which both can be used to recover lithium from hydrothermal and liquid resources. Both ion exchangers exhibit high selectivity for Li^+, in the range of 25–34 mg/g. Additionally, TiSbA can be used repeatedly for lithium recovery and the adsorbed lithium can be recovered after elution with HNO_3 (Abe & Chitrakar, 1987; Wang et al., 2023). However, liquid–liquid extraction is considered a limited extraction technique since only a few liquid–liquid extraction reference solutions are available. Primary alcohols containing C3-C5 carbons and aliphatic alcohols having C6-C8 carbons, with iso-butanol, are the most effective and promising alcohol in lithium recovery. Kitamura et al. reported the use of cyclohexane and tri-octyloxyphosphine to recover lithium after treatment with HCl and potassium phosphate (K_3PO_4), with more than 95% lithium recovery (Nihon-Kaisui-Gakkai, n.d.). Another study done by Luo et al. reported the use thenoyltrifluoroacetone trioctylphosphine oxide (HTTA–TOPO) mixture, among other solvents for lithium recovery. HTTA acts as a hydrogen bonding donor and TOPO as a hydrogen bonding acceptor, using HTTA–TOPO mixture, 93% of lithium was extracted and recovered (Luo et al., 2023).

Both liquid–liquid and ion-liquid extraction techniques were reported for lithium extraction, especially from brine sources. Gabra et al. proposed a liquid–liquid laboratory extraction scale experiment of Lithium Chloride (LiCl) using n-butanol and synthetic solutions containing lithium, potassium, sodium chloride, and calcium chloride. The recovery process is driven by the distribution coefficients and separation factors, and the proposed process can recover 99.6% of LiCl (Gabra & Torma, 1978). Bukowsky et al. proposed an ion-liquid extraction process using synthesized resin, aluminates composite, or inorganic ion exchanger, for lithium recovery from brine. They investigated the possible recovery of pure LiCl from brines containing high contention of calcium chloride ($CaCl_2$) and magnesium chloride ($MgCl_2$) brine sources through carbocation and ion exchange techniques (Soyekwo et al., 2024). The study reported the use of three different ion exchange resins: MC50 resin, (Chemie AG Bitterfeld Wolfen), TP207 resin (Bayer AG), and Y80-N Chemie AG (Chemie AG Bitterfeld-Wolfen). They found that the purification of LiCl solutions using Y 80 and TP 207 resin at 50 °C is possible (Bukowsky et al., 1991). Similarly, Sun et al. reported

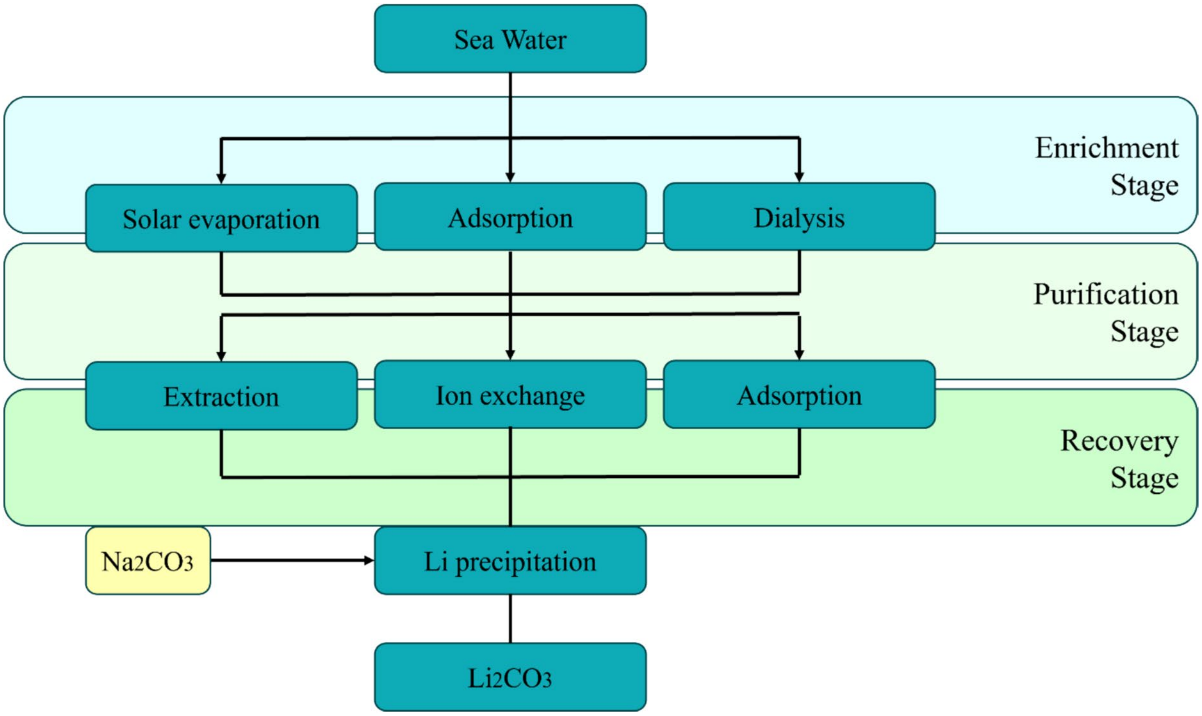


Fig. 3 Schematic diagram of lithium recovery processes and stages from seawater sources

a 96.2% adsorption capacity for Li^+ from the brine using an H_2TiO_3 ion exchanger at pH 12.3. The adsorption isotherm followed by the Langmuir model, with an exchange capacity of around 56.03 mg/g with a 3.8% capacity loss of materials (Sun et al., 2023). Table 1 shows the different ion exchangers used in liquid–liquid extraction process.

3.3 Membrane

Nanofiltration (NF) membrane is one of the most used techniques for Li recovery, it has gained popularity and commercial applications in recent years. The foremost advantage of NF is the fact that it combines both the ultra-filtration (UF) and reverse osmosis (RO) characteristics. The separation process using NF is based on size exclusion depending on the pore size, membrane thickness, charge, and surface density. Park et al. developed a polysulfone (PSf)-based mixture matrix of nanofiber diffused with lithium-ion particle sieves, when the solution flows through the membrane matrix the Li^+ will pass through the membrane, whereas other divalent ions will be rejected due to their larger size. The NF matrix mixture was prepared and activated using methods such as electrospinning, thermal annealing, and acid curing to activate Li^+ (Park et al., 2016). Other researchers used the same technique (NF) to separate lithium by creating mixed matrix electrospun nanofiber membranes. A multilayer membrane with a 15-crown-5 crown ether was incorporated in the Polyethylenimine (PEI) structure by reductive amination with polycation in PEMM formation through layer-by-layer deposition and was used for lithium recovery (Hoshino, 2013; Kazemabad et al., 2020; Sanaeepur et al., 2022; Zhang et al., 2023b). Sun et al. investigated the use of NF techniques for a possible Li/Mg separation using a Desal nanofiltration (DL-2540 NF) membrane. They noticed that the competitive coefficient of Mg^{2+} remains constant, and the Li^+ ion recovery is more favorable when the ratio Mg/Li is larger than 20 (Sun et al., 2015). In 2023, an investigation done by Li et al. using polyamide NF for lithium recovery from Salt Lake brine with a high magnesium/lithium mass ratio, results showed that the retention rates of Mg and Li were higher than 81% for Mg and less than 69% for Li, their mass ratio decreased 8.5 times in the permeate with 83% yield for Lithium. However,

Fig. 4 Different lithium ion (Li^+) sources and the most used recovery processes for each source

upon fouling the NF membrane, the functional groups of polyamides were redshift, and the content of inorganic species including Mg, Ca, Si, Cl, and carboxyl groups increased, leading to membrane surface damage, pore size disturbance, and decreased in hydrophilicity of the membrane's surface, thus affecting the separation and selectivity of the membrane after a long time. The authors demonstrated that the fouling of membranes was 68 times higher when Ca^{2+} ranged from 0 to 2 mmol/L, thus a decrease in calcium ions is necessary to mitigate membrane fouling when recovering lithium ions (Li et al., 2023a; Shi et al., 2024; Soyekwo et al., 2024).

Another membrane technology used for lithium recovery is electrodialysis (ED). Electro-driven membranes are a class of charged materials with the

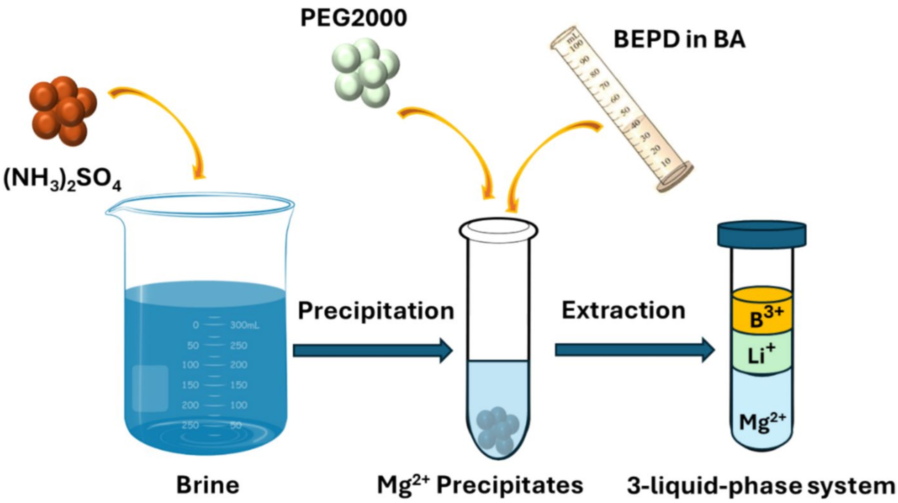


Fig. 5 An illustration of lithium ions\salts extraction using three liquid phase process; copyright @ (Ma et al., 2024)

