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*Review*

# Lithium in Energy Storage: A Comprehensive Review of Its Extraction, Utilisation, and Sustainability

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**Abstract:** Lithium (Li) batteries have been part of any citizen's daily life for about 30 years, although the knowledge about their potential dates to the early XX century. Being present in a wide range of applications, from small electronic appliances to hybrid or electric cars, Li has become essential to the most recent battery technology. In the need to change the harmful habits of fossil fuel usage, Li applications promise to provide a more sustainable way to deal with energy supply and improve energy storage devices efficiency. Resorting to Li carries the environmental burden of past battery technology since the materials used are well-known in the industry. Little changes have been made in Li battery manufacturing since it first became an industry, compromising its potential environmental benefits. The growing consumption drives efforts to extract Li and other scarce metals, but recycling rates are still too low for this industry to be considered a circular economy. Besides the quantifiable environmental indicators, many other intangible ones offer insight into the drawbacks and benefits of this emerging industry. In this study, the life cycle of Li-based energy storage devices is put into perspective from Li itself extraction, processing, and recycling. It was possible to identify many process variables in the Li life cycle using studies published in the last fifteen years, which can immediately reduce this promising technology's environmental footprint. Besides immediate improvements, recycling has proven to be a highly efficient way to recover and reuse enormous amounts of Li and other materials in battery manufacturing. Beyond Li usage, a significant effort should be made to improve the supply of the remaining materials in a battery. This work intends to provide a comprehensive analysis using structured information about the Li life cycle, helping to understand the benefits and drawbacks of the intensive use of this kind of metal.

**Keywords:** lithium; lithium carbonate; mining; energy storage; battery manufacturing; recycling; life cycle; sustainability

## 1. Introduction

Although Lithium (Li) as an element was discovered in 1817 by Swedish chemist Johan Arfwedson [1] *apud* [2] while studying petalite minerals, it was only in 1821 that English chemist William Thomas Brande successfully isolated it [3]. In 1818, during his attempts to isolate Li, Johan Arfwedson found minerals such as spodumene and lepidolite, which also contain Li [4]. By 1913, North American chemists Gilbert Newton Lewis and Frederick George Keyes studied the electrochemical properties of Li using its salts to determine this element's anode potential [5], paving the way to modern portable batteries that any citizen uses daily. With these findings, two prominent families of rechargeable Li batteries were created by several companies between 1950 and 1991 using solid or liquid electrolytes, with voltage ranging from 1.5 V to 3.6 V and an energy density of 10 Wh/kg to 190 Wh/kg [6]. In Figure 1, it is possible to see the display of the $Li^+$-ion battery components through a Scanning Electron Microscopy (SEM) cross-section image.

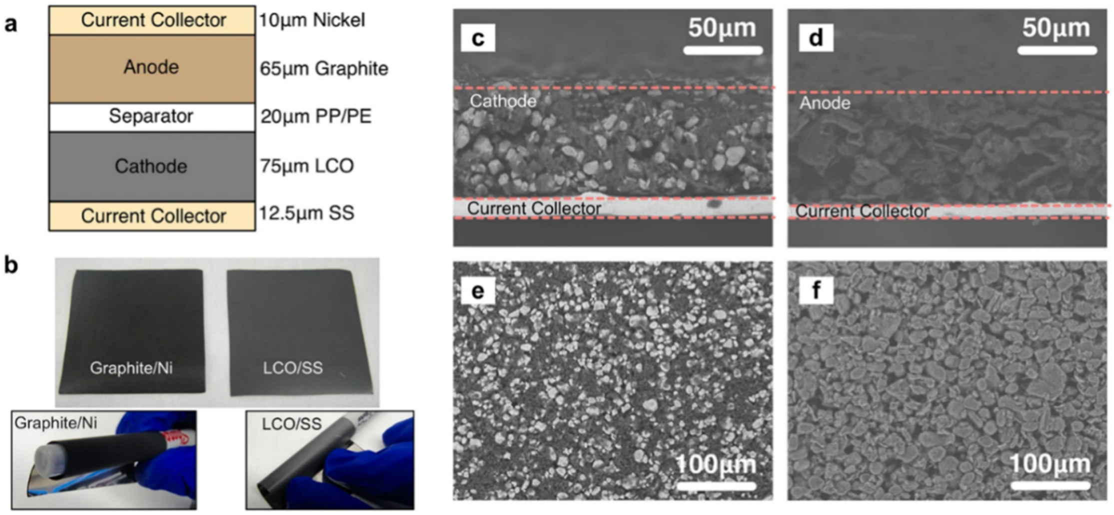


**Figure 1.** $Li^+$-ion battery system: (**a**) Cross-sectional schematic representation, (**b**) Optical image depicting the graphite electrode on Nickel (Ni) foil and the LCO electrode on stainless steel, shown both in a flat configuration (**top**) and bent around a pen with a diameter of 10 mm (**bottom**), (**c**,**d**) Cross-sectional SEM micrographs of the LCO and graphite electrodes, respectively, (**e**,**f**) Topographical SEM micrographs of the LCO and graphite electrodes, respectively [7].

Recent $Li^+$-ion batteries replaced Lead (Pb) acid batteries by improving both power density, from 250 W/kg to 800 W/kg, and energy density from 40 Wh/kg to 260 Wh/kg [8], or even higher values [9,10]. Depending on the Li compound used, batteries can have up to 7000 life cycles (charge/discharge) [11]. A Li battery, an electrochemical system, assembles a transition metal oxide cathode with Li or $Li^+$ ions, an anode usually made of carbon, current collectors, and an electrolyte [12,13]. Portable Li batteries in small electronic appliances are placed in the liquid electrolytes' family [14] because, even though the cathode tends to form dendrites, reducing the overall performance of the battery [15], they act as an excellent ionic conductor at room temperature ($T_{amb}$) [16]. This alternated structure repeats itself while rolled in cylindrical-shaped energy storage units or stacked into other shapes, as shown in Figure 2 [8].

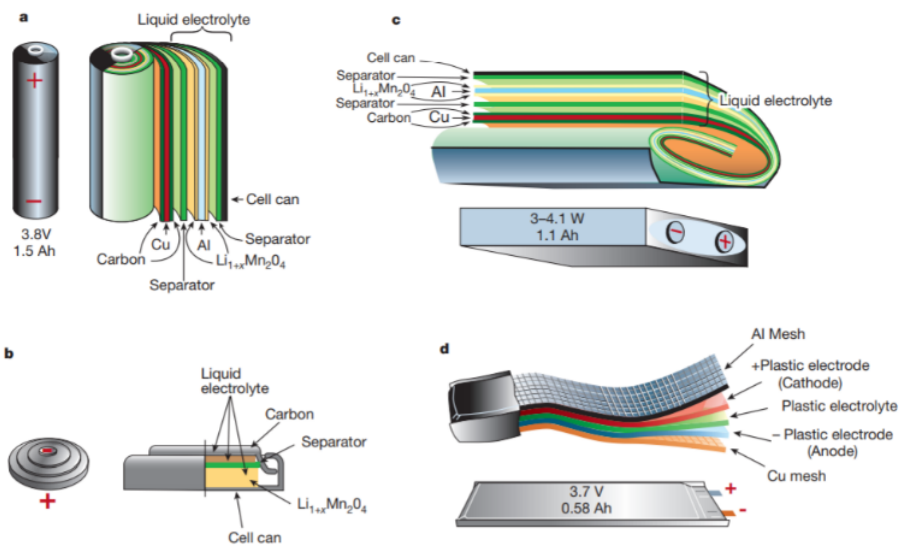


**Figure 2.** $Li^+$-ion batteries: (**a**) Cylindrical, (**b**) coin, (**c**) prismatic and (**d**) thin and flat shape [17,18].

To mitigate the issue of containing the electrodes in $Li^+$-ion batteries and avoid, or at least delay, the Li dendrites, many materials are used as dielectric [8,15] or electrolyte fluids [16]. On the other hand, solid-state batteries, including Li metal-type batteries, incorporate polymers and other non-metallic materials, proving to have a more significant energy density but are poorer ionic conductors [19]. Even though the manufacturing process varies on how the electrodes are incorporated into the battery, most batteries are functionally similar [20,21]. The variety and rarity of chemical elements and products applied in both Li metal [22] and $Li^+$-ion batteries [8] speed up the need to recycle these units pushed by the more noteworthy mining environmental concern [23]. Being a finite resource and with the growth of Li usage in batteries, its recycling is necessary to meet future consumption demands [24]. The process poses a challenge due to today's batteries complex design [8] and even the potentially hazardous materials used [8,16].

Building on the theoretical framework introduced in Section 1, Section 2 provides a detailed account of the methodology employed in this study, which adopts Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [25] and the Systematic Literature Review (SLR) [26] to identify pertinent research. Sections 3 to 8 delve into the latest advancements across key research areas, focusing on Li extraction, battery production, and recycling processes. Section 9 presents the content analysis findings, offering an in-depth exploration of emerging research trajectories and the challenges inherent in lithium technologies. Finally, Section 10 synthesises the principal conclusions and outlines potential future directions for the field.

