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Research Progress in Lithium Recycling: A Mini Review

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Abstract

The execution of the dual carbon strategy has expedited the swift advancement of the new energy sector, resulting in a substantial rise in the demand for lithium resources. The process of lithium recycling can mitigate the environmental challenges associated with lithium extraction, thereby underscoring the growing importance of lithium recycling. This paper focuses on the essential technologies utilized for the recovery of lithium and other metals from diverse categories of waste lithium-ion batteries. These technologies include pyrometallurgy, hydrometallurgy, and bio-metallurgy. Additionally, the paper delineates the various stages involved in the recycling process. This paper conducts a comparative analysis of various technologies used for lithium recovery, examining their respective processes, advantages and disadvantages, efficiency in lithium recovery, associated costs, environmental implications, and degree of commercialization. While there is a growing concern regarding the advancement of various lithium recycling technologies, the current efficiency of lithium recycling remains significantly constrained. It is anticipated that this paper will further stimulate interest in the field of lithium recycling.

Keywords: dual carbon strategy, lithium recycling, bio-metallurgy, environmental impact, commercialization

1. Introduction

Lithium, a lightweight metal commonly known as a green energy metal and referred to as “white oil”, is extensively employed across multiple sectors, including energy storage, the chemical industry, medicine, metallurgy, and electronics. At the regional level, lithium resources are predominantly located in South American nations, specifically Bolivia and Chile, in addition to Argentina, China, and the United States, as illustrated in Figure 1b. Lithium extraction predominantly occurs from Salt Lake brines and mineral ores, with a total of 72.3% of the identified resource reserves located in Salt Lake brines, and 20.3% situated in ores. Notably, approximately 40% of the world’s lithium is derived from ores, whereas production from Salt Lake brine surpasses 60% (Bae, H. & Kim, Y., 2021). Lithium demonstrates considerable reactivity, a notable electrochemical potential, and a high energy density, making it an optimal material for use in battery applications. As illustrated in Figure 1a, approximately 65% of lithium is utilized within the battery industry, 18% is dedicated to the manufacturing of glass and ceramics, while the remaining 17% is primarily assigned to various other applications, including polymers and lubricants (Tadesse, B., Makuei, F., Albijanic, B. & Dyer, L., 2019). In recent years, there has been a significant increase in the demand for electric vehicles, driven by heightened public awareness regarding environmental conservation, advancements in lithium battery technology, and supportive government initiatives. As illustrated in Figure 1c, the timeframe spanning from 2021 to 2024 is characterized by notably substantial growth in electric vehicle sales within China, in contrast to the more moderate growth observed in other regions (IEA, 2024). It is projected that in 2024, sales of electric vehicles may attain 17 million units, accounting for roughly one-fifth of the total automobile sales (IEA, 2024). Nonetheless, the efficacy of lithium batteries declines with the passage of time, suggesting that the volume of decommissioned lithium batteries is expected to rise substantially in the future, thereby presenting challenges for their management. While used batteries may pose challenges in waste management, they simultaneously provide manufacturers with the opportunity to obtain essential materials from a secondary source.

The extensive extraction of lithium often results in numerous adverse effects on the environment. In specific lithium mining areas, including the Atacama Salt Flat in Chile, the prevailing method of lithium extraction is significantly water-intensive, requiring the evaporation of 500,000 gallons of water for every ton of lithium produced. It is estimated that mining operations consume approximately 65% of the region's water resources, which has a detrimental effect on local farmers (Katwala, A., 2018). The International Energy Agency (IEA) forecasts that by the year 2040, the recovery of copper, lithium, nickel, and cobalt from batteries may fulfill 10% of the demand for these minerals. This advancement has the potential to significantly reduce dependence on mineral extraction and contribute to the alleviation of the environmental challenges associated with mining activities (International Energy Agency (IEA), 2025). Simultaneously, the improper disposal or inadequate management of lithium batteries can present significant risks to the health of animals, plants, and humans. This is primarily due to the potential leaching, decomposition, and degradation of the hazardous substances contained within these batteries (Energy & Environmental Science, 2021). Consequently, from the standpoint of environmental conservation, the appropriate recycling of lithium can alleviate adverse effects on the ecosystem. From an economic perspective, profitability is generally achieved through the recycling of high-value components, such as copper derived from cobalt, lithium iron phosphate batteries, and lithium manganese oxide batteries, which represent substantial revenue sources (Lander, L. et al., 2021). Despite the existing limitations in recycling efficiency and the high costs associated with the recycling process, there remains substantial potential for advancements in relevant technologies. Nonetheless, lithium recycling presents notable economic benefits. Recent studies suggest that the electrochemical extraction of lithium can reduce costs by 35.6% in comparison to conventional extraction methods, while simultaneously reducing carbon dioxide emissions by 75.3% (Bae, H. & Kim, Y., 2021; Zhang, H. et al., 2024). Consequently, advancements in technology are crucial for the successful implementation of lithium recycling processes.