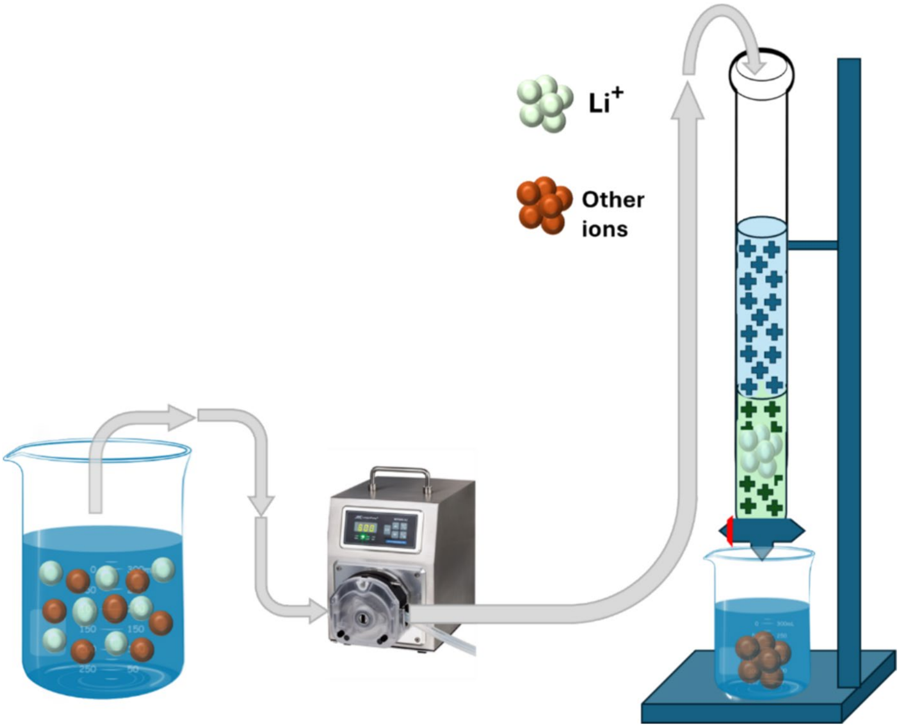
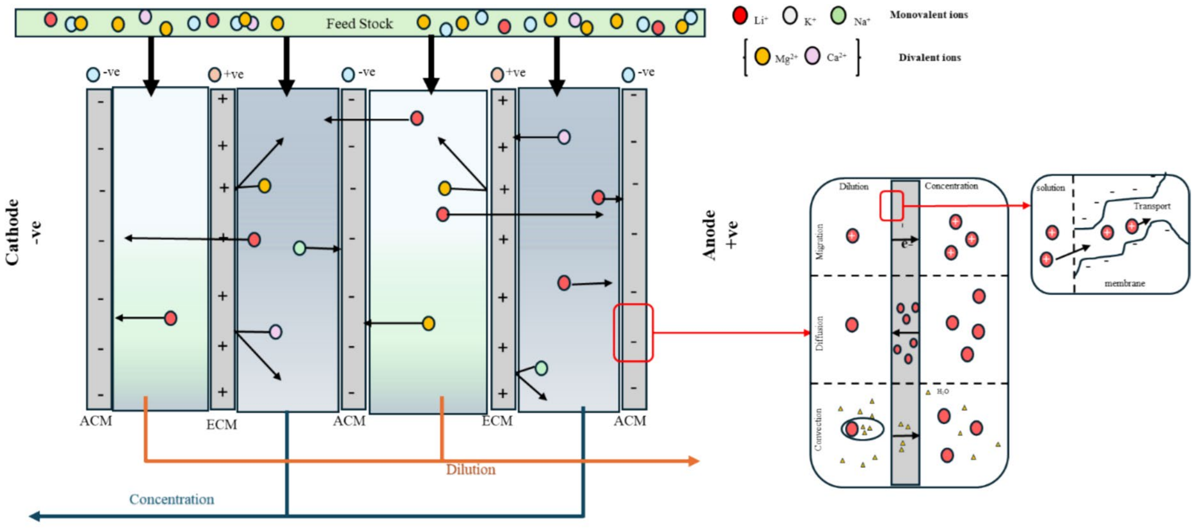


Fig. 6 The process of lithium recovery using the ion exchange; illustration was adapted from original copyright @ (Wesselborg et al., 2025)

ability to facilitate selective ion transport when used under a mono-directional electrical field. Both cation exchange membranes (CEMs), anion exchange membranes (AEMs), and bipolar membranes (BPMs) can be used and classified based on the selective electron-driven group type. Amphoteric ion exchange membranes (AIEMs) are similar to BPMs and were designed and proposed in recent years. These membranes are electro-driven, possessing positive and negative charged groups used for ion/water separation in electrodialysis and membrane de-ionization processes. For instance, Yang et al. proposed in their study the use of water-swollen (PDADMAC/PSS)$_3$PDASMAC films on Nafion membranes, their results showed a significant improvement in the ED selectivity of the K^+/Mg^{2+} and Li^+/Co^{2+} compared

Table 1 Various liquid–liquid processes

Technique	Strengths	Limitations	Efficiency Improvements	Ref
Solar Evaporation & Crystallization	Cheap, natural, scalable in dry climates	Very slow, climate-dependent, poor selectivity	Hybrid solar-mechanical systems, brine pre-concentration	Tran & Luong, 2015; Santoro et al., 2023
MnO_2/H_2TiO_3/TiSbA Ion Exchange	High selectivity, reusable, environmentally safe	pH sensitive, some capacity loss	Surface functionalization, cycle optimization	Abe & Chitrakar, 1987; Wang et al., 2023
Liquid–Liquid Extraction (HTTA–TOPO)	High Li recovery, good selectivity	Solvent toxicity, few options, scale-up challenges	Use of ionic liquids, membrane-assisted extraction	Luo et al., 2023
Ion–Liquid Extraction (MC50, TP207)	High purification, brine compatibility	Resin degradation, cost, regeneration complexity	Resin modification, staged columns, pretreatment of brine	Lin et al., 2024



*ECM: cation exchange membrane
*ACM: anion exchange membrane

Fig. 7 The process of lithium recovery using electrodialysis, a separation technique, is done by size exclusion, concentration gradient, diffusion, or migration of ions under an electric current flow. The illustration was adapted from the original copyright @ (Rahighi et al., 2022)

to bare Nafion membranes with 0.8 high separation efficiency for monovalent cations (Zhu et al., 2017). Similar results were also achieved in recovering Li from its liquid resources when a high voltage was employed. Moreover, Wang et. al. reported other types of membranes such as non-supported liquid membranes (NSLMs) and supported liquid membranes (SLMs) that can be used to separate mono and divalent ions more efficiently (Wang et al., 2022b). Jiang et al. reported that lithium hydroxide is the main product obtained during the membrane separation process electro–electro dialysis using bi-polar membranes (EEDBM) installed as follows: bipolar membrane – cation exchange membrane – bipolar membrane – cation exchange membrane in series as displayed in Fig. 7 where the simplest model of ECM and ACM can be built in a membrane and the size exclusion process. Several conventional stacks were constructed in a repeated assembly of five cation exchange membranes and four anion exchange membranes and employed as a pretreatment (Jiang et al., 2014). Throughout the process of conventional electrodialysis and the use of Na_2CO_3, around 98% pure lithium carbonate (Li_2CO_3) powder can be retrieved (Jiang et al., 2014). Lithium extraction can be further divided into sub-groups based on the materials used including MXene, graphene, transition metal dichalcogenides (TMD), Vermiculite (VCT), layered double hydroxide (LDH), hexagonal boron nitride (h-BN), covalent organic frameworks (c-MOF), graphitic carbon nitride (g-C3N4), and/or techniques such as Direct contact membrane distillation (DCMD) and electrically switched ion exchange (ESIX) (Zhao et al., 2022). Gullied et al. used the DCMD technique coupled with ESIX, as well as Li-selective electrodes such as ($LiAlO_2$) and activated carbon counter electrodes for lithium recovery. An enhanced hydrophobic membrane with a contact angle of 142.8° is prepared from PVDF with graphene oxide. The as-prepared membrane achieves high salt rejection, reaching 99%, a water flux of 7.30 L/m^{2}h, and significant Li recovery up to 91.8% from seawater reverse osmosis (GuLied et al., 2024). Table 2 shows the difference between different membrane extraction processes. One major advantage of membrane filtration is that it has different combinations, such as Ultrafiltration (UF) and Reverse Osmosis (RO) properties. Membranes can be engineered and tailored towards monovalent ions such as Li + or divalent ions (Mg^{2+}, Ca^{2+}). It can achieve high Li recovery (e.g., 83% yield reported). Enables selective transport of lithium using electro-driven separation. However, some of the drawbacks are: Fouling is a major issue, especially with Ca^{2+}, Si, Mg^{2+}, which can reduce hydrophilicity and damage the membrane. Selectivity decreases over time due to membrane degradation. High-pressure operation increases energy demand. Some of the improvements that can be made are by using anti-fouling coatings (e.g., graphene oxide, zwitterionic polymers), reducing Ca^{2+} concentration before NF to prevent fouling, or developing multi-layer or composite membranes for enhanced selectivity and durability. Applying backwashing or chemical cleaning protocols regularly to restore performance, Pre-treat brine to remove fouling species (e.g., Ca^{2+}, SiO_2). However, membrane transition to industrial-scale applications introduces significant technical and economic confronts that need to be analytically addressed. Present efforts must develop