## 2. Methods and Research

The research and data collection phases were executed using the SLR methodology, adopting a thorough, organised, and replicable process [27,28] and according to the PRISMA guidelines to ensure transparency and rigour [29]. This SLR drew upon comprehensive datasets from Scopus, particularly emphasising the most recent studies focusing on fundamental topics such as operational costs and the environmental impact of Li extraction, battery production, and recycling. The research methodology and data aggregation process underwent a rigorous quality assessment, incorporating metrics like citation counts and journal impact factors to ensure the robustness of the approach and a temporal range from ≈2010 to 2024. Data were sourced from highly credible publishers such as Elsevier, Springer, MDPI, and Taylor & Francis, all recognised for their authority in these research areas. Relevant keywords "Lithium", "Lithium Carbonate", "Mining", "Energy storage", "Battery Manufacturing", "Recycling", "Life cycle", and "Sustainability", and their combinations were employed to refine and focus the literature search. Analysis of research results using Dimensions.ai enabled the classification of articles into a myriad of academic domains (Table 1), demonstrating how comprehensive and multifaceted this paper is:

**Table 1.** Classification of the 136 papers addressed in the state-of-the-art.

| Classification | Sub-Classification |
| --- | --- |
| **Agricultural, Veterinary and Food Sciences (30)** | Crop and Pasture Production (3004) |
| **Biological Sciences (31)** | Industrial Biotechnology (3106) |
| | Plant Biology (3108) |
| **Biomedical and Clinical Sciences (32)** | Pharmacology and Pharmaceutical Sciences (3214) |
| **Built Environment and Design (33)** | Building (3302) |
| **Chemical Sciences (34)** | Physical Chemistry (3406) |
| **Commerce, Management, Tourism and Services (35)** | Transportation, Logistics and Supply Chains (3509) |
| **Earth Sciences (37)** | Geology (3705) |
| **Economics (38)** | Applied Economics (3801) |
| **Engineering (40)** | Chemical Engineering (4004), |
| | Electrical Engineering (4008), |
| | Environmental Engineering (4011), |
| | Manufacturing Engineering (4014), |
| | Materials Engineering (4016), |
| | Mechanical Engineering (4017), |
| | Resources Engineering & Extractive Metallurgy (4019) |
| **Environmental Sciences (41)** | Environmental Biotechnology (4103), |
| | Environmental Management (4104), |
| | Pollution and Contamination (4105), |
| | Soil Sciences (4106) |

**Table 1.** *Cont.*

| Classification | Sub-Classification |
|---|---|
| **Human Society (44)** | Development Studies (4404), |
| | Human Geography (4406), |
| | Policy and Administration (4407), |
| | Sociology (4410) |
| **Information and Computing Sciences (46)** | NA |
| **Law and Legal Studies (48)** | Environmental and Resources Law (4802), |
| | International and Comparative Law (4803), |
| **Physical Sciences (51),** | Biological Psychology (5202) |
| **Psychology (52)** | NA |

Figures 3 and 4 visually represent the research domains covered by the 136 papers, which focused on Li extraction, battery manufacturing, and recycling. Rather than simply enumerating the articles, the figure offers an aggregated overview, categorising the research papers based on the Fields of Research (ANZSRC 2020) from Table 1. The Figures are purposely divided into two parts to enhance readability.

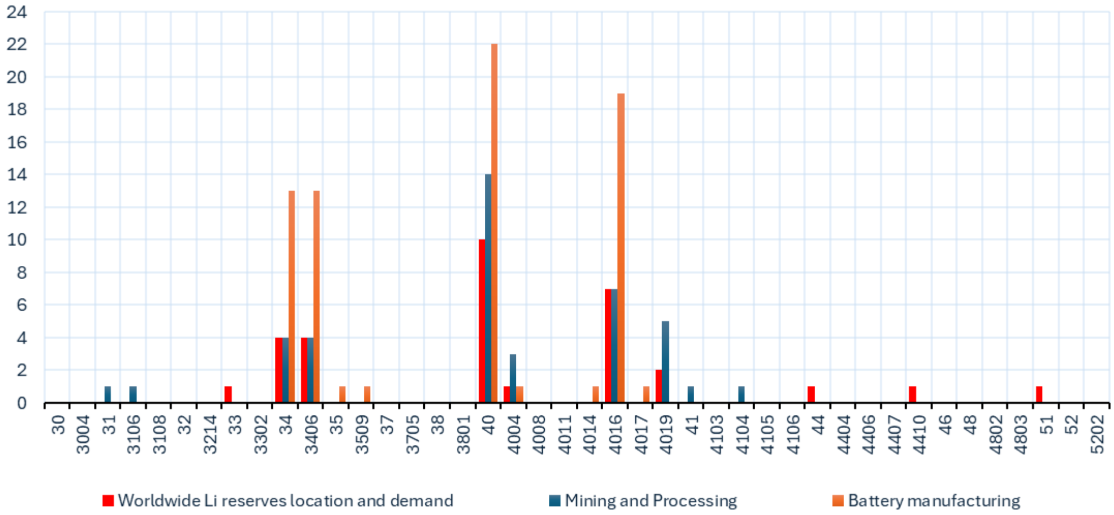


**Figure 3.** Categorisation of papers addressed in the review about Li used in energy storage according to the subjects addressed in this paper, part 1.

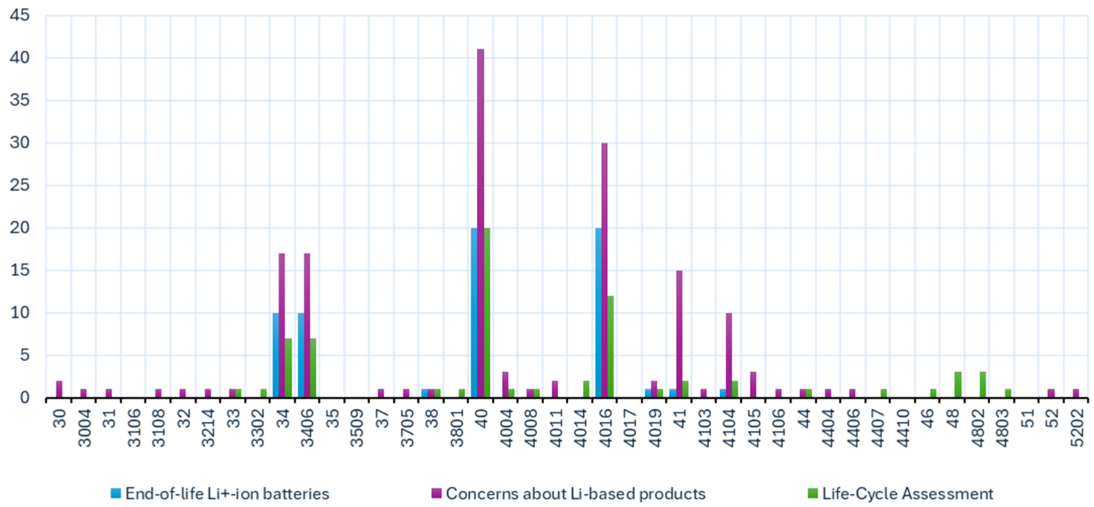


**Figure 4.** Categorisation of papers addressed in the review about Li used in energy storage according to the subjects addressed in this paper, part 2.

Sections 3 up to 8 provide an in-depth review of the literature on Li extraction, battery manufacturing, and recycling. This concise overview of these processes, particularly their growing importance in recent decades due to the rise of Electric Vehicles (EVs) [30] and renewable energy storage aims to deliver a systematic summary for newcomers and experienced professionals in the field. The methodological focus is on the relevance of these topics to the sustainable energy and manufacturing industries. A well-structured and systematic presentation of the information is essential to foster a deep and comprehensive understanding of the subject. Moreover, this research's substantial contributions to the field underscore its importance.

## 3. Worldwide Li Reserves Location and Demand

According to the most recent geological surveys, the total land Li reserves worldwide are about 21 million metric tonnes distributed per Figure 5. In 2021, it was estimated that 100,000 tonnes were produced globally, with Australia significantly surpassing other producers by generating 55,000 tonnes. Chile followed with 26,000 tonnes, China with 14,000 tonnes, and Argentina with 6200 tonnes [31,32].

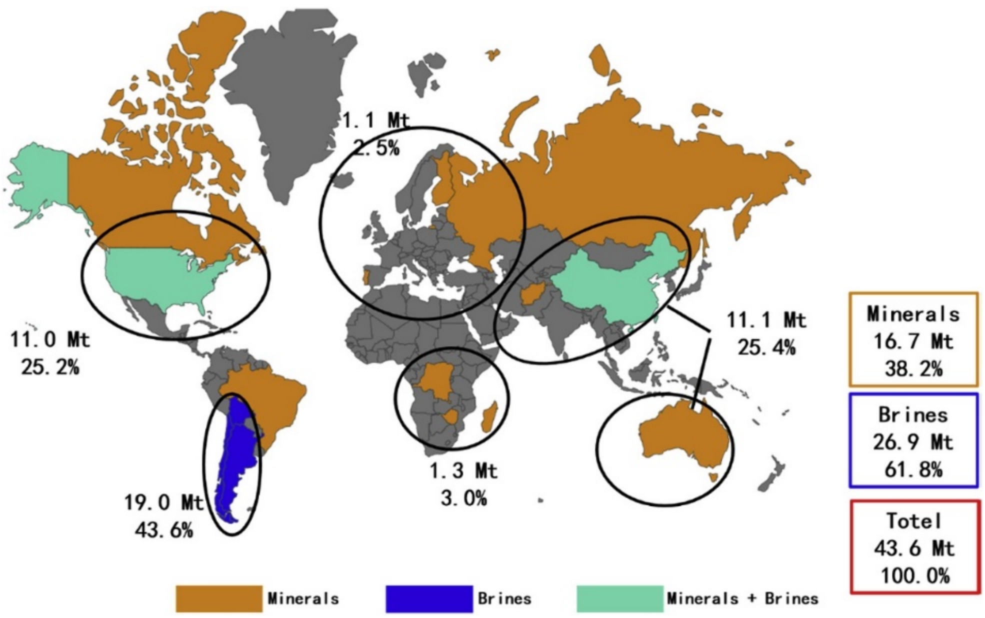


**Figure 5.** Countries with Li reserves worldwide, along with their level of reserves, a survey for 2020 [33].

The current Li deposits depend on the geographical location: the most relevant brine ponds (*Salars*) are in South America, while mineral deposits are in Australia [23]. Besides land reserves, Li can also be found in trace amounts dissolved in seawater [34,35], totalling about 230 billion metric tonnes [34,36]. Figure 6 depicts the demand for Li through different techniques. Li Carbonate ($Li_2CO_3$) production has been underestimated worldwide in recent years. From all the mining sources, 66% of the Li supply comes from brine pools, and up to 30% comes from pegmatite minerals, among other minor sources [37,38].