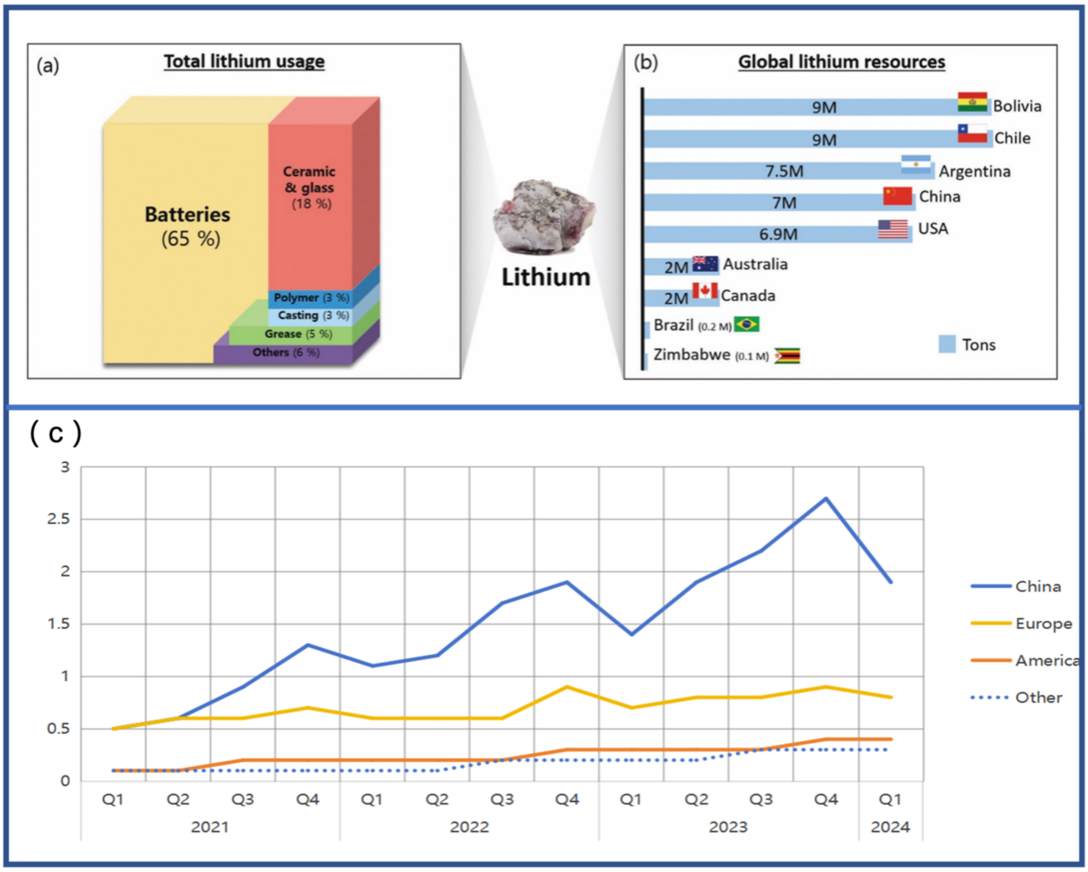

Figure 1. (a) Distribution of total lithium usage in 2019 (Tadesse, B. et al., 2019); (b) distribution of global lithium (Bae, H. & Kim, Y. 2021); (c) Quarterly electric car sales by region, 2021-2024 (IEA, 2024)

2. Primary Sources of Lithium Material Recycling

It is projected that a considerable quantity of lithium-ion batteries will reach the end of their operational life in

2025. These decommissioned batteries generally contain valuable metals such as lithium (Li), nickel (Ni), cobalt (Co), manganese (Mn), and copper (Cu) (Wojciech Mrozik et al., 2021). The recycling of these metals not only fosters sustainable development but also mitigates the environmental pollution associated with the disposal of lithium batteries. In addition to discarded batteries, lithium materials can also be reclaimed from the byproducts produced during the extraction of lithium ores and the manufacturing of lithium salts. These byproducts may contain lithium compounds that have not been completely recovered. By employing suitable processing methods, lithium can be effectively extracted from these materials.

2.1 Extraction of Lithium from Waste Batteries

The recycling of lithium materials predominantly stems from lithium batteries, especially lithium-ion batteries, which are extensively employed in rechargeable batteries. Lithium-ion batteries are primarily composed of positive electrode materials, negative electrode materials, electrolytes, current collectors, and sheathing materials. Notably, the high-value elements present in the positive electrode materials, along with the aluminum and copper utilized in the current collectors, hold considerable value for recycling purposes. As illustrated in Figure 2a, lithium-ion batteries can be categorized into various types, including lithium cobalt oxide (LCO) batteries, nickel cobalt manganese oxide (NMC) batteries, nickel cobalt aluminum oxide (NCA) batteries, lithium iron phosphate (LFP) batteries, and lithium manganese oxide (LMO) batteries. This classification is based on their chemical composition and the proportions of the materials that comprise them (Duan, X. et al., 2022). As illustrated in Figure 2b, fluctuations in chemical composition result in notable disparities in the recycling value of these batteries, with the presence of cobalt and nickel frequently being a pivotal factor. For example, the NMC111 battery, which possesses the highest recycling value, also contains the greatest concentration of cobalt, yielding approximately USD 42 in revenue for each kilowatt-hour of this battery type that is recycled. Conversely, lithium iron phosphate (LFP) batteries pose more significant challenges for commercial recycling due to the lack of high-value metals (Toro, L. et al., 2023).