Table 2 The strengths and limitations of each membrane process

Method	Strengths	Limitations	Improvements	Ref
Nanofiltration (NF)	Selective, scalable, commercial-grade membranes	Fouling, reduced performance over time	Use anti-fouling coatings, reduce Ca^{2+} pre-treatment	Soyekwo et al., 2024; Shi et al., 2024; Wen et al., 2024
Electrodialysis (ED)	High purity Li^+ recovery, scalable with stack designs	High voltage stress, fouling, complex configuration	Functional coatings, hybrid with DCMD or resin pre-treatment	Butylskii et al., 2024; Liu et al., 2019; Tran & Luong, 2015
Electro–electro dialysis using bi-polar membranes (EEDBM)	High-purity LiOH & Li_2CO_3; high monovalent selectivity	Stack complexity, sensitive to Ca^{2+}, Mg^{2+}	Optimize membrane spacing and electric load; hybrid configurations	Jiang et al., 2014
Direct contact membrane distillation and electrically switched ion exchange (DCMD + ESIX)	High Li^+ recovery and salt rejection; hybrid operation	Limited water flux, wetting issues	Improve membrane with GO, optimize gradient and ESIX control	Wang et al., 2022a; Gu Lied et al., 2024
Advanced Materials	High selectivity, new-generation membranes/sorbents	Expensive, mostly lab-scale	Composite integration, scale-up of synthesis methods	Santoro et al., 2023; Gu Lied et al., 2024

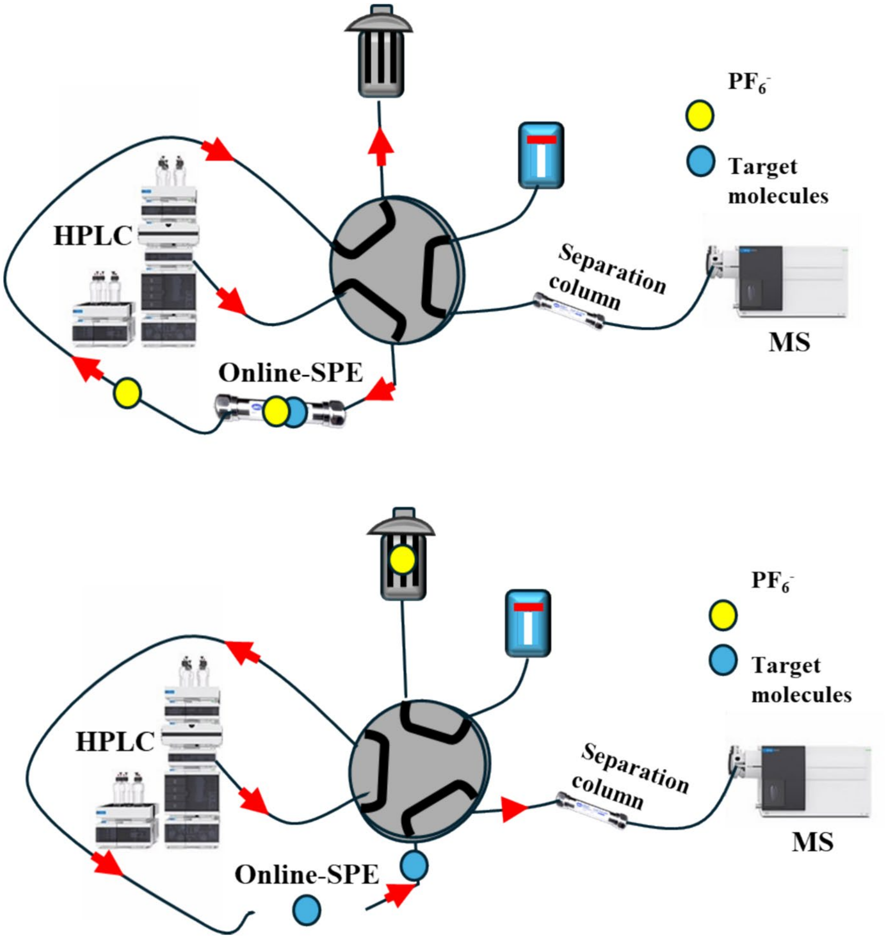


Fig. 8 The process of lithium recovery using the HPLC technique, the process is conducted using a separation salt (PF.$^-$) which binds with lithium ions allowing it to be separated and extracted easily. Copyright @ (Kösters et al., 2021)

from proof-of-concept technologies toward complete solutions efficient of operating effectively under real-world conditions (Foo & Lienhard, 2025). Membrane scaling for brine treatment faces a lot of challenges due to fouling, specifically in real brines, due to the presence of organic matter and scaling ions -Ca^{2+} and SO_4 $^{2-}$, which can drastically affect membrane performance. Real practical applications often engage with high salinity brines, leading to membrane fouling, scaling, flux decline, and reduced separation efficiency (Li et al., 2025).

3.4 Chromatography Process

In a study done by Koster et. al (2021) a thorough computational sample preparation methodology alongside online solid phase removal was employed using high-performance liquid chromatography (HPLC) for lithium recovery as illustrated in Fig. 8. HPLC technique permits large-volume injection at lower dilution rates and conditions. It is important to note that without proper dilution and sample preparation, the injection column and mass spectrometer (MS) will be subjected to build-up salt, some precipitation, and finally clogging. In the mentioned study, electrolytes in the form of pristine samples with trimethyl phosphate (TMP) and triethyl phosphate (TEP) as control substances, and liquid samples salts containing high concentration lithium hexafluorophosphate ($LiPF_6, \geq 1$ mol/L) were used. $LiPF_6$ was successfully and quantitatively removed after adjusting the flow/volume factor up to 50 and decreasing the dilution factor by 10. With these modifications, the detection limit (LOD) and the quantification limits (LOQ) were enhanced up to LOQ: ≤ 100 µg/kg, and the LOD: ≤ 35 µg/kg phosphorus content.

Another study was done by Khar et. al. used the gas chromatography–mass spectrometry technique

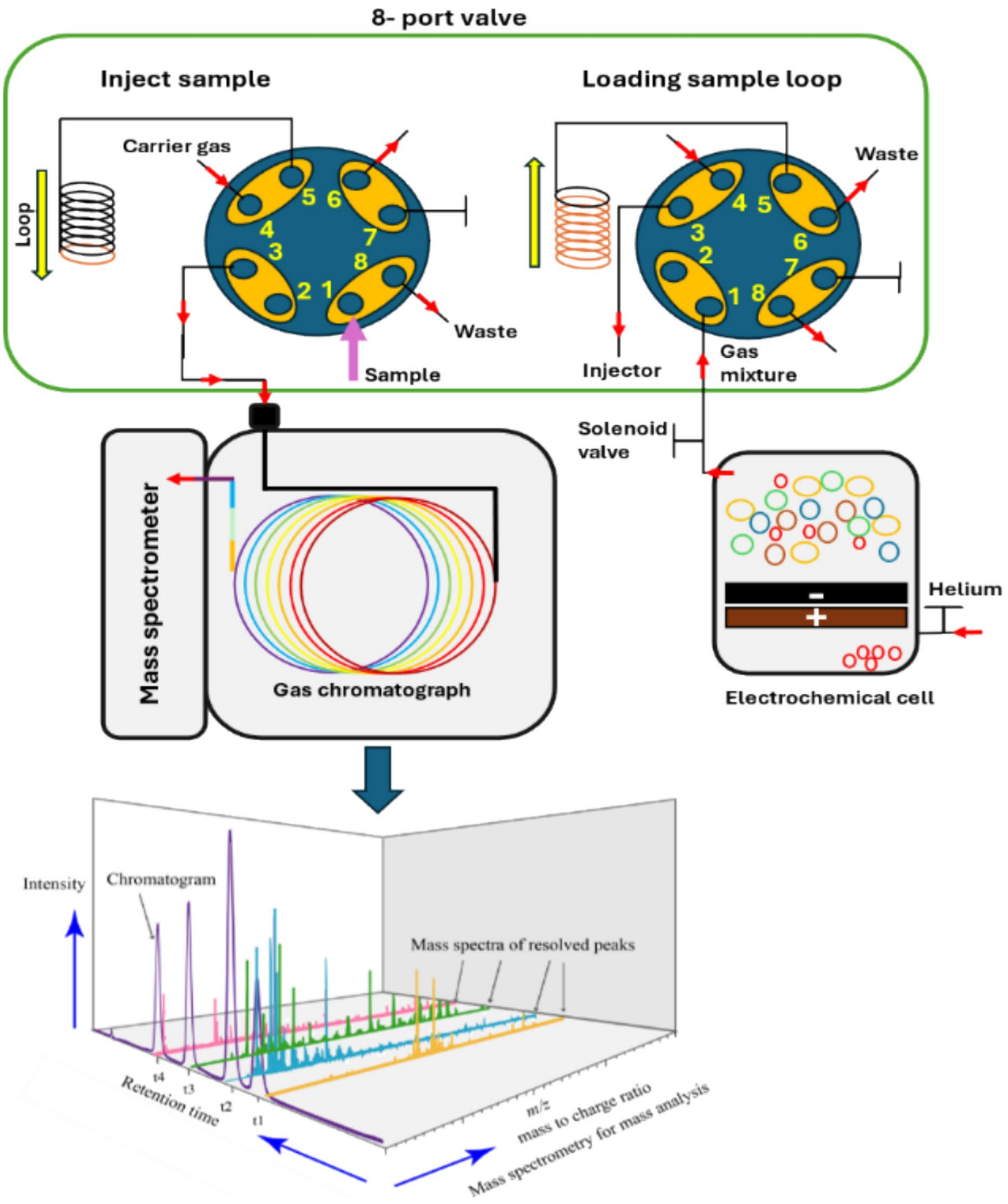


Fig. 9 Combination of GCMS process for identification of complex gas mixtures, allowing the separation of overlapping chromatographic signals (mass/charge ratio), Copyright @ (Kahr et al., 2024)