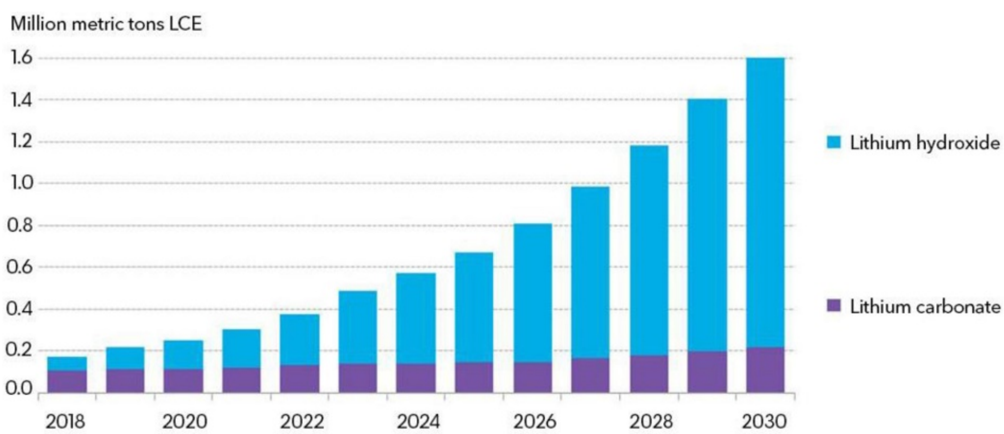


**Figure 6.** Demand for Lithium Hydroxide (LiOH) compared to $Li_2CO_3$ from 2018 to 2030 [11,39].

## 4. Mining and Processing

Li is hard to extract due to its low local concentrations and being a scarce element. It can be found diluted in sea, superficial or underground water, and minerals. The extraction methods and environmental impact greatly vary from each source [40].

### *4.1. Brine Ponds*

One of the most popular water extractions of Li is through brine ponds [41]. Underground or even superficial water with high concentrations of minerals (including Li), when compared to other water sources [23], is pumped into shallow ponds [40]. The pumped water has a concentration of $Li^+$-ions of around 230 ppm to 1500 ppm [42]. After several months of solar evaporation, when the concentration of Li Chloride (LiCl) reaches 6000 ppm, Sodium Carbonate ($Na_2CO_3$) is added to precipitate $Li_2CO_3$ [42,43]. Some steps might be repeated to obtain the target purity [42]. The extraction process, the sequential evaporation steps, and the chemical treatment of precipitation and purification can be summarised in Figure 7.

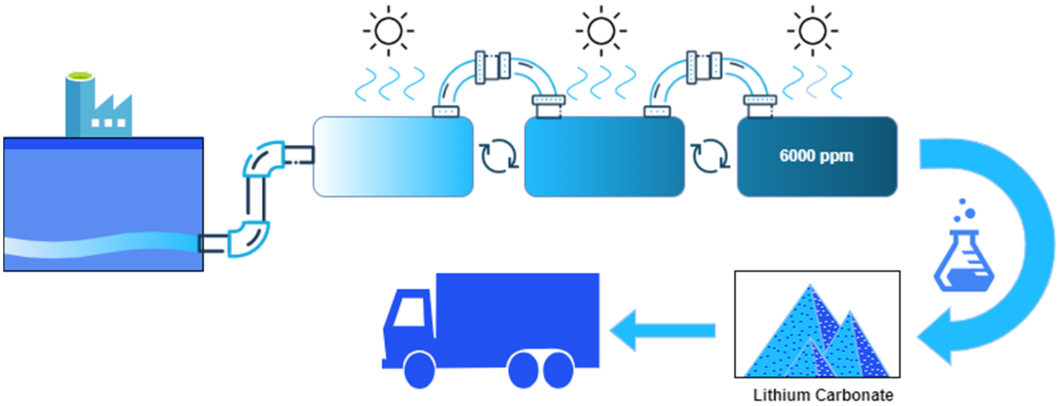


**Figure 7.** Diagram of the generic Li extraction from brine ponds-underground water is pumped out to shallow ponds, promoting evaporation until precipitation to $Li_2CO_3$.

### *4.2. Seawater*

Most Li (98% in the Earth's crust) can be found diluted in seawater, with concentration rates ranging from 0.1 ppm to 0.2 ppm, making most of the extraction methods used in brine ponds unsuitable from an economical point of view [36]. Several authors suggest experimental electrochemical techniques alongside selective membranes. Like a regular $Li^+$-ion battery, the $Li^+$-ions in seawater are pushed through a selective membrane to a cathode. Due to the small size of $Li^+$-ions, no other ion passes through it [36,44,45]. The process can be graphically represented in Figure 8. Even though the process is slow, it is compatible with green energy sources such as solar [36].

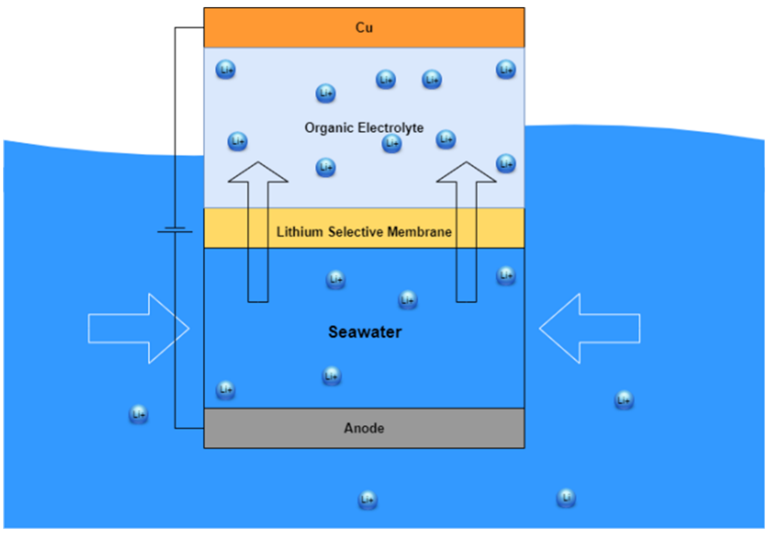


**Figure 8.** Diagram of the generic Li extraction from seawater–water minerals are pushed to the Cu-cathode, but the membrane only allows $Li^+$-ions to pass through.

*4.3. Minerals*

Pegmatites containing Li-Aluminosilicates (LAS) hold the most Li content in their composition compared to all the mineral sources. Besides the minerals listed in Table 2, many others exist [46], but spodumene, petalite and lepidolite are the most explored [39,47].

**Table 2.** Main mineral sources of Li: name, chemical composition, and Li content [46,48].

| Minerals Name | Chemical Composition | Actual $Li_2O$ Content (%) |
|---|---|---|
| Spodumene | $LiAlSi_2O_6$ | 4.5–8.0 |
| Petalite | $LiAlSi_4O_{10}$ | 2.0–4.0 |
| Lepidolite | $K(Li,Al)_3(Si,Al)_4O_{10}(F,OH)_2$ | 1.2–5.9 |
| Zinnwaldite | $K(Li,Fe,Al)(AlSi_3)O_{10}(F,OH)_2$ | 3.3–7.7 |
| Amblygonite | $LiAl(PO_4)(F,OH)$ | 4.5–10.0 |

The extraction of Li from spodumene and other siliceous minerals [46] starts with the ore crushing. This way, the efficiency of heat transfer and reaction of the upcoming processes is enhanced. The crushed ore is calcinated, so the mineral spodumene changes its structure from α to β, which is more reactive to sulfuric acid. This acid produces Li Sulphate ($Li_2SO_4$), which is later leached and transformed into $Li_2CO_3$ or Li Chlorite ($LiClO_2$, Figure 9) [37].

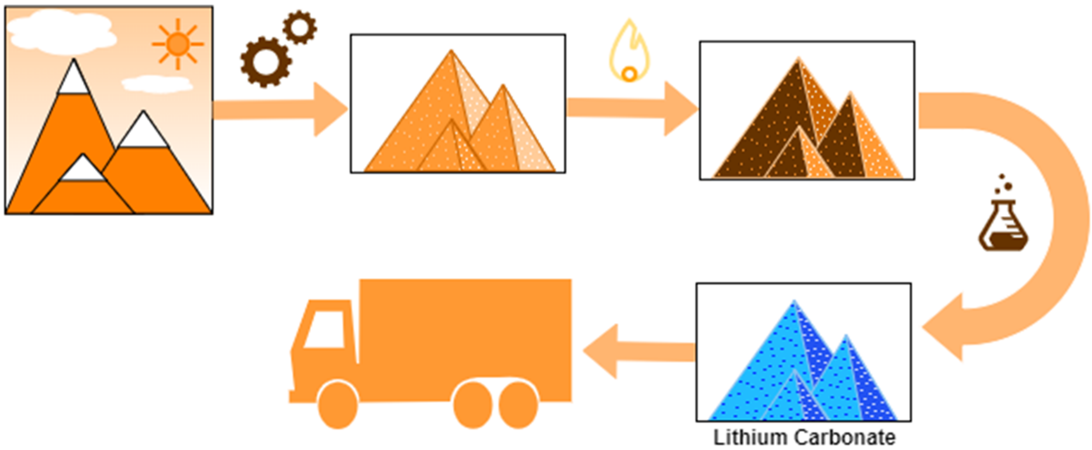


**Figure 9.** Diagram of the generic Li extraction from mineral ore-spodumene is extracted, crushed and calcinated before sulfuric acid leaches the Li to be further processed.

Some other promising processes are available or under development for [49], not only spodumene but also other Li-rich minerals, such as selective fragmentation [50] or gravity separation [48]. Building upon the hydrometallurgical recovery process for spent $Li^+$-ion batteries, Zhou et al. [51] developed an efficient and continuous synthesis process for industrial lithium carbonate within a microreactor system.

## 5. Battery Manufacturing

Immediately after the Li extraction, the resulting compound in the shape of a powder, $Li_2CO_3$, the most common, is transported to be directly used in battery manufacturing. The processes that take place to do so are described in the upcoming chapters.