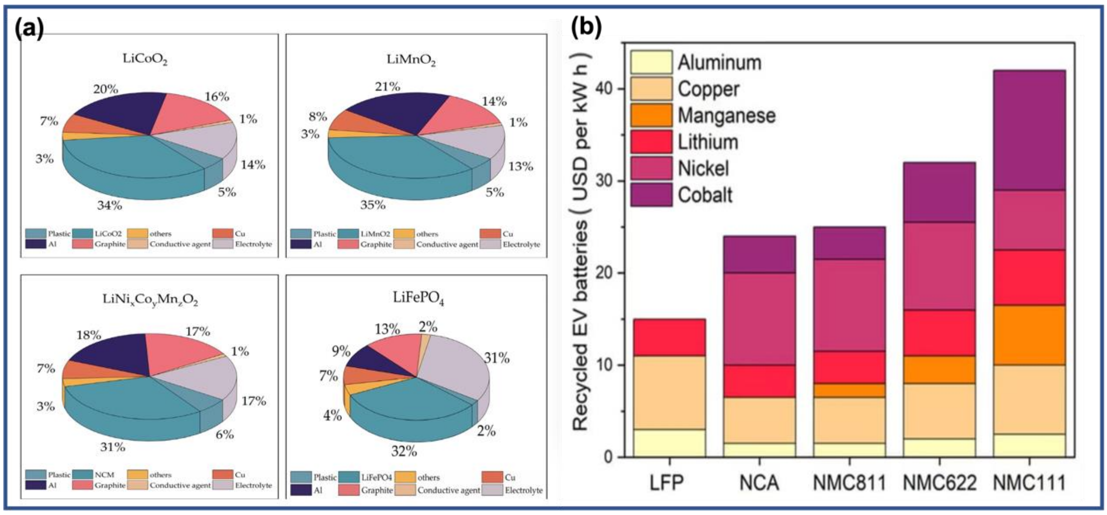

Figure 2. (a) Composition of different types of lithium-iron batteries (Duan, X. et al., 2022); (b) Recycling value of different types of EV batteries (Toro, L. et al., 2023)

2.2 Extraction of Lithium from Lithium Slags

Lithium slag refers to the byproduct produced during the smelting and manufacturing processes of lithium ore, which is formed at elevated temperatures. The primary constituents of lithium slag include silicon dioxide, aluminum oxide, and a range of other oxides, as detailed in Table 1. In industrial contexts, the production of one ton of lithium carbonate generally yields between 30 to 40 tons of lithium slags, thereby presenting a considerable challenge in terms of disposal due to the large volumes generated (Zhai M., Zhao J. & Wang D., 2017; Li, J. & Huang, S., 2020). Owing to its hydration activity, recycled lithium slag is frequently employed in the construction materials industry as a cement additive, which is regarded as the most effective means of utilizing lithium slag. Additionally, it is utilized in the formulation of clinker-free concrete and as a binding agent for mine filling materials, among various other applications. In the chemical sector, the silicon and aluminum components of lithium slag are harnessed in the production of molecular sieves, the manufacture of white carbon black, and the firing of ceramic aggregates and glazed tiles, among other purposes (Liu, C. Y. & Lu, J. S., 2023).

Lithium slag may also be utilized as a potential source for the extraction of lithium. Research has shown that lithium carbonate and lithium hydrate can be synthesized using acidified roasting and causticizing reaction techniques. In this procedure, lithium slag is integrated with spodumene, and through the process of acidified roasting, lithium is transformed into lithium sulfate. Following filtration, the resultant leachate undergoes a reaction with carbonate to yield lithium carbonate. This lithium carbonate can subsequently be mixed with lime, resulting in a causticizing reaction that produces lithium hydroxide. The caustic residue generated from this reaction can be reintroduced into the roasting process, thereby substantially improving the recovery rate (Wang, X., Wang, H. & Wang, Q., 2022).

Table 1. Main components of Lithium Slag

SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	SO_3	Na_2O	K_2O	TiO_2	Loss	–	Sum
47.62	21.56	2.02	0.48	0.12	0.03	10.68	3.05	3.46	0.14	10.84	100

2.3 Alternative Methods for Lithium Recovery

In addition to the extraction of lithium from lithium slag and discarded batteries, other suitable sources include industrial wastewater, lake water and seawater. In the process of lithium extraction from seawater, specific adsorbent materials characterized by high specific surface area have proven effective in adsorbing lithium ions from seawater. Experimental studies have shown that coal ash and slag generated from circulating fluidized bed combustion (CFBC) technology exhibit a significant capacity for the efficient adsorption of lithium ions from seawater. The adsorption efficiencies of lithium utilizing coal ash and slag are recorded at 12.1% and 6.8%, respectively (Kalak, T. & Tachibana, Y., 2021). The waste produced during the lithium extraction process from salt lakes generally contains lithium constituents that have not been completely extracted. For example, during this procedure, a solution may be left behind that contains impurities such as potassium and magnesium. The solution could potentially undergo further treatment to facilitate the additional extraction of lithium.

3. Recycling Process of Lithium Batteries

Lithium-ion batteries represent the principal source for the recycling of lithium materials. The recycling process not only aids in the recovery of lithium but also allows for the extraction of several high-value elements, such as cobalt and nickel, thus yielding significant economic advantages. The recycling process involves multiple steps, which include preprocessing, discharge, pyrometallurgy, and hydrometallurgy, and encompasses a range of methodologies.