Table 3 Strengths, limitations and efficiency improvements of analytical methods for Li ion recovery

	Strengths	Limitations	Efficiency Improvements
HPLC	High sensitivity, solid-phase removal, low LOD/LOQ for lithium electrolytes	Sample prep critical; not for bulk recovery; risk of clogging	Auto dilution, robust column materials, inline desalting, ICP-MS coupling
GC–MS	Broad compound detection, useful for degradation mapping	Thermal activation needed, complex prep, not practical for direct Li recovery	Pre-concentration, MS/MS coupling, TGA integration, safer overcharge protocols

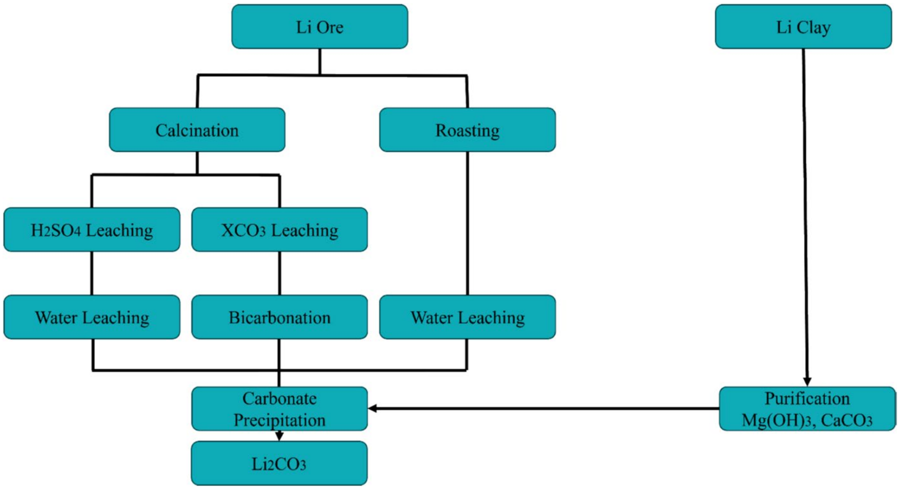


Fig. 10 A schematic flowsheet stating the steps involved in Lithium carbonate recovery processes from its primary resources such as ores and clays (Alhadad et al., 2023; Zhao et al., 2023)

(GC–MS) to recover lithium ions displayed in Fig. 9 (Kahr et al., 2024). This technique allows the decomposition of electrolytes with a carbonate-based mixture of LiPF6 liquified in ethylene carbonate and ethyl methyl carbonate mixture, and vinylene carbonate such as (1 M LiPF6/3:7 by weight EC-EMC/2wt % VC). As a result, the formation of 39 different compounds, that can be subdivided into fluorinated and un-fluorinated hydrocarbons, oxides, carbonyls, alcohols, ethers, silanes, carbonates, oxygen, and water is observed. The authors found that ethane gas was the most abundant hydrocarbon present during the decomposition process at 5.36 V vs. Li^+/Li, followed by carbonyls and ethers at 4.3 V vs. Li^+/Li, and finally, upon overcharging the cell, decomposition fluorinated hydrocarbons before the decomposition of $LiPF_6$ take place. The decomposition of $LiPF_6$ above the overcharged cell potential indicates that the reaction is thermally activated, and a higher cell potential needs to be reached to recover lithium.

Table 3 shows a structured breakdown of the strengths, limitations, and efficiency improvements of the analytical lithium recovery methods described: HPLC (High-Performance Liquid Chromatography) and GC–MS (Gas Chromatography–Mass Spectrometry).

4 Lithium Recovery from Ores and Clay

Lithium extraction from ores or clay consists of beneficiation of minerals and an extensive metallurgy process. The first stage of extraction is subjecting the ore to mineral beneficiation through physical separation techniques. The Metallurgy process consists of two hybrid processes: roasting and calcination known as the chlorination process; the simplified process scheme is shown in Fig. 10. Other recovery techniques include pressure leaching using different lithium-containing ores such as spodumene, petalite,

Table 4 Li metal content in natural ores (Labbé & Daw, 2012; Gao et al., 2023)

Ore	Formula	Li metal content (%)
Spodumene	$LiAl\ Si_2O_6$	3.73%
Petalite	$LiAlSi_4O_{10}$	2.27%
Lepidolite	$KLi_2AlSi_3O_{10}(OH, F)_2$	~1.92%

and lepidolite, each ore has a different lithium content percentage as reported in Table 4 (Labbé & Daw, 2012; T. ming Gao, N. Fan, W. Chen & T. Dai, 2023). Alhadad et al. reported that lithium extraction was done using a variation in the pH, regulated through different acid concentrations ranging from weak to strong acid extraction (Alhadad et al., 2023). In addition, the rate of extraction depends on various factors such as the concentration of the solution, temperature, pulp density, reaction time, and particle size. Additionally, the last process known for lithium extraction from ores is bio-leaching, which was investigated by Zhao et al. (Zhao et al., 2023). The basis of his study includes the use of microorganisms such as bacteria, especially Bacillus mucilaginous 21,699 and Raoultella sp. Z107. The study integrates microorganisms acquiring inorganic nutrients or energy from explicit minerals. Depending on its specific needs, the bacteria will selectively weather minerals. However, differences in metabolic components and processes of different functional bacteria will lead to diverse weathering results. Zhao et al. investigated the different leaching effects of two different bacteria with selective metabolic leaching on lithium silicate. As a result, the distraction of the crystal structure of lithium silicate was due to the microorganism action. The acidic silicate and organic acids produced and secreted into the leaching solution by Raoultella sp. Z107 were higher than Bacillus mucilaginous 21,699, which in turn reduces the pH of the solution and speeds up the leaching process, with lactic acid being the major organic acid produced at (11 g/L), followed by gluconic acid, malic acid (2 g/L) and citric acid being the lowest during the 15 days experiment. Indicating that functional groups such as polysaccharides and proteins present in bacteria strain 21,699 have lower decomposition rates and metal ions releases, than small molecular and organic acids produced by strain Z107 bacteria (Zhao et al., 2023).

Table 5 shows the efficiency comparison of each Lithium extraction process from ores or clay. Although many can be considered as a Cost-effective first step to concentrate lithium-bearing minerals, reducing downstream processing volume, and is environmentally friendly compared to other chemical methods at the early stage of extraction. However, lithium cannot be fully separated from its complex ores, various types of mineralogical composition exist, high energy input, generates CO_2 emission, multi-stage process, large amounts of acid intake, risk of scale formation, corrosion, generates acidic waste that needs neutralization., and dissolve unwanted metals (e.g., Fe, Al). One way to improve, and may dissolve unwanted metals, this technique is by using a finer particle size for better liberation, the use of hybrid furnaces or microwave-assisted roasting, using renewable energy for thermal processing, and integration of waste heat recovery systems.

5 Lithium Recovery from Lithium-Ion Batteries (LIB) Recycling

The global dependency on the electronic market is in rapid growth, and the demand for electronics such as mobile phones, laptops, electric vehicles…etc. has increased during the past years. This growth in turn leads to an increase in the number of required raw materials and rare earth metals production and mining such as gold (Au), silver (Ag), platinum (Pt), lithium (Li), copper (Cu), and others (Anik Hasan et al., 2023). Furthermore, LIBs nowadays are consumed as powerhouses and storage in most electric devices and appliances (Ra & Han, 2006; Nan et al., 2005). The global growth of LIB market growth increased by ~ 11% with a net value of $73 Billion by 2025, due to the rapid use of EVs and consumption of stationary powerhouses (Olivetti et al., 2017). Moreover, the process of finding and extracting raw materials to meet global demands is becoming scarcer, and unfeasible with time due to high cost (Prior et al., 2012). Other drawbacks include the non-renewability or recyclability of pure metal used in the production of LIB, which enforces the need to introduce new methods to reuse the valuable metals existing in LIB. However, the safety regulation and disposal of hazardous materials protocols are getting much stricter,

Table 5 Efficiency Comparison of different lithium extraction processes from ores/clay

Method	Lithium Recovery (%)	Energy Use	Time Required	Environmental Impact	Ref
Roasting + Acid Leaching	80–95%	High	Moderate (hours)	High (emissions/waste)	An et al., 2012; Gao et al., 2023; Qiu et al., 2025
Pressure Leaching	85–95%	Moderate-High	Short (hours)	Moderate	Qing et al., 2023; Lv et al., 2018
Acid Leaching	70–90%	Moderate	Short (hours)	Moderate-High	Zhao et al., 2023; Porvali et al., 2019
Bio-leaching	40–70%	Low	Long (days–weeks)	Low	Zhao et al., 2023; Ekberg & Petranikova, 2015