*5.1. Electrode Preparation*

The first step in manufacturing modern $Li^+$-ion batteries is to prepare a slurry of active elements that will be part of the electrodes [12]. Typically, both slurries are applied to their corresponding current conductor, which is presented as a Cu-foil (in the case of the anode slurry) and an Al-foil (in the case of the cathode slurry) [52]. The slurry is composed of $Li_2CO_3$ in the shape of a powder, alongside other active materials, depending on battery chemistry, mixed with a solvent, a binder, and often additives (such as thickeners, dispersants, or conductive agents) [12,53]. Each company has its combination of ingredients, the most common of which are compiled in Table 3. Due to the variety of chemical elements and compounds, not all interventions are compatible. On one hand, some water-based binders are incompatible with the cathode active materials. On the other hand, some binders might not dissolve in the solvent [54].

**Table 3.** Slurry composition by role, chemical composition, and commercial name [21,54–56].

| Cell Component | Chemical Composition | Commercial Name |
|---|---|---|
| Cathode active material | $LiCoO_2$ | LCO (Lithium cobalt oxide) |
| | $LiCo_xMn_yNi_zO_2$ | NMC (Lithium nickel manganese cobalt oxides) |
| | $LiFePO_4$ | LFP (Lithium Iron Phosphate) |
| | $LiMn_2O_4$ | LMO (Lithium Manganese oxide) |
| Anode active material | C | Graphite, hard carbon |
| | $Li_4Ti5O_{12}$ | LCO (Lithium titanate) |
| Binder | $(C_2H_2F_2)_n$ | PVDF (polyvinylidene fluoride) |
| | $(C_2F_4)_n$ | PTFE (polytetrafluoroethylene) |
| | $C_4H_5ClO_2$ | PVA (polyvinyl alcohol) |
| | $CH_2CO_2H$ | CMC (carboxymethyl cellulose) |
| | $CH_2$=CH-CH=$CH_2$ and $CH_2$=$CHC_6H_5$ | SBR (styrene butadiene rubber) |
| Solvent | $C_5H_9NO$ | NMP (N-methyl-2-Pyrrolidone) |

The alternative method is air-spraying the active materials to the foil, which does not require drying; it needs to heat the binder [57]. The morphology of the compound can be seen in Figure 10.

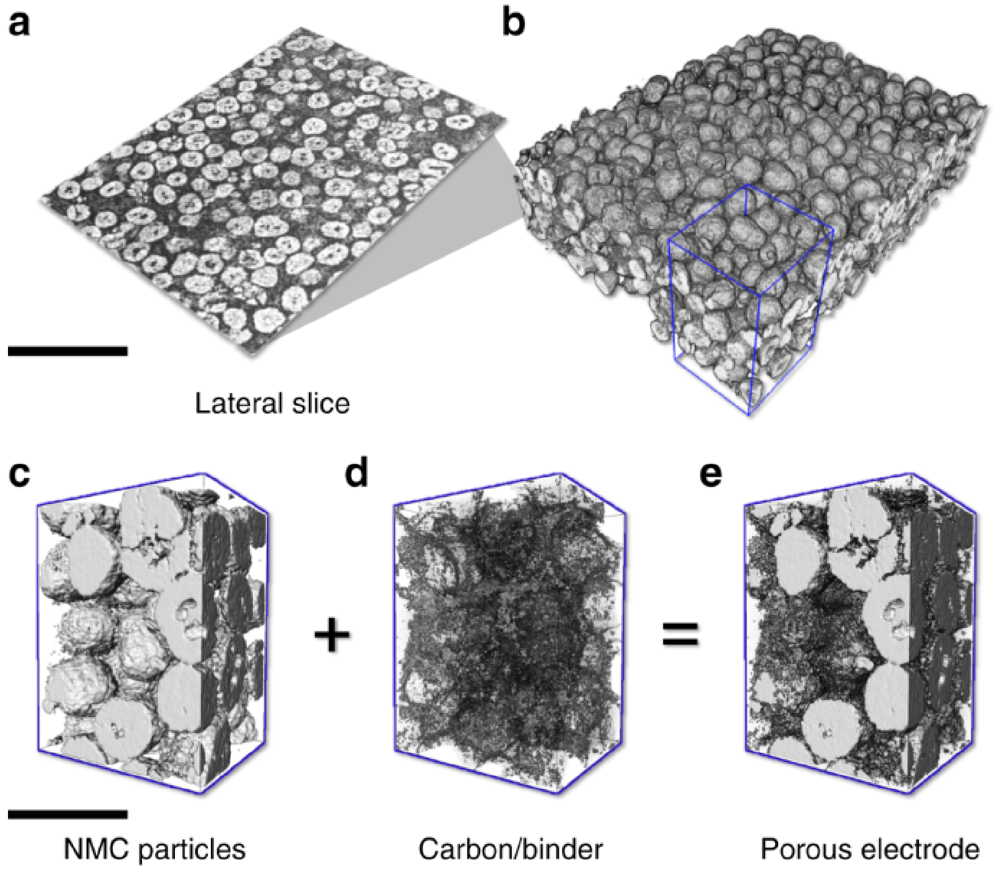


**Figure 10.** (**a**) Plane and (**b**) space morphology of cathode mixture: isolated NMC active (**c**) material, (**d**) binder and (**e)** joint space display of the active material and binder [58].

The powdered electrode active materials and binder can be air-sprayed directly to the foiled current conductor. This alternative process requires a specific voltage (V) applied to the foil and spray gun [57,59]. Soon after the slurry is applied to the foiled current conductors, a drying process takes place to evaporate the solvent [60], leaving the binder to link the particles of the active material [54]. Each of the foils is later calendared to achieve the desired thickness of the active material [61] and slit according to the shape of the battery. Due to Li's reactivity in water, vacuum drying is needed to remove any moisture from the active material after slitting [13]. The diagram of the generic manufacturing process of Li batteries can be observed in Figure 11.

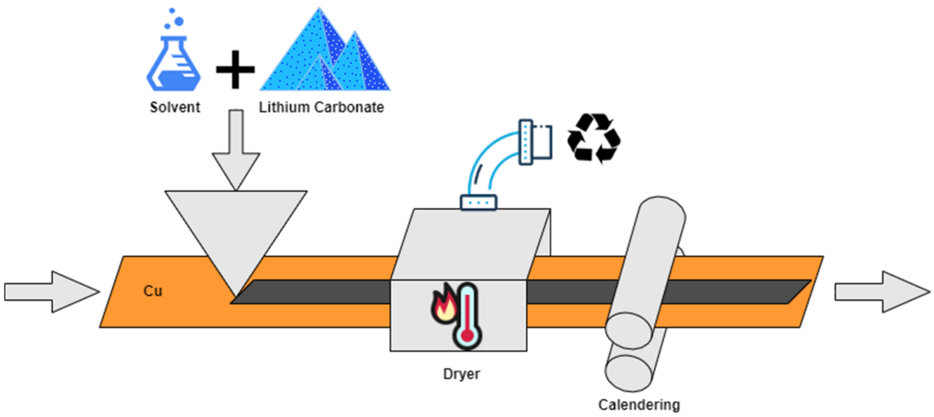


**Figure 11.** Diagram of the generic manufacturing process of Li battery anode–electrode materials are blended and spread on a Cu-foil; the foil is dried to evaporate solvent and later calendared.

### *5.2. Battery Packaging and Activation*

The next stage of battery manufacturing is to input a dielectric between the electrodes before stacking and sealing the battery. If the battery contains an electrolyte fluid, it will be injected after the sealing and before welding the foils [13]. Among many others, the most used barriers, solvents and/or salts found in Li-battery electrolytes are listed in Table 4.

**Table 4.** Liquid electrolyte solvent or salt in Li batteries: (1) solvent; (2) salt; (3) cases applied to Lithium-Sulphur (Li-S) batteries (4) cases applied to $Li^{+}$-ion batteries; separator (5); ceramic coatings to act as dielectric or compound to composite dielectric (6) [62–65].

| Compound | Chemical Composition | Commercial Name |
|---|---|---|
| Dimethoxyethane[13] | $C_4H_{10}O_2$ | DME |
| 1,3-Dioxolane[13] | $C_3H_6O_2$ | DOL |
| Tetrahydrofuran[13] | $C_4H_8O$ | THF |
| Lithium bis(trifluoromethane sulfonyl)imide[23] | $LiC_6F_6NO_4S_2$ | - |
| Dimethyl Sulfoxide[13] | $C_2H_6OS$ | DMSO |
| Lithium perchlorate[23] | $LiClO_4$ | - |
| Lithium trifluoromethane sulfonate[23] | $LiCF_3SO_3$ | - |
| Dimethylformamide[13] | $C_3H_7NO$ | DMF |
| Lithium hexafluorophosphate[24] | $LiPF_6$ | - |
| Ethylene carbonate[14] | $C_3H_4O_3$ | EC |
| Dimethyl carbonate[14] | $OC(OCH_3)_2$ | DMC |
| Propylene carbonate[14] | $C_4H_6O_3$ | PC |
| Diethyl carbonate[14] | $C_5H_{10}O_3$ | DEC |
| Ethyl methyl carbonate[14] | $C_4H_8O_3$ | EMC |
| Tetraglyme[24] | $C_{10}H_{22}O_5$ | - |
| Polyimide[5] | Not applicable | PI |
| Polyethylene[5] | $(C_2H_4)_n$ | PE |
| Polypropylene[5] | $(C_3H_6)_n$ | PP |
| Polyvinylidene difluoride[5] | $(C_2H_2F_2)_n$ | - |
| Silicon dioxide[6] | $SiO_2$ | - |
| Aluminium oxide[6] | $Al_2O_3$ | Alumina |
| Titanium dioxide[6] | $TiO_2$ | - |
| Aluminium oxide hydroxide[6] | AlOOH | - |
| Carboxymethyl cellulose[6] | $CH_2$-COOH | CMC |

The electrolyte can also be formed by a gel containing a salt and a solvent acting as a plasticiser [64]. After the sealing and probable insertion of electrolyte fluid, the current collectors are separately welded through ultrasonic welding for small pouch-type batteries or resistance spot welding for bigger batteries such as those in EVs [13,30]. The batteries are then pre-charged and undergo an ageing process lasting up to 3 weeks. The electrolyte will decompose during this process to form a Solid Electrolyte Interface (SEI). The SEI is essential so the anode can be protected from overpotential, the electrolyte is not permanently consumed, and the formation of Li dendrites is prevented [13]. Upon packaging, the batteries are ready to ship to the product manufacturer.