3.1 Preprocessing

Preprocessing generally encompasses a series of operations, including discharging, dismantling, crushing, sorting, separating, dissolving, and thermal treatment (Kim, S., 2021). The procedures associated with preprocessing are of paramount importance. The inadequate execution of preprocessing may result in the ignition of lithium batteries during the recycling process. This, in turn, could lead to damage to recycling machinery and present a considerable risk to the environment (Wojciech Mrozik et al., 2021; Hu, L. Q. 2022).

3.1.1 Discharge

Discarded electronic devices will initially be subjected to recycling processes and undergo preliminary disassembly. Prior to the disassembly of the battery, it is imperative to first discharge it. This precautionary measure is implemented to mitigate the risk of fires and explosions, thereby safeguarding the safety of personnel and preserving the integrity of the disassembly equipment. In most cases, the discharge undergoes a thermal pretreatment, as illustrated in Figure 3. Solutions of sodium chloride (NaCl), manganese sulfate ($MnSO_4$), and iron sulfate ($FeSO_4$) are frequently utilized as discharge media. It is essential to recognize that the efficiency of the discharge process and the resultant products are influenced by the specific type of discharge media employed. Among the available media, ferrous sulfate has been demonstrated to exhibit the highest discharge efficiency, with the predominant residues comprising copper and iron. The gases released are comparatively environmentally benign (Yao, L. P. et al, 2020). Furthermore, Na_2S and $MgSO_4$ may also serve as effective discharge media. Studies suggest that the efficiency of discharge is more significantly influenced by the molar concentration of the solution rather than its ionic strength (Torabian, M. M., Jafari, M. & Bazargan, A., 2021).

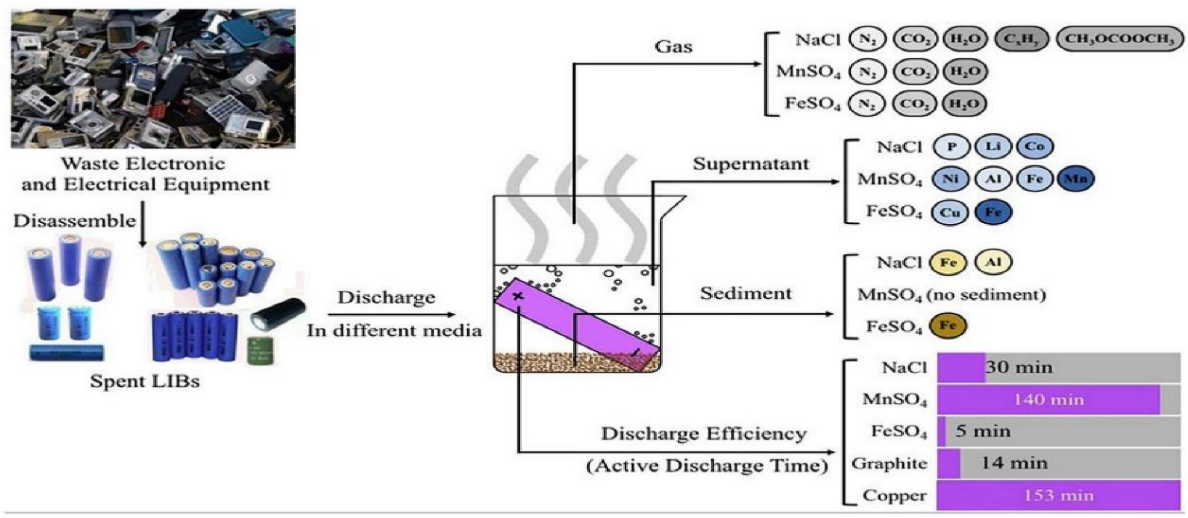

Figure 3. Discharging lithium-iron batteries by different solutions (Yao, L. P. et al, 2020)

3.1.2 Mechanical Processing, Separation, Dissolution, and Thermal Treatment

Following the discharge of a lithium-ion battery, the initial step will involve mechanical processing. Mechanical preprocessing includes various processes, such as crushing, screening, magnetic separation, fine crushing, and classification. Nevertheless, it is important to note that mechanical processing may pose a risk of equipment damage during the stages of magnetic separation and screening. Magnetic separation is an efficient method for isolating metal particles from various materials, including shells, copper foil, and aluminum foil. Subsequent processes, including solvent treatment, calcination, and physical separation, are then employed to obtain copper, aluminum, black matter, and plastics. The black matter is comprised of a combination of cathode and anode active materials, which possess a considerable recycling value (Ekberg, C., Petranikova, M., 2015; Neumann, J. et al., 2022; Zhao, G. J. et al., 2024). The active materials obtained can undergo additional processing to extract valuable metals through the methods of pyrometallurgy, electrolysis, and hydrometallurgy.