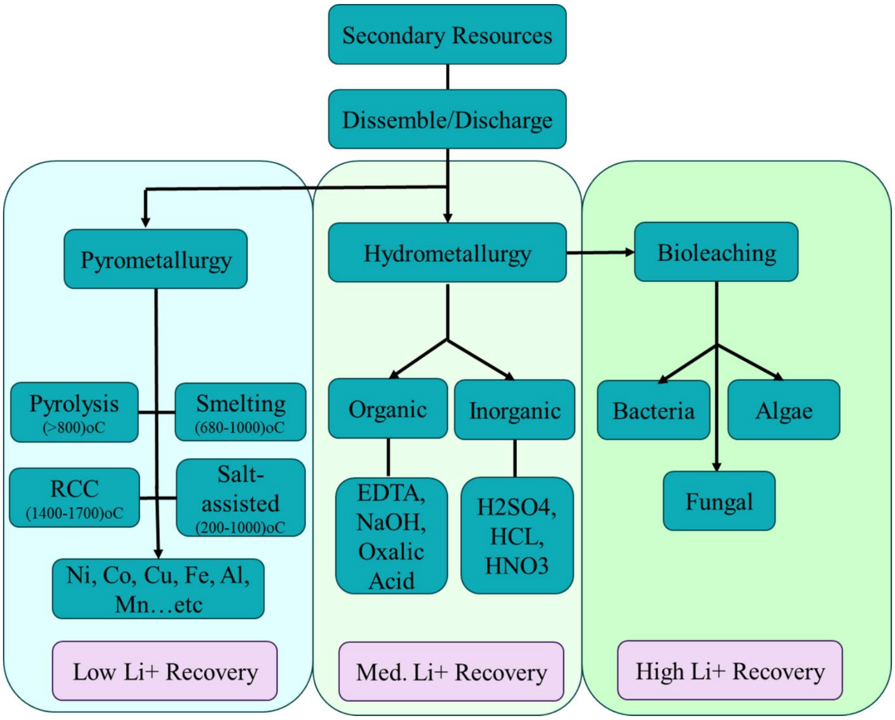


Fig. 11 The flowchart illustrates the three different techniques -pyrometallurgy, hydrometallurgy, and bioleaching- used to recover lithium from its secondary resource (LIB\LIMOB), and the experimental conditions and the chemicals involved in each process

especially for spent batteries that contain contaminated electrolytes and toxic metals, which increases the challenges of managing the waste produced by LIB (Zhang et al., 2018). Two processes are widely used and associated with LIB recycling lithium extraction from law grade or used ores. These traditional processes are hydrometallurgy and pyrometallurgy lithium extraction (Norgate et al., 2007). Additionally, Bioleaching, known as bio-hydrometallurgy, is a third technique recently introduced for lithium extraction from spent LIB that uses micro-organisms to extract lithium (Roy et al., 2021). Figure 11 shows a scheme of the process used to recover lithium from secondary resources, covering the three processes: pyrometallurgy, hydrometallurgy, and bioleaching. The most widely used process in managing the recyclability and recovery of metals of LIB is pyrometallurgy (Tunsu & Retegan, 2016). However, this technique requires a high-temperature process, high consumption of energy, and high cost to recover lithium and other metals from LIB, and induces hazardous emissions and gases (Sun & Qiu, 2011; Xiao et al., 1966). Wearies hydrometallurgical techniques possess more advantages than pyrometallurgy in many areas including sustainability, low energy, and cost-efficiency during metal extraction (Lv et al., 2018). Nevertheless, one of the limitations of this technique is the usage of highly concentrated reagents such as hydrochloric acid (HCL), nitric acid (HNO_3), sulfuric acid (H_2SO_4), and other concentrated lixiviants, that introduce complicated and additional disposal processes. Up to this date, bio-hydrometallurgy offers more advantages than the previously mentioned techniques, since it offers safe greenhouse emissions and a wide range of e-waste metal recovery technologies. Moreover, bio-hydrometallurgy has a promising role in urban mining, metal extraction, and electronic metal waste recovery given the usage of safe bio-organisms (Islam et al., 2020; Jain et al., 2016; Morin et al., 2006). Table 6 states the difference between hydrometallurgy, pyrometallurgy, and bio-leaching, as well as ways of improvements of LIB extraction processes.

Table 6 The advantages and limitations of different LIB processes

Method	Strengths	Limitations	Efficiency Improvements	Ref
Pyrometallurgy	Mature process, handles mixed LIBs, recovers Co/Ni/Cu	High energy, low Li recovery, toxic gases	Microwave/induction heating, post-leach slag processing, emission control	Hu et al., 2021a; Moazzam et al., 2021; Qu et al., 2024
Hydrometallurgy	High Li recovery, low temp, selective leaching	Uses strong acids, toxic effluents	Eco-lixiviants, closed-loop systems, hybrid solvent/membrane recovery	Anik Hasan et al., 2023; Chen et al., 2019; Domin Gues & Souza, 2024
Bioleaching	Green method, low energy, uses microbes, scalable for e-waste	Slow rate, sensitive to conditions, not fully commercialized	Genetic engineering of microbes, parameter optimization, hybrid pre-treatment methods	Anik Hasan et al., 2023; Islam et al., 2020; Li et al., 2023b; Alavi et al., 2021

5.1 Hydrometallurgy Process

The hydrometallurgy recovery process involves socking and immersion of the spent batteries in a liquid solution to transfer and liquefy all the metals in the solution through a series of chemical reactions leaving only the solution full of reactive ions. The process uses either organic or inorganic acids to dissolve the materials. The most used inorganic acids are sulfuric acid, hydrochloric acid, and nitric acid, due to their volatile nature (Chen et al., 2019, 2021; Porvali et al., 2019; Qing et al., 2023). Additionally, a wide range of organic acids are also commonly used, including citric acid, ascorbic acid, and oxalic acid (Ding et al., 2024; Nayaka et al., 2016; Xiao et al., 2021). However, despite being environmentally friendly, organic acids have lower efficiency in recovery and high prices which limit their use. In the hydrometallurgy process using an inorganic liquid–solid process, the Li recovery efficiency percentage depends on the type of solvent, time, and temperature. Ding et al. reported a 99.6% Li acid leaching efficiency using HCl as a solvent and hydrogen peroxide (H_2O_2) as an oxidant at room temperature, 96.85% Li efficiency using H_2SO_4 as a solvent and H_2O_2 as oxidant at 60° for 2 h, 98.46% Li efficiency using H_2SO_4 at 85° for 35 min and 98% Li efficiency using the same solvent at 85° for 4 h. Another inorganic solvent used was sodium hydroxide (NaOH) at 50° for 2 h and the recovery

Table 7 The experimental conditions required for each leaching agent, the recovery percentages, and advantages

Leaching Agent	Conditions	Efficiency	Advantages	Ref
$HCl + H_2O_2$	Room Temp	99.6%	High reactivity, strong acid, effective oxidizing synergy with H_2O_2	Porvali et al., 2019; Su et al., 2023
$H_2SO_4 + H_2O_2$	60 °C for 2 h/85 °C for 35 min–4 h	96.85%–98%	Non-volatile, cost-effective, scalable, strong leaching capacity	Roy et al., 2021; Xiao et al., 2021
NaOH	50 °C for 2 h	98.2%	Alkaline method; milder conditions, less corrosive equipment	Anik Hasan et al., 2023; Nan et al., 2005
H_3PO_4	50 °C for 3 h	95.1%	Less volatile, moderate leaching power	Anik Hasan et al., 2023; Ghassa et al., 2020

percentage was found to be around 98.2%. As for phosphoric acid (H_3PO_4) at 50° for 3 h the result was 95.1% Li recovery (Ding et al., 2024). However, the efficiency of Li recovery using organic solvents was found to be relatively less than inorganic solvents, this might be attributed to the ball milling process preceding the liquid–solid process and not to the leaching process. For instance, mechanical pretreatment activation takes place before the leaching process of lithium recovery, to increase recycling and recovery efficiency. These pretreatment pyrometallurgical processes include ball milling, roasting, or microwave techniques, which aid in increasing the recyclability of waste and byproducts produced by batteries ensuring a cleaner, more economic, and better recyclable technology. Moreover, this prior mechanical treatment provides the necessary energy required to break the chemical bonding of $LiFePO_4$ in the LiB and increases the recovery efficiency. In a study done by Ding et al., 2024, using leaching agents without mechanical pretreatment resulted in 60% lithium efficiency, while the efficiency percentage reached up to 92.04% post-treatment. Indicating that mechanical preparation can alter the physical and chemical properties of $LiFePO_4$ such as crystal structure, particle size, defects and dislocations, chemical bonding, and reactions. This in turn will reduce the activation energy and increase the reaction activity of individual species, improving the recovery efficiency of Li^+ over $LiFePO_4$ bond breakage and regeneration during the extraction process. However, the same group of researchers had reported using organic solvents such as EDTA, NaCl, Oxalic acid, and ammonium sulfate $(NH_4)_2SO_4$ with H_2O_2 and H_3PO_4 as leaching agent's post-mortem to the mechanical treatment increasing subsequently the recovery percentage up to 94.29%,93%, 99.5% of lithium respectively. However, when using NaCl during the ball-milling process, Na^+ substitution for Li^+ in $LiFePO_4$ causes a distortion in the lattice structure and results in yielding $NaFePO_4$ as a precipitate due to its similar crystal structure to $LiFePO_4$. Additionally, adding Na_2CO_3 will lead to precipitating Li element without the usage of any acid. The obtained lithium percentage was found to be around 27 wt% (Ding et al., 2024). Table 7 summarizes the experimental conditions for each reagent used, the recovery percentage, and the advantage. To increase the recovery percentage several steps need to be done including: (I) pretreatment, (II) higher temps (up to 85 °C) correlate with higher yields, (III) leaching by strong acids and oxidants promote metal dissolution, (IV) sufficient soaking time enhances reaction completeness, and (V) using additives such as H_2O_2 improves oxidative dissolution; Na_2CO_3 enables precipitation without acid.

5.2 Pyrometallurgy Process

Currently, the pyrometallurgy process is the most dominant to recover valuable metals, due to its applicability on a wider scale, simplicity, flexibility, and usage on different types of batteries. This technique required the usage of elevated temperatures to recover metals. At relatively low temperatures, phase changing occurs and other structural modifications take place whereas, at high temperatures, chemical reactions dominate leading to bond breaking, leaving the metals prone to recovery (Tunsu & Retegan, 2016). However, despite the simplicity and scalability of this process, undeniable drawbacks are noted including high energy input, high operation cost, loss or damage of lithium metal, toxic emissions, and poor waste recycling management (Tunsu & Retegan, 2016). Based on an article published in Waste electrical and electronic equipment (WEEE), around 10–1000 + tons/day of electrical waste is being burnt in municipal incinerators, whereas < 1 ton/day (manual) is being burnt in open burning facilities due to environmental regulations and permits (Tunsu & Retegan, 2016).