### *5.3. Manufacturing Variables*

During manufacturing, the processing parameters of the active materials and dielectrics can significantly influence the battery's overall performance [66]. Thickness, during the coating stage, affects specific power and specific energy. As a result of the calendaring stage, a reduced thickness contributes to an increased adhesion of the electrode active material [67]. The porosity, which is mainly controlled by calendaring [61], was shown to be inversely proportional to discharge capacity [68], which correlates with the health state of a battery [69]. Thin dielectrics contribute to batteries' higher energy density [65]. Reducing the slurry solvent can decrease the drying process but requires new techniques to coat the current conductor foils [13].

## 6. End-of-Life $Li^+$-Ion Batteries

A battery can fail after a handful of cycles or earlier than it was designed for. The reasons may vary, but the culprit is usually the dielectric: due to mechanical, electric, or thermal abuse, the structural integrity of the dielectric is compromised, leading to a short circuit and ultimately rendering the battery useless [70]. It can recover more than 90% of the battery's active material [71–73], enabling the European Union (EU) regulation for the upcoming decades. For instance, Gao et al. [74] aimed to maximise the recovery of Li and Co from the black mass of spent $Li^+$-ion batteries by implementing an optimised high-temperature thermal pre-treatment process. Even though the EU recognises the need for Li supply, this element is not considered economically valuable compared to other components [75].

### *6.1. Li Recycling Steps*

Batteries undergo several stages to retrieve the materials effectively and safely [72], using simple separation methods, although the challenges of recycling Li are enormous due to the battery design and the variable state of spent batteries [76]. Because of this, the European Union issued a proposal to regulate and thus facilitate the recycling process by creating a "battery passport", providing insights into its composition [73]. Regardless of the regulation, each recycling company has a functional process identical to the one in Figure 12 [11,77].

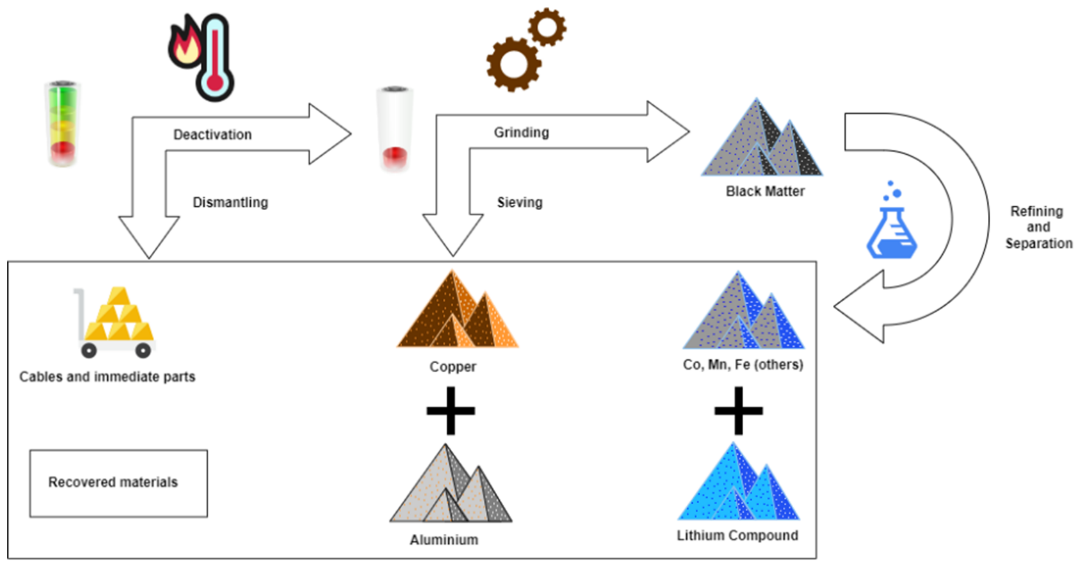


**Figure 12.** Diagram of the generic recycling process of Li batteries-dismantling the casing and other components; deactivation by pyrolysis; grinding and sieving of the foils; leaching of black matter.

#### 6.1.1. Sorting and Disassembly

The recycling industry of batteries specialises in their families, designs, components, or chemistry [78]. In the first approach, the batteries are sorted through different methods: visual inspection, X-ray, magnetic separation [79], and others. The challenge of this step lies in industrial-grade batteries due to their unique design, size, and, therefore, weight [11,80]. The manual disassembly of batteries provides easy first recovery of components such as cables and other potentially profitable apparatuses [11]. This stage can sometimes be automated [80]. Also, in this step, it is possible to directly recycle some components with little treatment before being reinstated to new batteries [71].

6.1.2. Deactivation

Some need to be discharged from the selected batteries, specifically LMO and NMC, which are more reactive and prone to risk of explosion or fire. Discharging a battery involves immersing it in a current conductive liquid, like a saline solution. The remaining ones will undergo a pyrolysis process at 550 °C, allowing the binder and separator in the active material to melt, causing a short circuit. Much of the solvents in the electrolyte can be recovered by condensation [11,81]. The pyrolysis process requires a vacuum atmosphere to recover the materials efficiently; otherwise, the electrodes would oxidise, become fragile, and become deformed. Under such a controlled atmosphere, the risk of fire or explosion is drastically reduced [11].

6.1.3. Mechanical Treatment

The resulting material from the deactivation step is submitted to a series of mechanical processes to pre-sort the materials. The material is shredded thinly and sorted through sieving, magnetic and density separation [11,82]. This process step allows the separation of the Al and Cu from both current collector foils [83]

6.1.4. Refining and Recovery of Metal

Hydrometallurgical processes can separate Cobalt (Co), Manganese (Mn), Li, and other valuable metals from the black powder [84,85]. Such methods, with recovery rates generally close to 100%, involve inorganic leaching, using chloride ($Cl^-$), Sulfuric acid ($SO_4^{2-}$), organic leaching, involving acetic ($CH_3COOH$) and maleic acid ($C_4H_4O_4$), bioleaching, resourcing to bacteria or other microorganisms and ammonia ($NH_3$) leaching [71,85,86]. Pyrometallurgy is often used as an alternate or complementary process [87,88]. Since this process is less selective regarding separating the elements [86], it can be used to produce secondary raw materials for construction materials due to high Nickel (Ni) content [89]. The now-dissolved metal ions can be purified and precipitated to be repurposed [86].

## 7. Concerns about Li-Based Products

The global transition to eco-friendly, low-carbon mobility and the increasing usage of electronic devices puts the sustainability of Li-based energy storage systems into perspective. Data shown in Figure 13 suggests a rapid increase in Li-based batteries from 2015 and projected to 2030. Figure 14 shows the tendency of the projected global development of EV stock until 2050.

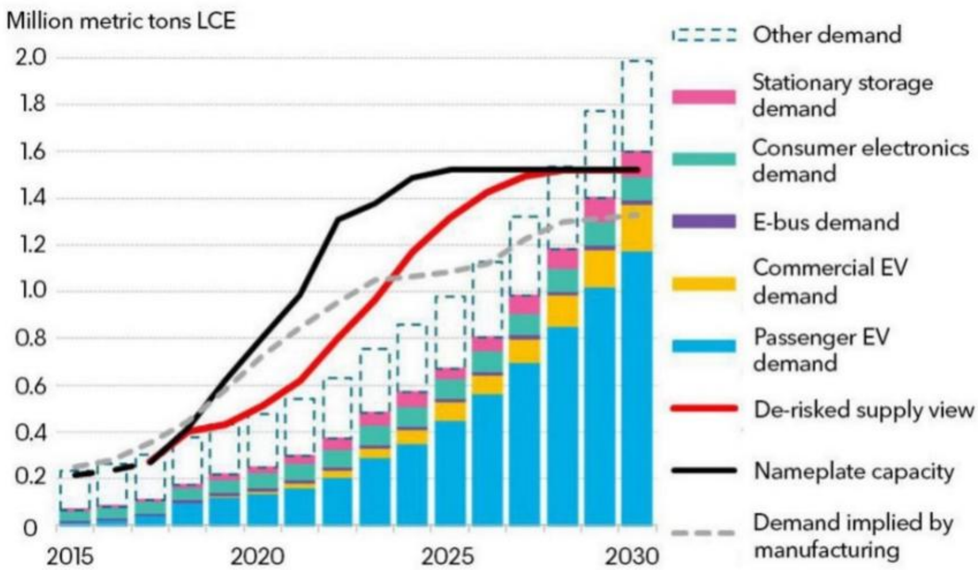


**Figure 13.** Forecast of global Li supply and demand across various sectors from 2015 to 2030 [11,39].

The increased consumption of Li-based batteries follows the price of $Li_2CO_3$. With such demand and the prospects of continuous growth in Li battery manufacturing, it is expected that $Li_2CO_3$ prices will keep increasing [90]. Even after the COVID-19 period, a growing tendency is referred to by the literature [91,92].