3.2 Pyrometallurgy

Pyrometallurgy is a conventional metallurgical technique that entails the extraction of metals and other valuable substances via high-temperature processing. In the field of lithium battery recycling, pyrometallurgy predominantly utilizes high-temperature smelting and roasting methods. This approach is advantageous for its wide applicability and ease of operation, rendering it a favored option for the large-scale processing of lithium batteries (Zhao, G. J. et al., 2024). Nonetheless, pyrometallurgy presents several drawbacks, including elevated energy consumption, considerable gas emissions, low recovery efficiency, and the inability to recover specific metals, leading to significant material losses (Villen-Guzman, M. et al., 2024). The primary challenges associated with pyrometallurgy include high energy consumption, integration with other processes, and the reduction of environmental pollution. In pyrometallurgy, additives such as sulfides and chlorides are utilized to regulate temperature and enhance efficiency. Alternatively, emerging technologies, such as Flash Joule Heating, can be employed to mitigate environmental impact and improve economic benefits. By incorporating it with additional processes, it is feasible to mitigate the constraints associated with pyrometallurgy (Mei, Y. R. et al., 2024). Addressing these challenges has a profound effect on environmental conservation and contributes to the enhancement of economic advantages.

Table 2. Comparing Pyrometallurgy and Hydrometallurgy

Process	Advantages	Disadvantages	Challenges
Pyrometallurgy	• Simple operation • No requirement for pretreatment • High efficiency	• High energy consumption • More waste gasses • Low efficiency of recovery • Li and Mn are not recovered	• Decreasing energy consumption, pollution, emissions and environmental hazards • Combining it with hydrometallurgy
Hydrometa-llurgy	• High recovery rate • High purity product • Low energy consumption • Less waste gas • High efficiency	• More consumption of water and chemical reactants • More wastewater • Long process	• Wastewater treatment • Optimization of the process • Circular hydrometallurgy

The batteries that have been preprocessed are gathered and subsequently subjected to pyrometallurgical roasting. Due to lithium's strong oxytropism, it generally manifests as slag after the roasting procedure. When lithium batteries are exposed to elevated temperatures, the extraction of lithium and cobalt is facilitated through the incorporation of reducing agents and slag modifiers. This procedure yields a cobalt alloy and slag composed of CoO and C_3O_4, in addition to Li_2O and Li_2CO_3, which function as extraction materials. Subsequently, these substances undergo further processing to isolate lithium in its elemental state (Jose, S. A. et al., 2024). It is essential to acknowledge that the recycling rate may fluctuate based on the specific types of batteries and the processing techniques utilized. For example, Table 3 demonstrates the variations in recycling rates that arise from different processing methods applied to cathode materials such as $LiNiMnCoO_2$, $LiCoO_2$, and $LiCoNiO_2$ (Liu, P. et al., 2019; Zheng, Y. et al., 2019; Peng, C. et al., 2019; Tang, Y. et al., 2019; Shi, J. et al., 2019; Li, J. et al., 2016; Ren, G. et al., 2017).

Table 3. Pyrometallurgy process and operating conditions for spent LIB recovery processes

Cathode Material	**Pyrometallurgy Process**	**Additive**	**Condition**	**Separated Material**	**Recovery Rate (%)**	**Reference**
$LiNiMnCoO_2$	Reduction roasting and water and acid leaching(H_2SO_4)	Carbon	650 °C, 30 min	$LiCo_3$, Co, Li, NiO, MnO, CO_2(g)	Li: 93.67; Ni: 93.3; Co: 98.1; Mn: 99.5	(Liu, P. et al., 2019)
$LiNiMnCoO_2$	Plasma spray pyrolysis	-	600 °C	Regenerated $LiNiMnCoO_2$		(Zheng, Y. et al., 2019)
$LiCoO_2$	Nitration roasting and water leaching	NHO_3	250 °C, 60 min	$LiNO_3$, $Co(NO_3)_2$, NO(g), H_2O(g)	Li: 93; Co: 92.9; Ni: 92.9; Cu: 92.9	(Peng, C. et al., 2019)
$LiCoO_2$	Vacuum pyrolysis and water leaching	Carbon	600 °C	Co, CoO, $LiCO_3$, CO_2	Li: 93, Co: 99	(Tang, Y. et al., 2019)
$LiCoO_2$	Sulfation roasting and water leaching	SO_2(g)	700 °C, 120 min	$Li2SO_4$, $Li_2Co(SO_4)_2$, CoO, O_2(g)	Li: 99.5; Co: 17.4	(Shi, J. et al., 2019)
$LiCoO_2$	Oxygen-free roasting and wet magnetic separation	Carbon	1000 °C, 30 min	$LiCO_3$, Co	Li: 98.93; Co: 95.72	(Li, J. et al., 2016)
$LiCoNiO_2$	Carbothermic reduction smelting, manual separation of slag and alloy communication	NH_4CI	1450 °C, 30 min	Co, Ni, Cu, and Fe Alloy and slag FeO, SiO_2, AI_2O_3, CaO, MgO	Ni: 98.4; Co: 98.8; Cu: 93.6	(Ren, G. et al., 2017)

In recent years, traditional pyrometallurgy has experienced ongoing enhancements, and initiatives have been undertaken to incorporate it with alternative methodologies. Windisch-Kern et al. conducted a study on the lithium removal rates utilizing two distinct types of reactors, with the aim of enhancing the management of waste lithium-ion batteries. During the processing of lithium cobalt oxide, a lithium removal rate of 76% was attained utilizing Al_2O_3 crucibles following exposure to gas flow. The elevated purity achieved after this processing facilitates subsequent treatment procedures. The utilization of MgO crucibles can achieve a lithium removal rate of up to 97% (Windisch-Kern, S., Ponak, C. & Raupenstrauch, H., 2021). Öfner, W. et al. integrated pyrometallurgical techniques with hydraulic mechanical pretreatment to effectively eliminate suspended solids, thereby decreasing the carbon content from 33 wt.% to 19.23 wt.%. This innovative approach yielded a high-purity mixture of active materials suitable for lithium batteries, and subsequent pyrometallurgical processing produced a lithium-free metal alloy (Holzer, A. et al., 2022). These techniques have the potential to improve the purity of recycled metals.