For instance, the energy input to recover copper metal is estimated at around 6.3 MJ/Kg Cu, and the CO_2 emission during this process is 0.44 kg/Kg of Cu (RecycLing, 2008). Four different types of pyrometallurgy processes exist: pyrolysis, carbothermic reduction roasting (CRR), smelting, and Incineration (Cornelio et al., 2024). The materials recovery from LIB in the pyrolysis, for example, depends mostly on the direct heating at high temperatures above 800 °C, of cathodic and anodic parts without the usage of any medium or substrate. Chemical and organic bonds will break, detach, decompose, or even vaporize during this process, and fluorine gaseous emission will start leaving nothing but the cathodic and anodic materials to be collected (Tao et al., 2022; Zhang et al., 2021a).

On the other hand, the carbothermic reduction roasting (CRR) process is mainly used on metal oxides at temperatures ranging between 680–1000 °C. This process uses carbon resources as a reducing agent for cathodic reduction, which induces the conversion of metals into simpler forms for easier recovery (Geng et al., 2021). In typical procedure, cathodic materials such as lithium cobalt oxide ($LiCoO_2$) and lithium manganese dioxide ($LiMnO_2$) are mixed with reducing agents such as carbon (C) and carbon monoxide (CO) the blend is then subjected to a roasting temperature in a heat treatment process. The process reduces and decomposes the cathodic materials yielding metal oxides such as Li_2O, MnO, NiO, O_2, CoO, and CO as reducing agents (Lin et al., 2024; Yuan et al., 2023).

Similar to the CRR process the smelting takes place at a temperature range between 1400–1700 °C. The process focuses mainly on the reduction of cathodic materials in LIB with the addition of Carbone as a reducing agent to form slag and other material oxides. The materials are heated above their melting temperature to enhance the separation process and liquefy them in an immiscible molten state, eliminating any prior treatment requirements or any passivation process (Ren et al., 2020; Qu et al., 2024). After direct feeding of the materials into the furnace, this process can be performed in two pathways, (i) the cathodic materials are heated at low temperatures to allow the evaporation of electrolytes and avoid material's explosion due to sudden high temperatures and overpressure inside the furnace (Rona & Schmuckler, 1973), (ii) heating at elevated temperature after pressure release to melt the materials. In this process all the organic substances and bonding are broken and evaporated, feeding the system more energy to carry the process. The final products are a mixture of alloys of Ni, Fe, Co, Cu, and other byproducts containing Al, Mn, and Li. One of the major drawbacks of this technique is the loss of Li due to its size and the high consumption of energy (Hu et al., 2021a, b).

Incineration is a salt-assisted roasting process. In this process, all the cathodic materials are transformed into water-suitable components and classified based on the reagents used during the liquefying process. The widely employed processes are sulfation, nitration, and chlorination. Among all the previous pyrometallurgy processes, salt-assisted roasting has a high selectivity for lithium as it enhances the separation of metal oxide transitions. Additionally, this process is performed in the temperature range between 200–1000 °C, which is considered relativity lower than the previous processes (Gao et al., 2024; Liu et al., 2023; Yu et al., 2020). In the sulfonation roasting process, materials containing sulfates such as H_2SO_4, $NaHSO_4$, and $(NH_4)_2SO_4$ are mixed with the electrode materials to start the sulfonation process, the cathodic materials ions including Co and Mn, experience a reduction process forming metal sulfate compounds. Similarly, lithium ions can undergo the same process forming lithium sulfate compounds ($LiSO_4$). This technique involves mainly two routes, (i) at the initial stage, the materials such as (Mn, Co, and Ni) react with sulfuric acid and undertake a reduction process and sulfation, (ii) the next step involves solid phase reactions with H_2SO_4 and carbon at high temperatures. In the latter, unstable sulfated compounds ($CoSO_4$ and others) transform into metal oxide (Co_3O_4) and further reduce to (CoO). The final products in the roasting procedure can be found in the forms of (Co_3O_4, CoO, Li_2SO_4, and some C). A similar concept applies to the chlorination roasting process with the presence of (NH_4Cl, $CaCl_2$, and Cl_2) agents, with NH_4Cl being the most used chlorinating agent (Su et al., 2024; Teng et al., 2024). During this process, most of the nitrates undergo decomposition in the presence of NH_4Cl at lower temperatures (125–250) ^{o}C in the solid–solid phase, transition forming $LiCoO_2$ and $LiNO_3$ requires high decomposition temperature at 600 °C. After the nitration process, a decomposition process takes place transforming all the materials into insoluble metal oxides to be recovered (Tang et al., 2020; Zhang et al., 2021b).

5.3 Bio-leaching Process

Bioleaching is a microbially and bio-organism-catalyzed method, built on the concept of redox reactions between the acidic environment responsible for leaching and the complexation activity of existent microorganisms. In this process, the cathode materials and metals undergo a liquifying process and enter the liquid phase as dissolved active ions. Before the initial contact and bioleaching process with LIB, the microorganisms must be cultivated and grown to trigger their functionality in acidic environments (Bakhtiari et al., 2011). Bio-hydrometallurgy offers a promising green alternative to pyrometallurgy and hydrometallurgy technologies for the recovery of metals from e-waste. Eventually, biohydrometallurgy will be essential in urban mining, particularly for metal recovery from LIB and e-waste (Islam et al., 2020). Bioleaching falls within the scope of biohydrometallurgy due to its alignment with the established use of microorganisms and their metabolic activities to recover metals from spent LIBs. This process of metal dissolution/recovery by microorganisms offers several advantages over other recycling techniques:

1. Environmentally friendly.
2. Less harmful emissions and less toxic gases
3. Less energy consumption
4. Low operational costs.

These advantages are attributed to the process being performed at low temperatures, less energy input, low toxic gaseous emissions, and easier to handle, preventing environmental contamination (Baniasadi et al., 2019). However, one of the challenges in this bioprocess is maintaining stable microbial growth with proper function, since some of these activities (bacteriostatic and bactericidal) can affect the heavy metal, leading to microorganism toxicity and malfunction (Jang & Valix, 2017). The stimulation of microorganisms to spent LIB metals is biphasic and can affect the growth of microorganisms. For instance, low heavy metal concentrations may stimulate the growth of microorganisms, whereas at higher concentrations the microorganism growth can be inhibited as well as its metabolic activities (Jang & Valix, 2017).

Roy et al. in 2021 managed to recover 60% of lithium and 94% of copper in 72 h using autotrophic bacteria known as *Acid Thiobacillus Ferrooxidans* and by increasing biogenic medium of H_2SO_4 in a mixture of $LiCoO_2$ LIB, the experiments were conducted at high pulp densities of 70 g/L and 100 g/L using bacterial culture and diverse pulp density (S/L ratios) preliminary from 5 g/L and reaching to 100 g/L in bioleaching of $LiCoO_2$-based LIB batteries (Heydarian et al., 2018; Roy et al., 2021). Other studies used *Archaea* to recover lithium. In particular, Ghassa et al. in 2020 used *Ferroxidans spp* a type of Archaea to recover valuable metals, they managed to recover 73% Li, 98% Ni, and 79% Co. The addition of ferroxidane (Fe^{2+}) in the presence of H_2SO_4 does not affect the releasing mechanism of Li by acid dissolution mobilization mechanism (Bahaloo-Horeh & Mousavi, 2017; Ghassa et al., 2020; Roy et al., 2021). However, other metals such as Ni, Co, and Mn recovery increased with the increase of ferrous ions (Fe^{2+}) concentration (Baniasadi et al., 2019). Most of the lithium recovered was extracted from waste lithium-ion batteries (secondary lithium source) with moderately thermophilic bioleaching, the whole process was done within 2 days. The elevated leaching kinetics of this technology provides it with superiority for recycling LIB waste in comparison to bacterial recovery processes (Ghassa et al., 2020; Liu et al., 2024; Roy et al., 2021). On the other hand, Horeh et al. in 2016 used fungi to extract lithium from LIB. They were able to recover 95% Li, 38% Ni, 45% Co, and 70% Mn using *A. niger fungi*, *Aspergillus niger* is a haploid filamentous fungus uncovered in mesophilic commonly found in food decaying, vegetation, and soil. The use of these fungi was reported for waste management and bioleaching (Alavi et al., 2021; Bahaloo-Horeh & Mousavi, 2017; Roy et al., 2021; Schuster et al., 2002). Table 8 summarizes the highlights of bioleaching process and scalability level for each controlling factor.

Table 8 The key factors in controlling the scalability of bioleaching process for LIB (Moazzam et al., 2021)

Factor	Current Status	Scalability Outlook
Environmental sustainability	High	Favorable
Cost efficiency	Moderate-High	Favorable with scale
Amount of material used (Tons\Days)	Low < 10 kg/day in most cases	Needs improvement
Industrial maturity	Low Almost non-existent for LIBs – limited to metals like Cu, U in mining	In early development
Process control complexity and Technology Readiness Level (TRL)	Moderate TRL 3–4 (Lab-scale or small pilot studies)	Manageable with tech

6 Lithium Recovery from Metal Oxide Batteries (MOB)

In the past ten years, amorphous glass metal oxides have been intensively studied due to their amorphous structure and ability for lithium recovery from cathodic electrochemical reactions. Metal oxide anode glasses are known for their high dis/charge capacity and cyclic stability, granting them the potential to replace the current known low-capacity performance of graphite anode in LIB. Therefore, more studies are focused on metal oxide materials possessing higher specific capacity than graphite. In some studies, nickel cobalt manganese oxide cathodes were studied for LIMOB recovery (Venkatraman et al., 2004). Others reported using tin oxide (SnO_2) due to its high specific capacity of 992 mAh/g (Shang et al., 2023). However, during the process of dis/charging, the tin anode exhibits a volume change, the anodic side volume expands, and the cycling process results in electrode crushing, loss of electrical collector, and tin alloy particle agglomeration. Therefore, the use of a phosphate matrix is required to suppress the formation and agglomeration of Li-Sn alloys (Shang et al., 2023). In 2013 Yamauchi et al. proposed a systematic lithiation reaction process for the conversion of metal oxide and lithium ion. During the process the lithium ions can easily embedded in the amorphous structural defects of the metal oxide anode creating what is known as amorphous lithium oxide matrix (Jiang et al., 2021). Moreover, Zhang's team reported in 2018 the use of vanadium oxide (V_2O_5) metal oxide glass for the lithium/de-lithium potential process in electrochemistry, the full procedure can be found in his research paper (Souri, 2010). They found that the cycle of a vanadium-based glass anode is stable and has a longer lifespan; thus, the discharge-specific capacity is considered to be lower than that of tin. Nonetheless, further studies to improve the phonon-assisted hopping model (SPH) in the temperature range 305–472 K must be done to expand the field of LIMOB.