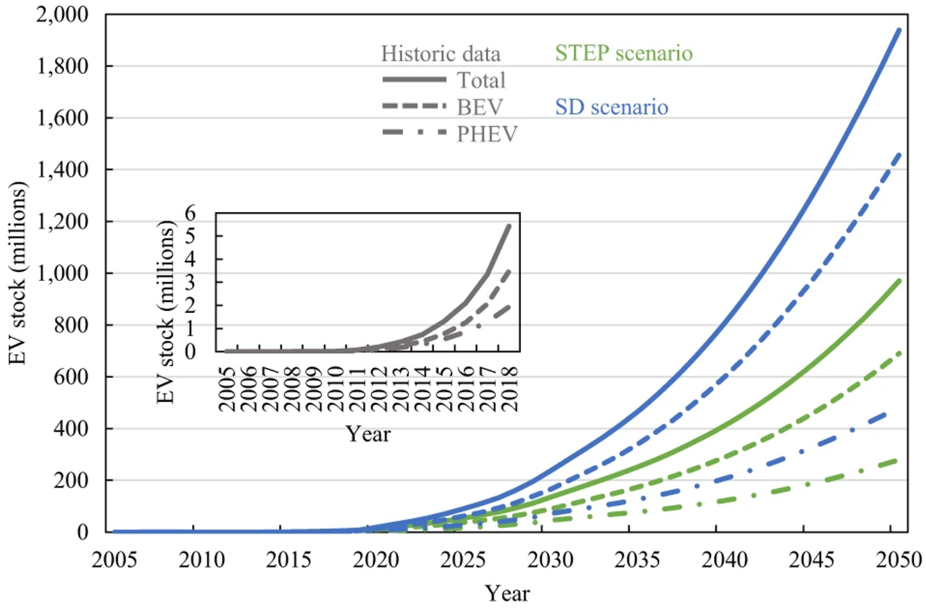


**Figure 14.** Projected global development of EV stock until 2050. Caption: BEV refers to a battery electric vehicle, PHEV denotes a plug-in hybrid electric vehicle, STEP represents the Stated Policies scenario, and SD represents the Sustainable Development scenario [93].

Considering the ever-increasing prices, other sites with low Li concentrations will be regarded as profitable. According to the United States Geological Survey, several mining operations were shut down due to decreased demand or increased extraction worldwide. The mining activities in these sites will negatively impact the local ecosystems, water bodies and health [90,94]. At this rate, it is expected that by the year 2080, the land deposits of Li will be depleted [34].

### *7.1. Environmental Issues*

Like many industries, there are environmental concerns regarding the impact of Li extraction, battery manufacturing, and recycling. Several indicators can quantify the environmental impact, the most relevant being the energy consumption $CO_2$ emissions, besides other intangible ones.

### *7.2. Mining Activities*

Due to its complexity, the environmental impact of brine mining in underwater systems is uncertain, although testimonials from Salar Atacama residents in Chile might offer hints regarding the situation. The locals describe the tendency of a dryer landscape compared to their memories from past years. They also report local shifting of dry-to-wet and wet-to-dry areas without apparent reason [95]. Thanks to the relatively high concentrations of Li, about 130 kg (Chile's *Salar*) to 620 kg (Bolivia's *Salar*) of water are to be processed to produce 1 kg of $Li_2CO_3$. The energetic costs of this process can be reduced thanks to solar evaporation [96]. The literature reports a wide range of values of resources allocated to the process, from which it was possible to compile Table 5.

**Table 5.** Li extraction through brine-energy intake (kWh) and $CO_2$ emissions per 1 kg of $Li_2CO_3$.

| Energy Intake (kWh) | $CO_2$ Emissions (kg) | Source |
|---|---|---|
| 28.43 | 2.02 | [96] |
| 10.00 | 3.28 | [97] |

Besides the energy consumption related to electrochemical devices, such as brine pond extraction and seawater, Li mining relies on water evaporation. An extensive environmental impact in coastal ecosystems is estimated to achieve relevant $Li_2CO_3$ quantities. Due to the low recovery rate and the low concentration of Li, it would take 5,430,000 kg of seawater to extract 1 kg of $Li_2CO_3$ [96], associated with 7634 kWh of energy input [98]. Although no other data related to seawater extraction has been found, this process can soon become a viable source of Li, given the rising prices [99]; thus, more effective and sustainable energy sources are being developed to mitigate the enormous energy intake during the process. As for the mineral extraction to obtain $Li_2CO_3$, much of the wasted water and tailings are not treated, containing harmful chemical by-products [100]. Besides this, mining operations lead to land rearrangement that might interfere with superficial and underground water bodies [101]. Literature also reports various environmental indicators for Li-rich minerals, as shown in Table 6.

**Table 6.** Li extraction from mineral ore-energy intake (kWh) and $CO_2$ emissions per 1 kg of $Li_2CO_3$.

| Energy Intake (kWh) | $CO_2$ Emissions (kg) | Source |
|---|---|---|
| 9.41 | 2.27 | [96] |
| 62.08 | 20.82 | [97] |
| 3.83 | 15.69 | [101] |

7.2.1. Manufacturing of Batteries

When analysing the environmental impact of the battery manufacturing stage, the authors chose to quantify the energy and $CO_2$ emissions per kWh of battery capacity rather than the kg produced. Depending on the battery design and chemistry, the conversion can be made using battery-specific energy (kWh/kg). Figures in literature dramatically vary, as per Table 7, and comparisons are difficult due to the modelling parameters: most authors consider electrical vehicle batteries only, some consider manufacturing components within the battery that are not used in portable devices and other factors.

**Table 7.** Li battery manufacturing-energy consumption and $CO_2$ emissions per kWh battery capacity.

| Energy Intake (MJ/kWh) | $CO_2$ Emissions (kg/kWh) | Source |
|---|---|---|
| 2318 | 424.0 | [102] |
| 1500 | 140.0 | [103] |
| 1960 | 150.0–200.0 | [104] |
| 1126 | 72.9 | [105] |

Most of the energy consumption from the battery manufacturing stage, and consequently, $CO_2$ emissions, are attributed to the cathode slurry [105] and the cell production [102,103,105,106]. Some authors attribute the highest slice of the environmental impact to producing other cell materials, such as Al, used in batteries' colling systems [105,107]. Excluding the casing of the battery and other cell components, cathode preparation takes up around 40% of the energy consumption in the manufacturing stage due to generating heat to dry the slurry mixture. Besides this stage, only the final ageing/activation step of cell manufacturing consumes a significant amount of energy (around 20%) [13].

7.2.2. Recycling

$Li^+$-ion battery recycling is crucial due to increased production and environmental concerns [108,109]. Depending on the recycling method, $CO_2$ emissions and energy consumption may vary [110]; however, compared to the mining activity [77,111], the recycling process is feasible and much cleaner. Some authors estimate a more conservative percentage of around 50% savings in $CO_2$ emissions and energy consumption [112]. Recycling supports the recovery of materials at a lower environmental cost [107,111,112]. More focus is being placed on developing efficient recycling technologies, like hydrometallurgy [113], that enhance sustainability and create a more circular battery economy [108]. For instance, Li et al. [114] apud Liu et al. [115] investigated the recycling of spent $LiCoO_2$, $LiMn_2O_4$, and NMC using vacuum carbothermal reduction. The reaction mechanism was examined using $LiMn_2O_4$ as a model, and the plausible pathway for the conversion reaction was explored, as depicted in Figure 15.

Rimpas et al. [116] addressed that hybrid energy storage systems combining ultracapacitors and Li-ion batteries could discourse the limitations of high-temperature operation in EVs and additional investigation into hybrid systems and second-life applications for renewable energy storage to enhance the environmental benefits of EV battery usage and disposal should be tackled. With the rise of EVs, the demand for efficient recycling methods for Li batteries must grow even further. Resource recovery is critical, and improving Li battery recycling methods, including, notably, automation in battery disassembly [117], sorting technologies, such as X-ray and optical methods [118], bio-hydrometallurgy [119–121], and green leaching technologies [122] to reduce costs and environmental impact is paramount and imperative [123]. However, challenges such as (1) limited industrial-scale application of sustainable recycling, (2) technological gaps, (3) economic constraints, (4) collection and logistics issues, (5) regulatory gaps [124], (6) the increasing Li demand, (7) limited life cycle [125], (8) recycling high costs and (9) incomplete recovery of metal elements from pre-treatment processes and black mass processing/lack efficient sorting by cathode material [118,126,127], (10) varying battery chemistries and limited automation in dismantling [117] are still hindering this phase, which leads to meagre values of practised Li recycling. Economic, logistical, and technological barriers also thwarted the sustainable recycling of Li batteries despite the promise of green hydrometallurgical methods [122]. Expanding direct recycling technologies and addressing industrial and market trends for scaling up battery recycling across global markets could be a solution to ramp up the effectiveness of the process [128].

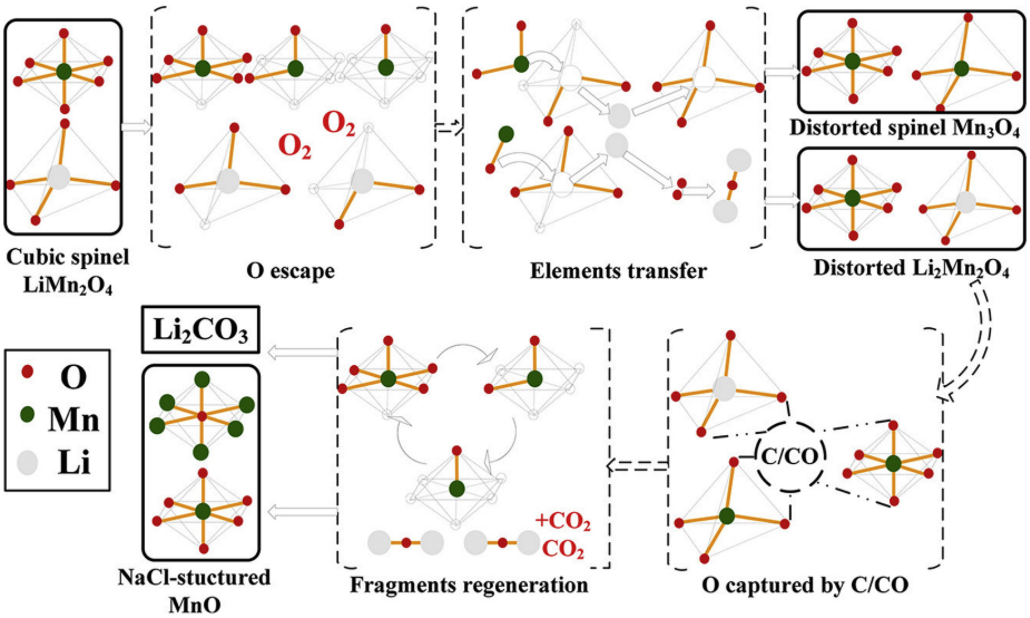


**Figure 15.** Plausible pathways for the conversion of mixed powders from spent $LiMn_2O_4$ batteries under enclosed vacuum conditions [115].