Lithium exhibits a pronounced oxytropism, which ultimately leads to the formation of slag during the process of pyrometallurgy. The InduRed reactor, as proposed by Holzer et al., presents a viable solution to this challenge.

The researchers conducted an investigation into the performance of nickel-rich cathode materials and black mass under reducing conditions, utilizing heated microscopic experiments, thermogravimetric analysis, and differential scanning calorimetry. In a subsequent series of experiments, the investigations conducted within the InduRed reactor were further employed to examine the transferable coefficients of metals. The findings demonstrate that within the reaction temperature range of 800°C to 1,000°C, nickel, cobalt, and manganese display considerable recovery potential, while the slagging of lithium is substantially reduced (Windisch-Kern, S. et al., 2021).

3.3 Hydrometallurgy

Hydrometallurgy is a metallurgical technique that utilizes solvents and chemical reactions to facilitate the extraction of metals from mineral sources or waste materials. In the domain of lithium battery recycling, hydrometallurgy predominantly pertains to the methodology of extracting metallic materials from spent lithium batteries utilizing chemical solvents, with the objective of recovering valuable metals. Hydrometallurgy offers several benefits over pyrometallurgy, including enhanced recovery rates, improved product purity, and reduced energy consumption. Concurrently, hydrometallurgy poses certain challenges, notably the significant consumption of water resources. While hydrometallurgy does not emit significant volumes of exhaust gases, it has the potential to produce substantial quantities of wastewater during the recovery process, which could pose an environmental concern. The current challenges encountered in hydrometallurgy include equipment corrosion arising from the leaching process and diminished material adaptability. These issues underscore the need for further optimization of the process (Villen-Guzman, M. et al., 2024; Lv, W. et al., 2018). Hydrometallurgy can be further divided into various procedures, including, but not limited to, acid leaching, alkaline leaching, and bioleaching. Figure 4 provides a comprehensive depiction of the hydrometallurgical process, delineating the essential steps involved in the extraction of lithium salts from the solution. (Neumann, J. et al., 2022)