Salces et al. used graphite to recover lithium from recycled batteries, especially $LiFePO_4$ and $LiMnO_2$ (Ding et al., 2024; n.d.; Salces et al., 2022). When LIBs are separated or recycled, they separate into two components: (i) a coarse fraction which contains the electrode foils, and (ii) a fine fraction known as the "black mass" containing the active materials of the electrode. The coarse fraction can be treated mechanically to separate plastic or metal casing, separator, and other large components. Whereases, Hydrometallurgy is used to process the fine fraction and dissolve the lithium-ion metal oxide (LIMO)s followed by treatment with organic or inorganic acids before filtering it through a graphite flotation feed. Using this experimental setup, 80% of LIMOs were recovered after three flotation processes (Salces et al., 2022). The major strength of MOB is its capacity, metal oxide anodes (e.g., SnO_2, V_2O_5) offer significantly higher lithium storage capacity than traditional graphite (up to 992 mAh/g for SnO_2), which limits its performance in high-demand applications. The amorphous nature of glass metal oxides allows better lithium-ion accommodation through structural defects, improving charge/discharge efficiency. Materials like V_2O_5 show long cycle life and thermal stability, making them reliable for extended battery use. Graphite flotation and hydrometallurgical processing enable the recovery of up to 80% of lithium metal oxides from recycled LIBs, supporting circular economy goals. However, drawbacks can be found in the expansion and degradation of tin oxide anodes, which suffer from large volume changes during cycling, causing electrode pulverization and reduced electrical connectivity. Nevertheless, the recycling process involves multiple steps (mechanical separation, acid treatment, filtration), which can be time-consuming and resource-intensive, and without stabilizing agents like phosphate matrices, lithium alloy particles tend to agglomerate, reducing the efficiency and life of the electrode. One way of improving this cycle is by (I) Material engineering, incorporating flexible or composite matrices (e.g., phosphate, carbon coatings) to buffer volume changes and prevent particle agglomeration. (II) Structural design; enhancing the porosity and defect engineering of amorphous metal oxides can improve lithium diffusion and structural stability. (III) Integration cycling; combining mechanical, thermal, and hydrometallurgical treatments into a continuous system may reduce energy use and processing time. (IV) Enhancing Phonon-Assisted Hopping (SPH) Mechanism; Further studies on temperature-optimized ion transport could improve the performance of vanadium-based and other glass anodes across wider operating ranges.

7 Advantages and Limitations

Lithium recovery from various resources is a global issue due to the limited access to some resources and regions. The rising demands for Li to fulfill the expanding global needs in the medical, environmental laws, manufacturing, and energy sectors encounter enormous challenges. These challenges include the manufacturing and production costs, the difficulties of the recovery processes, the type of final product, and market needs. Table 9 summarizes the percentage of each Li recovery process from various resources and the most effective reagents used for extraction, along with the experimental conditions and the final lithium product.

Since the traditional Li recovery processes from ores\clay are much more expensive due to the mining, treatment, and manufacturing processes, other unconventional techniques were developed for Li recovery from other sources including primary resources such as brine, geothermal brine, and seawater. Li recovery is also reported from secondary resources such as LIB and LIMO processes but is still critical and requires alternative clean energy. Based on some data collected from different resources, the production cost and recovery of lithium from ore and clay resources is estimated to be > 230 billion $US including the excavation, mining, recovery, and treatment processes (Makuza et al., 2021). However, the cost can be higher depending on the targeted ores. On the other hand, the cost of lithium recovery from brine is around 18 billion $US, and from secondary resources such as LIB it can start from 20,250,000 $US for cathodic parts and 17,550,00 $US for anodic parts underscoring a sum of 221billion $US for the whole process with a production rate of 80 K mt/year by 2026 (Shang et al., 2024). Despite having a high recovery rate and economic availability, lithium recovery from primary resources such as ores and clays possess environmental restrictions due to the secondary pollutants emission, high energy consumption, extensive use of acids and bases, wide range of pH, and long process. Moreover, pure Li extraction forms are much more difficult to produce due to the occurrence of interference with Mg^{+2}, Ca^{+2}, Na^{+}, and K^{+} ions in brine and seawater resources, which in turn causes a reduction in the recovery effectiveness of Li (Liu et al., 2019; Yu et al., 2022). Some of the pros of the brine recovery process of lithium are the low operational cost compared with other resources, the high recovery percentages of lithium from various techniques such as precipitation, membrane, ion exchange, and chromatography, and simple process routes. However, this process requires long recyclability of the byproducts and uses harmful concentrated acids and bases to maintain the pH along with many chemicals. On the other hand, lithium recovery in the LIB and LIMO fields has recently grown due to the market demands despite the high cost. One of the foremost advantages of LIB recovery techniques is the recovery of high-purity lithium, where no complex chemicals are required, and minimal experimental conditions are employed. In contrast, the main disadvantage can be summarized in the high energy consumption, low recyclability rate of the byproduct, and multi-step process which in turn increases the operation time.

Table 9 Comparison of different lithium recovery processes

	Process	Advantage	Disadvantage	pH	Reagent	Product	Recovery%	Ref
Brine	Precipitation	High purity Li Less time Low cost Regeneration of chemicals	Low Recyclability Long process Use of many chemicals	3–7.2	Lithium aluminate, $Ca(OH)_2$, $Na_2C_2O_4$, $\mathbf{Na_2CO_3}$,	LiCl	~99.55%	Lv et al., 2018; Li et al., 2015
	Liquid–liquid exchange				**MC50 resin**, TP207 resin, Y80-N Chemie AG, n-butanol		~78%	Shiraishi et al., 2000; Luo et al., 2023
	Ion liquid extraction				$\mathbf{H_2TiO_3}$ **ion exchanger**, $NaHCO_3$ $ZnCl_2$, $FeCl_3$, $CrCl_3$, Tributyl phosphate, kerosene, methyl isobutyl ketone		92–93%	Alsabbagh et al., 2021; Abe & Chitrakar, 1987; Luo et al., 2023; Sun et al., 2023
	Chromatography				Polyacrymidegel, **Bio-Gel P-2** and Blue Dextran 2000		~98%	Rona & Schmuckler, 1973; Lee, 1967; Lv et al., 2018; Suarez et al., 2011; Hossain et al., 2023
	Membrane				Bipolar membranes	LiOH, Li_2CO_3	~98%	Hoshino, 2013; Jiang et al., 2014; Li et al., 2015; Liu et al., 2015
Ore	Alkali leaching	economically available environmentally friendly Higher recovery efficiency	suitable for lab scale only long process high energy secondary pollutants Unfeasible	2–13	$\mathbf{Na_2SO_4}$, CaO	Li_2CO_3	~81%	Liu et al., 2019; Mends & Chu, 2023; Swain, 2017; Tran & Luong, 2015; Zhao et al., 2023; Morin et al., 2006
	Bioleaching, Acid treatment		Use of acid costly		miroorganism, HF, H_2SO_4		~98%	Tran & Luong, 2015
	pyo- hydro metallurgy, Acid leaching				soda ash, 20% HCl, limestone		~70%	Alhadad et al., 2023; Morin et al., 2006

Table 9 (continued)

	Process	Advantage	Disadvantage	pH	Reagent	Product	Recovery%	Ref
Seawater	Co-Precipitation	Low cost Regeneration of chemicals Economically available	high concentration of alkali and alkaline metals with similar characteristics as lithium	6.5–14	$Al(OH)_3$, **Na_2CO_3** + HCl	Li_2CO_3	~92%	Alsabbagh et al., 2021; Um & Hirato, 2014; Epstein et al., 1981
	Ion-Exchange				Titanium (IV) antimonate cation exchanger (TiSbA), H_2TiO_3		~56%	Liu et al., 2019; Mends & Chu, 2023; Swain, 2017; Bukowsky et al., 1991
	Liquid–Liquid extraction				Cyclohexane tri-octyloxyphosphine, Thenoyltrifluoroacetone (TTA) and TOPO		~80%	Liu et al., 2019; Luo et al., 2023; Sun et al., 2023
	membrane				Bipolar membranes, Bipolar membranes		~89%	Hoshino, 2013; Li et al., 2015; Liu et al., 2015
LIB LIMOB	Hydrometallurgy	no additional chemicals high efficiency high Li purity	energy consuming < 1% recyclability time-consuming	1.5–2.6	Organic · Oxalic acid · EDTA · NaOH Inorganic · HCl · **H_2SO_4** · $NaHSO_4$ · $(NH_4)_2SO_4$	Lif Li_2CO_3 Li_3PO_4	88–95%	Porvali et al., 2019; Chen et al., 2021; Ding et al., 2024
	Pyrometallurgy	simple process simple operation conditions high recover efficiency	multi-step process energy consuming short life span			Li_2CO_3	~87%	Anik Hasan et al., 2023; Islam et al., 2020; Qu et al., 2024; Ghassa et al., 2020; Cornelio et al., 2024
	Bioleaching				*Acidithiobacillus ferrooxidans* bacteria ***Aspergillus niger fungi*** bis(2-ethylhexyl) phosphate (D2EHPA), PC-88A, LIX 84, and tri-n-butyl phosphate		70–96%	Anik Hasan et al., 2023; Islam et al., 2020; Qu et al., 2024; Ghassa et al., 2020; Cornelio et al., 2024; Liu et al., 2024

8 Technical and Economic Analysis Trade-Offs Lithium Recovery Processes

Based on what have been discussed in Sect. 3 – advantages and disadvantages- and Table 2. Primary resources such as Brine and Seawater offer high recovery efficiency at low costs, with Brine being the most economically favorable. While ore-based methods are the least economical, with extremely high costs. Secondary resources, including the Recycling of LIBs (Lithium-Ion Batteries) is also very expensive, but the increasing supply of spent LIBs might offset future costs (Hao et al., 2024). Table 10 states the technical and economic analysis of the best lithium recovery process from its sources.