7.2.3. Fauna and Flora Impact

Recycling $Li^+$-ion batteries is effective at recovering valuable materials; however, the environmental impact of the recycling process itself is often neglected [129]. Batteries that are not correctly disposed of and end up in landfills are likely to pollute the ecosystems due to their toxic materials that involve organic electrolytes and heavy metals such as Co and Ni [90]. Some other common materials that compose the battery are dangerous when their ion concentrations are abnormally high: Cu-ions are toxic to fish and Zinc (Zn) to human beings [130]. Field-based reconnaissance and strategic planning to direct Li extraction toward sites with the most negligible environmental impact is imperative, and the assessment for cumulative impact analyses is evermore needed [131]. Li concentrations increasing above naturally occurring levels can disrupt cellular activity. The elevated presence of soil and plants poses potential health risks to humans, animals, and ecosystems. In plants, although Li has potential in agriculture for crop biofortification, enhancing nutritional value if applied at appropriate concentrations (24–196 mg/l) [132], in higher absorptions, metabolism and photosynthesis may be reduced [133,134]. It can also disrupt the metabolism mechanisms of aquatic fauna since it affects other mineral intakes, such as Na, Potassium (K), and other ions [135]. In human beings, a parallel situation: Li is beneficial, under a specific dose, to treat mental disorders such as schizophrenia or depression [136], but when the intake is consumed in higher concentrations, it can cause neural, hormone, heart, and kidney damage. Symptoms can vary from coma, muscle seizures, nausea, vomiting, psychosis, myocarditis and many more [137].

Environmental burden reduction could be managed through optimised energy use, careful selection of leaching agents, and improved treatment of by-products [129]. Environmental, social, and governance challenges, especially water scarcity, community involvement, and outdated and insufficient regulatory standards [138], are significant obstacles to sustainable Li extraction [139].

Future research should focus on performing Direct Li Extraction (DLE) tests on real brines and addressing multivalent ions to ensure broader applicability, alongside evaluating water and energy demands [140]. Also, the long-term impacts of Li on soil health will be focused on to elucidate and explore the role of organic amendments in mitigating Li toxicity and the biochemical mechanisms of Li's effects in agricultural settings [132,134]. The controlled use of Li in biostimulation and biofortification could benefit crop production and human health, presenting a promising avenue for agrarian use [132].

### 7.3. Life Cycle Assessment (LCA)

End-of-life batteries should not be the end of the life cycle of Li usage [141]. Battery recycling should be enforced [142] to stimulate the current near-linear economy and close the loop to form a circular economy [141]. Given all the steps of Li usage, it was possible to build Figure 16, on which the represented arrow thickness generically highlights its flow throughout the cycle.

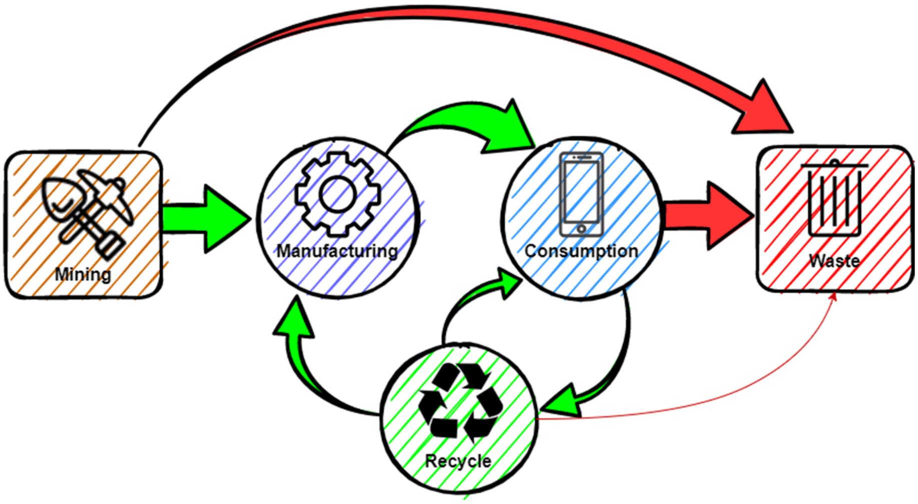


**Figure 16.** Li life cycle applied to energy storage devices.

Several studies suggest that Li battery applications will exponentially increase in the upcoming years [143,144]. This tendency can be easily explained by the regulatory reduction of fossil fuel usage, which is set to reduce global warming, and the search for green electric solutions [130,145,146]. Integrating circular economy principles and practices into society [118] must be swiftly expanded regarding Li batteries recycling, including reuse, refurbishing, and remanufacturing, alongside recycling to reduce dependence on raw materials [147].

Tolomeo et al. [148] applied Life Cycle Assessment (LCA) to evaluate the environmental impact of $Li^+$-ion batteries for EVs [149], focusing on recycling and reuse. LCA showed potential for reducing GreenHouse gas (GHG) emissions in EVs but lacked primary data on battery recycling stages. Future research should emphasise battery recycling and second-life applications to optimise environmental benefits. Lai et al. [150] explored an LCA framework that evaluates $Li^+$-ion batteries across production, use, secondary utilisation, and recycling stages, focusing on environmental impacts. $Li^+$-ion battery production contributes significantly to GHG emissions and resource use, but recycling and secondary use present substantial ecological and economic benefits. Green energy sources are critical to reducing the carbon footprint during $Li^+$-ion batteries production and usage. More research is needed on remanufacturing and secondary use. Zhang et al. [151] conducted a comprehensive LCA to compare the environmental impact of various $Li^+$-ion batteries chemistries (Li-S, LFP, NMC) in the context of EVs, focusing on carbon emissions. Li-S batteries performed best in terms of environmental cleanliness. The power structure heavily influences the carbon footprint, with coal power increasing emissions. Optimising regional power structures is necessary for cleaner EV operations, and Li-S batteries show promise for low-carbon battery technology.

Paul et al. [152] reviewed the LCA of Li batteries, focusing on environmental, economic, and social impacts for a comprehensive sustainability analysis. Data availability and methodological inconsistencies are challenges in LCA. Improvements in data quality and alignment with Sustainable Development Goals are needed. Future research should focus on better-integrating sustainability pillars and improving data transparency for reliable LCA of battery technologies. Nastasi and Fiore [153] performed a case study evaluating the environmental impacts of $Li^+$-ion battery life cycle, focusing on urban bus fleets in Turin, Italy, which revealed potential for significant $CO_2$ emissions reduction; however, $Li^+$-ion battery production and end-of-life management stages lack sufficient data for Europe and other regions. Future efforts should focus on improving data for all life cycle stages of $Li^+$-ion batteries and exploring regional energy mixes to optimise the environmental benefits, and Sánchez et al. [154] combined Social Life Cycle Assessment (S-LCA) with gender aspects for $Li^+$-ion batteries used in EVs to evaluate social impacts across the life cycle. The batteries present positive social impacts, particularly for workers and gender inclusivity, but supply chain issues like child labour in Co mining remain. Further research is needed to ensure gender-neutral designs and address social risks in raw material extraction.

### *7.3.1. Rational Li Consumption*

In the current situation, reducing and mitigating Li demand by increasing other materials in the cathode composite is possible. With the manufacturing of LFP, NMC, and LCO-type batteries, Li usage can be reduced, even though this would lead to increased Ni, Co, and Mn content and consumption. This adjustment, which only considers Li supply, would increase the price of electricity and its environmental impact [155]. While $Li_2CO_3$ requires an energy input of 28.43 kWh [96], Co requires 79.17 kWh, and Ni 46.39 kWh [112].

### *7.3.2. Li Waste*

Recycling spent batteries promises to be an effective way to recover Li, but it is still in the early stages of development [156]. For that, and according to what was previously stated and analysed, the below might provide an insight into the current extraction issues. In the process of brine pond extraction, up to 50% of Li loss is due to evaporation, even though the process can be significantly more efficient [38]. The losses can be higher depending on the Mg/Li ratio: the higher the ratio, the higher the losses [46]. This process heavily depends on solar and wind activity, increasing the time needed to extract Li. Numerous measures can be applied to improve the efficiency of this process: reduce the amount of underground water by using the selective filter to make the brine more concentrated in Li-ions; apply adsorbent beds to enhance the capturing of Li; the use of electrolysis devices [44,157].

Regarding Li extraction from mineral deposits, various interventions have been identified to improve the efficiency of the process. Even though Li content in spodumene is relatively high, the mineral is very resilient to acidic and alkali treatment. Using Sodium Chloride (NaCl), achieving up to 98% of the recovery rate from the spodumene is possible, leaving the crushing stage of the ore the main responsible for the wasted Li [158]. Most recycled Li currently comes from rechargeable or non-rechargeable batteries [159] due to its high content [160]. Unfortunately, less than 5% of spent Li batteries are recycled [161], with an estimated increase to 9% by 2025 [162], even though the amount of cathode active material can be as high as 40% [78] of the battery weight [163,164]. Recycling is vital to recovering Li and its scarce and expensive materials, such as Co and Ni [165].

## 8. Discussion

### *8.1. Prospects for Reducing the Environmental Footprint*

Li batteries alone can reduce environmental footprint but can be significantly enhanced when using low-carbon energy sources throughout their life cycle [9,90]. In contrast with fossil fuels, using Li batteries in car locomotion can reduce between 0.4 Gtones to 2.2 Gtones of $CO_2$ by 2030 if only renewable energy is used to recharge the vehicles' batteries [90]. Much more can be made of the water that results from brine mining. For instance, it could be treated and reused in agriculture or other industrial purposes or reinstated to the aquifer from where it originally came. Even before it is pumped to the shallow ponds, the water can be filtered to increase the concentration of $Li^+$-ions, reducing the evaporation steps, and, therefore, the area needs to do so [42].