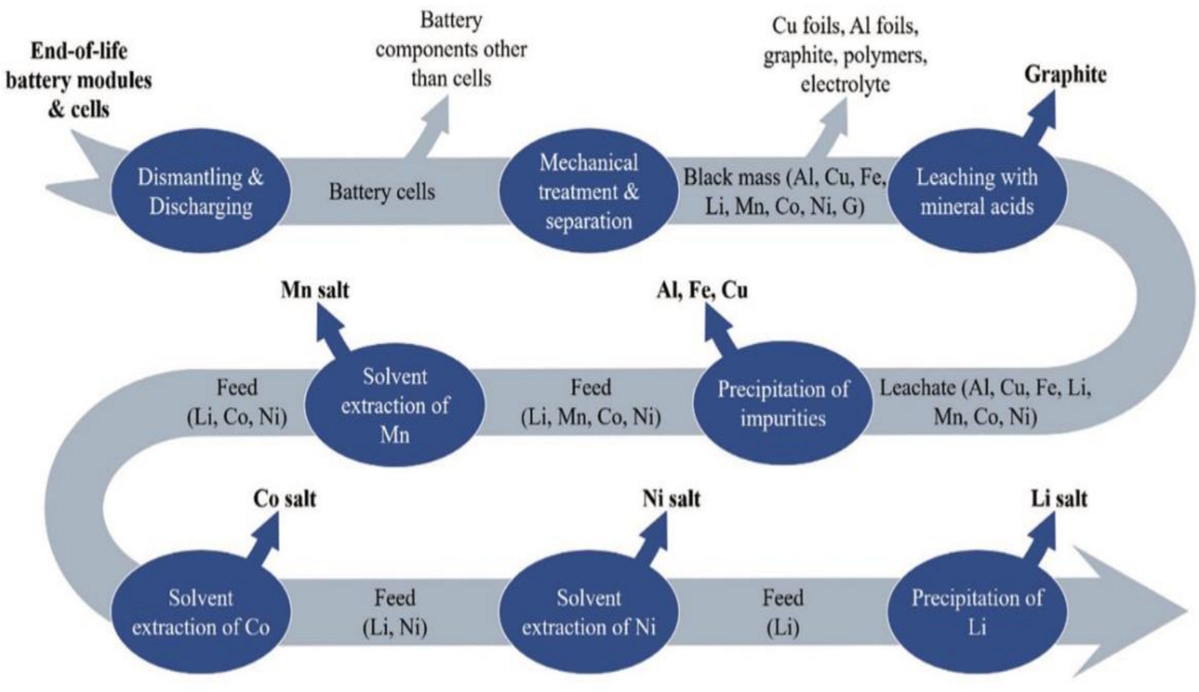

Figure 4. Overview about traditional hydrometallurgical processing

3.3.1 Acid Leaching

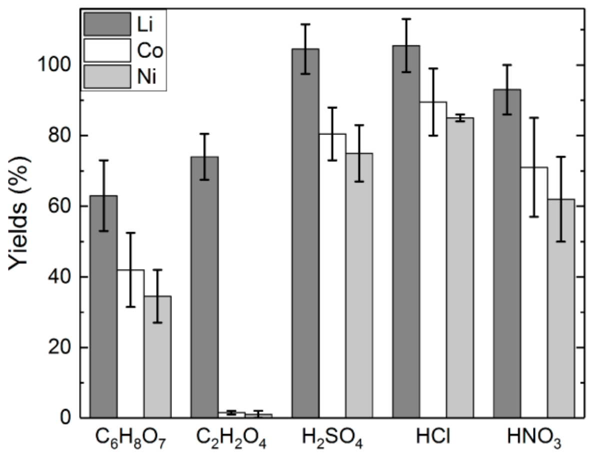

Figure 5. Metal recovery efficiency of different acids after adding hydrogen peroxide

Acid leaching can be categorized into two distinct types based on the nature of the acid utilized: inorganic acid leaching and organic acid leaching. Aaltonen et al. conducted a study to examine the leaching efficiency of different types of acids. As shown in the following figure, Figure 5 illustrates the metal recovery efficiency of various acids when hydrogen peroxide is employed as a reducing agent, while Figure 6 showcases the metal recovery efficiency of different acids in the absence of hydrogen peroxide. The recovery rates associated with inorganic acids typically surpass those of organic acids. Particularly, sulfuric acid and hydrochloric acid have been proven to be the most effective methods for leaching lithium from lithium-ion batteries (LIBs). Conversely, the efficacy of the reducing agents is prioritized in descending order as follows: ascorbic acid ($C_6H_8O_6$), D-glucose, and trioxidane (H_2O_3).

The extraction efficiency is optimized when a 10% solution of ascorbic acid is employed in conjunction with sulfuric acid (Aaltonen, M. et al., 2017).

While organic acids may not possess the same level of potency as inorganic acids, Fatima et al. effectively extracted nearly all valuable metals from the solution by submerging discarded lithium batteries in citric acid, which functioned as a chelating agent, and ascorbic acid, which served as a reducing agent. This technique presents an innovative and environmentally sustainable method for utilizing organic acid reagents (Fatima, S. et al., 2024). While organic acids are considered more environmentally sustainable and do not emit toxic gases, their elevated cost presents significant challenges for their application in industrial settings. (Wei, Y. F. et al., 2023)

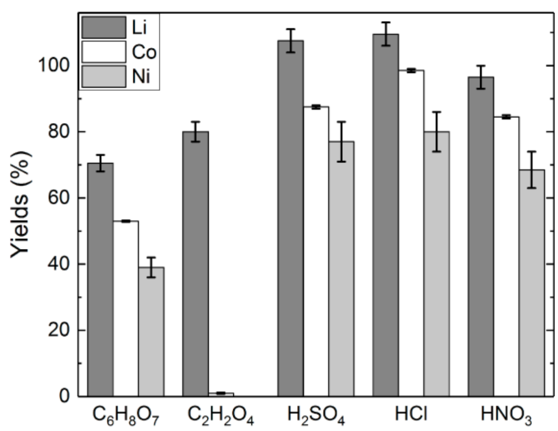

Figure 6. Metal recovery efficiency of different acids without adding hydrogen peroxide

3.3.2 Alkaline Leaching

Alkaline leaching, commonly known as ammonia leaching, utilizes ammonia water as a leaching agent to selectively recover valuable metals from the cathode materials of spent lithium-ion batteries. The fundamental principle of this process is that ammonia (NH_3), in an alkaline medium, can engage in complexation reactions with various metals. The primary benefit of this method lies in its capacity to selectively extract the desired metal; however, it exhibits a lower level of efficiency (Pan, Y. L. et al., 2024). Wang et al. conducted a leaching process on nickel-cobalt slag utilizing a solution composed of ammonia and ammonium sulfite hydrate. Under ideal conditions, the nickel leaching rate achieves 90.09%, while the cobalt leaching rate reaches 89.24%. This discovery presents a new methodology for alkaline leaching (Wang, Y. et al., 2022). In comparison to alternative processes, alkaline leaching, although facilitating selective leaching, demonstrates a reduced leaching rate, produces elevated temperatures during the reaction, and presents difficulties in the recovery of the leachate (Wei, Y. F. et al., 2023).

3.3.3 Bioleaching

Bioleaching refers to the process of employing the metabolic activities of microorganisms to engage with lithium battery powder in a leaching system, thereby promoting the dissolution and recovery of metallic elements. Biological leaching provides a superior recovery rate, reduced energy consumption, and is more environmentally sustainable in comparison to alternative hydrometallurgical techniques. Additionally, it functions independently of industrial machinery and does not require extreme reaction conditions. While bioleaching represents a highly promising recycling technique with the potential to develop into an environmentally friendly and sustainable recycling technology, it currently faces several challenges, including low efficiency, demanding leaching conditions, and prolonged cultivation periods (Zanoletti, A. et al., 2024). The key determinants affecting bioleaching encompass the selection of microbial strains (such as bacteria and fungi), leaching conditions (e.g., leaching methodologies, temperature, and the solid-liquid ratio), and cultivation conditions (e.g., culture media and nutrient substances) (Lü, M. Y. et al., 2023).