From an economic standpoint, brine-based extraction, particularly precipitation, emerges as the most cost-effective option, offering high lithium recovery ($18 billion). Seawater methods, such as co-precipitation, also show promise with moderate costs ($221 billion) and good recovery rates, achieving high recovery (88–95%) and supporting sustainability goals, making it strategically important despite current cost barriers. Overall, the economic analysis highlights brine and seawater extraction as the most viable options for immediate, large-scale lithium production, while LIB\LIMOB recycling holds long-term value in a circular economy framework (Mossali et al., 2020; Sonoc et al., 2015). Table 11 states economic, environmental, technical and long-term potential analysis for each lithium recovery resource.

9 Research Gaps and Limitations

The overhead-highlighted processes discussed in this review and other research papers have their peculiar perspectives and possibilities to support their claims regarding the economy and environment for lithium recovery and its extraction, separation, purification, recovery, and recycling. Some of these lithium recovery processes face challenges and worldwide limitations that necessitate deep investigation for novel procedures. Many literature reviews and research show that Li_2CO_3 is the most targeted form of lithium to recover due to its wide application in pharmaceutical and industrial fields. Moreover, the necessity to utilize and build new feasible and more efficient lithium recovery technologies is required to keep up with the

Table 10 The technical and economic trade-offs of lithium recovery sources and the advantages, disadvantages, optimum processes and their scalability

Li source		Advantage	Disadvantage	Optimum extraction process	Scalability	Ref
Primary	Brine	High purity, low cost Quick chemical regeneration	Long process many chemicals low recyclability	Precipitation (99.55% recovery, low cost)	under controlled conditions site-specific process optimization based on regions	Christ Mann et al., 2015; Yu et al., 2022; Balaram et al., 2024; El Makki et al., 2024
	Ore	Efficient recovery eco-friendly under lab settings	Costly energy-intensive not scalable easily	Bioleaching (~98% recovery)	limited industrial scalability	Swain, 2017; Tran & Luong, 2015; Gao et al., 2023; Balaram et al., 2024
	Seawater	Abundant source low cost in some methods	Competition from similar ions (Na+, Mg2+) lower selectivity	Co-precipitation (~92% recovery)	High, given the seawater's abundance and improved membrane technologies	Swain, 2017; Alshuiael & Al-Ghouti, 2022; Lee et al., 2025; Yu et al., 2023
Secondary	LIB\LIMOB	High purity, sustainability, growing waste sources	Energy-intensive Complex steps involve	Bioleaching (~96% recovery)	TRL 3–4 (Lab-scale or small pilot studies) Scaling depends on kinetic limitations, optimizing microbial systems	Olivetti et al., 2017; Domin Gues & Souza, 2024; Ghassa et al., 2020; Zhou et al., 2024; Wei et al., 2023; Chagnes, 2015

Table 11 Lithium recovery resources economic, environmental, and technical data analysis

Source	Economic Viability	Environmental Impact	Technical Feasibility	Long-Term Potential
Brine	★★★★★	★★★★☆	★★★★★	★★★★☆
Seawater	★★★★☆	★★★★★	★★★★☆	★★★★★
Ore	★☆☆☆☆	★★☆☆☆	★★☆☆☆	★★☆☆☆
LIB\LIMOB	★★☆☆☆	★★★★★	★★★★☆	★★★★★

growing market demands, especially in the secondary lithium resources sectors including LIB and LIMOB. Despite the widespread LIB and growing demands, the field lacks a proper recycling process for byproducts and still has a low recovery percentage compared with other fields such as brine and seawater resources. Additional investigations are necessary to create a procedure for lithium recovery and recycling lithium from LIB itself and not only by using recycled lithium from a primary resource in LIB. If found, this procedure will also propose an alternative manageable option to LIB waste control, limit the environmental impact, and increase the ability of energy circulation and consumption, alongside stimulating economic growth. Regardless of the current three methods used in the LIB, pyrometallurgy can be impeccable on a large scale if we can control the high amounts of investment and high energy demands. However, this process is not the best option when it comes to recovering byproducts and metals, since it eliminates most of them. On the other hand, bioleaching of LIB is still in the growing stage and a lot of research needs to be done. Lastly, hydrometallurgy can be implied on a much smaller scale than pyrometallurgy and it uses lower energy requirements, inducing minimal emission of CO_2 gas, and most preferably can be designed based on the targeted metal to be recovered. Many other processes such as hybrid processes, including membranes, chromatography, and liquid exchanges need more attention and investigation for efficient lithium recovery from LIB while minimizing the negative impact on the economy, environment, and industry. Since the primary methodologies employed for the recovery of valuable metals from spent lithium-ion batteries (LIBs) include pyrometallurgical and hydrometallurgical processes are most applied, regardless of their drawbacks, which includes high energy consumption, the generation of hazardous gaseous emissions, and considerable lithium loss, all of which negatively impact both environmental sustainability and the overall efficiency of resource recovery. A new study group in 2024 led by Jiacheng Hao et al. has proposed recovering lithium from spent ternary lithium-ion batteries, which contain various hazardous substances, including heavy metals, organic compounds, and other environmentally toxic constituents (Hao et al., 2024). This study presents an innovative method for the selective separation of lithium and transition metal ions from leachates derived from ternary cathode materials using the "(+) $LiFePO_4$/$FePO_4$ (-)" electrochemical deintercalation/intercalation (EDI) method. The proposed technique achieves a lithium recovery efficiency of approximately 99%, significantly outperforming conventional hydrometallurgy, pyrometallurgy, and bioleaching methods. Additionally, the process is characterized by minimal chemical reagent consumption and does not introduce extraneous impurities, thereby contributing to a reduction in solid waste generation and enhancing the overall environmental sustainability of lithium recovery operations.

10 Conclusion

The rapid consumption of lithium worldwide enforces the need for new recycling techniques. With less than a 3% recycling rate, global demand cannot be met unless a higher percentage is achieved. While Lithium consumption and technological innovation increase, the implementation of faster metal recovery without disregarding economic and environmental regulations is required. The recycling of lithium from secondary sources, such as lithium-ion batteries (LIBs) and lithium ion metal oxide batteries materials (LIMOBs), bypasses several preliminary steps required in the extraction of lithium from primary sources, including mining, ores, and clays. This approach aligns with environmental safety regulations and supports clean energy initiatives by promoting sustainable and eco-friendly practices.. Many industries are recovering lithium from their primary sources; however, few are focusing on recycling, this is mainly due to the lack of proper procedures, and limited resources. Nevertheless, some researchers use alternative pathways for recycling lithium by using bio-organisms to create a safer and green alternative to recover lithium through the bioleaching process. This review summarizes some research used in Li recovery. Each procedure has its potential and results aiming primarily towards supporting the environment, economic, and safety regulations, extending the process of extraction to the recovery, separation, purification, and recycling of lithium. Additionally, some processes such as pyrometallurgy are only applicable on large scales and require more energy inputs, and high production and maintenance costs despite the high recovery rates, which in turn affect the safety regulations and environment. On the other hand, hydrometallurgy can be applied to smaller scales, is safe for the environment, and has mild toxic emissions but still lacks scalability, and the use of concentrated acids during the recovery process is an alarming drawback of this procedure. Until recently, bioleaching has offered the best option for lithium recovery since it respects safety regulations and has green energy consumption, as well as the presence of diverse designs of bio-organisms covering various needs. The optimization and scaling of bioleaching can be done by (I) rebusting an efficient bio-organisms tailored toward lithium ions recovery, (II) by designing a bioleaching system adabtable to perform under different experimental conditions and with different types of batteries, (III) by creating a hybrid system (e.g. hydrometallurgy and bioleaching) to over come the limitations of individual methods, (IV) by replace concentrated acids in hydrometallurgical processes with eco-friendly alternatives, (V) by performing comprehensive environmental and economic analyses to integrate recycling technologies into existing industrial processes. As for the industrial implication and policies: (I) governments and regulatory bodies must implement incentives, subsidies, or regulations that promote the establishment of lithium recycling facilities, (II) standardized procedures are needed to ensure safe, efficient, and scalable recycling operations, particularly for LIBs from consumer electronics and electric vehicles, (III) collaboration between academia, industry, and government can accelerate R&D and commercial deployment of advanced recycling technologies, and (IV) policymakers should prioritize lithium sourced from recycled materials in green energy initiatives to reduce dependency on environmentally damaging primary extraction.

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Declarations

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Consent for Publication Not applicable. No person's data (e.g., images or videos) is included in this manuscript.

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