Another hazardous by-product to be considered is the tailing from the mineral mining of Li ore. There are some methods to reduce the waste of these activities, such as the production of ceramics [166] or other materials [167], using tailings, or simply soil treatment [137]. Currently, 70% of the Li supply comes from mining activities from Chiles' *salars*, which must be transported all around the globe, translating to an increase of 15 to 25% of the raw material costs, besides greenhouse emissions and other environmental impact factors [159]. These ecological burdens can be reduced through recycling, bringing the economic opportunity for countries or locations that do not produce Li to start recovering Li and install a new economic activity, reducing the environmental impacts as well [168]. Besides the mentioned manufacturing impact, around 20 to 30% of NMP solvent is lost during drying. This toxic organic solvent has a boiling point of 202 °C, inducing the high costs of this process step [13]. Around a quarter of the energy consumption related to this process can be reduced if a water solvent is used [169]. According to the 2006/66/EC European Parliament directive [170], an increase in the recycling rate of batteries is expected, making most of the materials recovery possible and reducing the environmental impact of extracting virgin materials [171]. With the prospect of empowering the industry to reduce carbon emissions, predictions show a growing improvement in existing ones, such as hydrogen ($H_2$) production with zero emissions [172].

### *8.2. Impact of the Literature on the Field*

The reviewed literature significantly advances the understanding of Li batteries, particularly regarding sustainability, environmental impact, and recycling technologies. The LCA of Li batteries provides a comprehensive view of the ecological footprint across production, usage, and end-of-life stages. Studies have shown that despite the benefits of Li batteries in reducing GHG emissions, the extraction and production processes carry substantial environmental and social burdens. These insights are critical for researchers, policymakers, and industries as they strive to balance technological advancement with sustainability goals.

### *8.3. New or Surprising Information*

Including gender aspects in the LCA of Li batteries is a notable contribution, as shown by Sánchez et al. [154]. By incorporating social life cycle assessments (S-LCA) with gender perspectives, this study highlights the importance of a socially inclusive approach in designing and producing Li batteries. This aspect is rarely covered in traditional environmental assessments, making it an innovative angle for future research and industry practices. Another surprising aspect is the potential of hybrid energy storage systems, combining Li batteries with ultracapacitors, to mitigate some limitations of high-temperature operations in EVs. Rimpas et al. [116] reported that this combination can significantly enhance power efficiency and extend battery life.

### *8.4. Comparative Results*

The literature shows a clear consensus that recycling and secondary use of $Li^+$-ion batteries present the most viable options for reducing the environmental burden. However, studies such as those by Zhang et al. [151] indicate that the ecological impact of $Li^+$-ion batteries varies significantly depending on their chemistry, with Li-S batteries outperforming other chemistries like NMC and LFP in reducing $CO_2$ emissions. This finding underscores the importance of selecting the proper battery chemistry for minimising environmental footprints, especially in regions reliant on coal power.

Comparatively, while hydrometallurgical recycling methods are effective in recovering valuable metals such as Co and Li, the efficiency and sustainability of these methods still need improvements. Direct recycling technologies, as explored by Pražanová et al. [127], He et al. [128] and Li et al. [169], show promise, particularly for large-scale applications, but challenges remain in terms of industrial scalability and economic viability.

### *8.5. SWOT Analysis*

To summarise the information presented, three SWOT analyses on the Extraction and Refinement of Lithium (Table 8), $Li^+$-ion battery manufacturing and usage (Table 9) and Li recycling (Table 10) are provided to foster the knowledge apprehended in this paper systematically.

**Table 8.** SWOT analysis on extraction and refinement of Li.

| | Positive Factors | Negative Factors |
|---|---|---|
| **Internal factors** | **Strengths**<br>– Abundant Li reserves in particular geographical areas (Australia, South America),<br>– Vital component for renewable energy technologies and EV batteries,<br>– - Key role in reducing fossil fuel dependency. | **Weaknesses**<br>– High environmental impact, including $H_2O$ consumption, land degradation, and ecosystem disruption,<br>– Significant energy requirements for extraction processes, increasing $CO_2$ footprint,<br>– Dependency on specific geographical regions, leading to potential geopolitical risks. |
| **External factors** | **Opportunities**<br>– Increasing global demand for Li due to the transition to electric mobility and renewable energy,<br>– Potential for technological advancements in more sustainable extraction methods,<br>– - Exploration of new Li sources, such as seawater, could provide new avenues for supply. | **Threats**<br>– Environmental regulations may impose restrictions on extraction activities,<br>– Over-extraction could lead to resource depletion and more stringent regulations,<br>– Local community opposition and social conflicts over resource use and environmental degradation. |

**Table 9.** SWOT analysis on Li+-ion battery manufacturing and usage.

| | Positive Factors | Negative Factors |
|---|---|---|
| **Internal factors** | **Strengths**<br>– High energy density, making $Li^+$-ion batteries ideal for electric vehicles and renewable energy,<br>– Constant improvements in battery technology enhancing performance,<br>– Versatility, applicable in a wide range of consumer electronics, EVs, and grid energy storage. | **Weaknesses**<br>– Limited life cycle, leading to frequent replacements and disposal challenges,<br>– High manufacturing costs and resource-intensive processes,<br>– Sensitivity to extreme temperatures and potential safety risks (e.g., thermal runaway). |
| **External factors** | **Opportunities**<br>– Growing demand from EV markets and renewable energy storage sectors,<br>– Research into next-generation batteries (solid-state, etc.) can further boost efficiency,<br>– Government incentives for clean energy technologies support battery adoption. | **Threats**<br>– Raw Co and Ni can lead to supply chain disruptions and price volatility,<br>– Competition from emerging alternative energy storage technologies (e.g., $H_2$ fuel cells),<br>– Environmental impacts of battery production could face stricter regulations. |

**Table 10.** SWOT analysis on Li recycling.

| | Positive Factors | Negative Factors |
|---|---|---|
| **Internal factors** | **Strengths**<br>– Recycling reduces reliance on raw material extraction and lessens environmental damage,<br>– Potential to recover valuable materials like Li, Co, and Ni,<br>– Supports circular economy principles by extending battery life through material recovery. | **Weaknesses**<br>– Current recycling technologies are inefficient and costly,<br>– Low global recycling rates, with most batteries ending up in landfills,<br>– Complex battery designs complicate disassembly and material recovery. |
| **External factors** | **Opportunities**<br>– Significant room for technological advancements to improve efficiency and reduce costs,<br>– Increased regulatory pressure for mandatory recycling programs,<br>– Growing demand for recycled Li as raw material prices increase. | **Threats**<br>– High energy and resource requirements for recycling can diminish its environmental benefits,<br>– Rapid changes in battery technology may render some recycling methods obsolete,<br>– Competition from more environmentally friendly battery technologies may reduce reliance on recycling. |

## 9. Conclusions

In light of the comprehensive analysis presented, the following conclusion summarises the essential findings and offers insights into the future direction for sustainable $Li^+$-ion battery development and management:

- $Li^+$-ion batteries have emerged as a critical technology enabling the transition to transport and energy storage electrification. Their widespread adoption reflects their role in addressing environmental challenges, but it also presents significant ecological and social concerns;
- Environmental and social impacts of Li extraction and battery production are substantial, especially in resource-rich regions like the Li Triangle, where water scarcity, pollution, and social issues such as child labour are prevalent. The inclusion of these factors in the assessment frameworks is vital for sustainable $Li^+$-ion battery management;
- Recycling and second-life applications for $Li^+$-ion batteries offer a promising path toward reducing the environmental burden. Despite advances in recycling technologies, current rates of recycling are insufficient to meet the growing demand for Li and other critical materials;
- LCA, when combined with gender and social aspects, offer a more comprehensive approach to understanding the impact of $Li^+$-ion batteries;
- Hybrid energy storage systems combining $Li^+$-ion batteries with ultracapacitors show potential for enhancing the efficiency and lifespan of energy storage, particularly in EVs. These innovations can mitigate challenges such as high-temperature operation and limited battery range;

- Policy frameworks must evolve to support sustainable Li production and battery recycling. Establishing more transparent regulations, including a "battery passport," could help streamline recycling processes, improve transparency, and ensure better management of end-of-life batteries.
- Future research directions should focus on:
- Enhancing the efficiency of $Li^+$-ion batteries recycling technologies and reducing economic and logistical barriers;
- Expanding the scope of life cycle assessments to include both environmental and social dimensions, ensuring that future technologies are not only sustainable but also equitable;
- Investigating second-life applications for $Li^+$-ion batteries to reduce waste and extend the utility of batteries, particularly in renewable energy storage solutions.

This conclusion summarises the literature's critical findings and prospects, underscoring the need for continued innovation in $Li^+$-ion battery technology and management.

## Author Contributions

Conceptualisation: A.F.V.P., F.J.G.S. and I.M.P.; methodology: A.F.V.P., F.J.G.S., C.R.R. and I.M.P.; validation: F.J.G.S., C.R.R. and I.M.P.; formal analysis: M.D.M.; investigation: A.F.V.P. and M.D.M.; data curation: F.J.G.S., C.R.R. and I.M.P.; writing—original draft preparation: M.D.M. and A.F.V.P.; writing—review and editing: F.J.G.S., C.R.R. and I.M.P.; visualisation: C.R.R.; supervision: F.J.G.S. and I.M.P.; project administration: F.J.G.S.; funding acquisition: F.J.G.S. All authors have read and agreed to the published version of the manuscript.

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## Data Availability Statement

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## Conflicts of Interest

The authors declare no conflict of interest. Given the role as Editor-in-Chief, Francisco J. G. Silva had no involvement in the peer review of this paper and had no access to information regarding its peer-review process. Full responsibility for the editorial process of this paper was delegated to another editor of the journal.

## Use of AI and AI-assisted Technologies

No AI tools were utilized for this paper.

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