Boyden et al. identified an acidophilic chemolithoautotrophic organism from the sediments of a severely metal-contaminated acid mine lake. The study involved culturing this organism on agar plates supplemented with iron, sulfur, or a combination of both. The organism exhibited the highest growth and oxidation rates, alongside the lowest microbial diversity, and demonstrated a gradual adaptation to environments with escalating concentrations of metal ions. Ultimately, it achieved a recovery rate of up to 100% for lithium, cobalt, nickel, manganese, and aluminum (Boyden, L. M. et al., 2021). Microorganisms may exhibit a reduction in metabolic activity when exposed to elevated concentrations of metal ion solutions, potentially leading to a decreased rate of processing. Zhao et al. have put forth a methodology aimed at alleviating microbial stress induced by light metal ions through the incorporation of chemical agents (such as spermine and glutathione). Furthermore, they have recommended the application of electrochemical measurement techniques (e.g., Tafel scanning) to assess the health status of microorganisms (Zhao, C. et al., 2020).

3.4 Bio-Metallurgy

Bio-metallurgy is defined as the process of extracting metals from waste materials and minerals utilizing microorganisms and their metabolic byproducts. This technique is frequently utilized for the leaching of copper sulfide ores, the extraction of uranium mines and rare earths, and the oxidation pretreatment of refractory gold ores. It represents a vital method for advancing green and sustainable development within the metallurgy sector (Yang, B. J. et al., 2024). In comparison to alternative extraction methods, bio-metallurgy is characterized by a slower processing rate. Nevertheless, it presents numerous advantages, such as reduced emissions, enhanced environmental sustainability, significant selectivity for metals, and lower processing costs. Specifically, pyrometallurgical costs are estimated to be between USD 100 and USD 200 per ton of ore, while hydrometallurgical costs range from USD 50 to USD 100 per ton of ore. In contrast, the costs associated with bio-metallurgy are approximately USD 20 to USD 50 per ton of ore. As illustrated in Table 4, bio-metallurgy demonstrates a significant recovery rate for the recovery of metals including copper, uranium, and gold. Nevertheless, it is essential to acknowledge that, while bioleaching exemplifies the potential of bio-metallurgy and although bio-metallurgy has been used in metal recovery for many years, the application of bio-metallurgy for lithium recovery is still relatively rare. This domain is still in its nascent stages and necessitates further investigation and advancement.

Table 4. Percentage of metals extracted from e-waste through Bio-hydro-metallurgy

Copper (Cu)	The recovery of Cu often ranges from 50% to over 90%, which depends on different situations. In some cases, the near-complete copper is possible.
Gold (Au)	The recovery of Gold is typically ranging from 60% to 90%, which will be affected by different effects, like the specific microbial strains employed.
Uranium(U)	The recovery of Uranium often can be significantly high, even exceeding 90%,
Cobalt (Co)	Extraction of Cobalt by bio-hydro-metallurgy can achieve recovery between 60% and 80% in

	certain cases.
Nickel (Ni)	The recovery of Nickel can range from 50% to 80%.
Zinc (Zn)	The recovery of Zinc can range from 70% to 90%.
Silver (Ag)	The recovery of Silver can range from 50% to 90%.

4. Conclusions: Future Perspective of the Research

In summary, there exist various methods for recycling lithium, with the predominant techniques involving the extraction of lithium from lithium slag and the recycling of discarded lithium batteries. Each recycling technique presents distinct advantages and disadvantages, necessitating the selection of the most suitable method according to particular requirements. Pyrometallurgy is well-suited for the large-scale processing of batteries or slag, whereas hydrometallurgy offers the highest recovery rate, rendering it especially efficient for the extraction of precious metals. The continuous advancement of technology has given rise to the development of efficient and environmentally sustainable recycling methods, which facilitate the efficient recovery of rare and precious metals from power batteries. This progress contributes to a reduction in reliance on primary resources. It is expected that the industry will experience sustained growth over the next five years, with market size forecasts indicating an increase from approximately RMB 36.6 billion in 2023 to RMB 68.6 billion by 2027. This growth is projected to yield a compound annual growth rate (CAGR) of nearly 13.38%. This suggests that the market for recycling used lithium-ion batteries possesses considerable potential for growth. Future research endeavors concerning the recycling of used lithium batteries will focus on the development of innovative processes to overcome the technical challenges associated with a single treatment method. Additionally, this research will necessitate the integration of both chemical and physical methodologies to ensure effective processing. The market’s exceptionally efficient recycling model is expected to facilitate the development of new technologies to a certain degree. As processes are continually refined in the future, additional industrial systems for the recycling of power batteries will be established. Concurrently, traditional methods will also undergo continuous enhancements to address existing challenges.

In conclusion, the recycling of utilized lithium-ion batteries is crucial for environmental protection and the circular use of resources. Given the advancements in technology and the rising demand in the market, this sector is positioned to encounter significant growth opportunities.

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