**OPEN ACCESS**

Volume: 4

Issue: 3

Month: September

Year: 2025

ISSN: 2583-7117

Published: 09.09.2025

Citation:

Dr. Santosh Kumar Nathsharma"Lithium-Ion Battery Components and Its Recycling Methods – A Review" International Journal of Innovations in Science Engineering and Management, vol. 4, no. 3, 2025, pp. 322–335.

DOI:

10.69968/ijisem.2025v4i3322-335



# Lithium-Ion Battery Components and Its Recycling Methods – A Review

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**Abstract**

*The increasing prevalence of lithium-ion batteries in electric vehicles, consumer electronics, and renewable energy systems has led to a pressing demand for efficient recycling methods. This review delves into the essential elements of lithium-ion batteries and examines the primary recycling techniques: pyrometallurgy, hydrometallurgy, and direct recycling. Every approach presents unique advantages and obstacles regarding expenses, energy consumption, efficiency of recovery, and ecological effects. Pyrometallurgy is frequently employed, yet it requires elevated temperatures and generates emissions. Hydrometallurgy provides enhanced material recovery, yet it involves a greater use of chemicals and intricate processes. Direct recycling, currently being explored, demonstrates promise in maintaining material value. Even with advancements in technology, obstacles like inconsistent regulations, inadequate collection systems, and limited public awareness continue to persist. Tackling these challenges is essential for establishing a sustainable and circular battery economy. This paper seeks to provide a comprehensive overview to aid in future research and policy formulation regarding battery waste management.*

***Keywords; Lithium-ion batteries, Recycling methods, Pyrometallurgy, Hydrometallurgy, Sustainability.***

## INTRODUCTION

Lithium-ion batteries (LIBs) have become integral to modern energy storage solutions due to their high energy density, long cycle life, and relatively low self-discharge rates. First commercialized by Sony in 1991, these batteries revolutionized portable electronics and later found extensive application in electric vehicles (EVs), renewable energy systems, and industrial backup power. (T. Wang, 2023)

The basic operation of a lithium-ion battery centres around the transfer of lithium ions between the anode and cathode via an electrolyte (Costa et al., 2021; Denk & Wiechers, 2024). When discharging, lithium ions move from the anode, usually made of graphite, to the cathode, which can be lithium cobalt oxide or lithium iron phosphate, while generating electrical energy along the way (Vieceli et al., 2021). This reversible ion exchange underpins their reusability and efficiency.

The appeal of LIBs in the current landscape lies in their remarkable scalability and adaptability. Lithium-ion batteries provide a versatile solution for power management, ranging from small mobile devices to large-scale grid storage, playing a vital role in the shift towards low-carbon technologies (Gaines, 2018). Nonetheless, the growing reliance on these batteries brings to light issues regarding resource exhaustion, ecological consequences, and disposal strategies, particularly since essential materials such as lithium, cobalt, and nickel are finite and frequently sourced under dubious environmental or ethical practices. (Bai et al., 2020)

With the increasing global demand, it is crucial to comprehend the makeup and lifecycle of these batteries (Chagnes & Pospiech, 2013). This knowledge is vital for enhancing performance and developing effective recycling methods. This context emphasizes the importance of a comprehensive examination of lithium-ion battery parts and their recycling routes.

**Table 1 Importance of Recycling Lithium-ion Batteries**

| S. No. | Aspect | Description |
|---|---|---|
| 1. | **Resource Conservation** | Recycling helps recover critical materials like lithium, cobalt, nickel, and copper, reducing dependence on virgin mining and conserving finite reserves. (Holzer et al., 2021) |
| 2. | **Environmental Protection** | Prevents hazardous chemicals from leaching into soil and water, thereby minimizing ecological and public health risks associated with improper disposal. (Sojka et al., 2020) |
| 3. | **Energy Efficiency** | Recovering materials through recycling often consumes significantly less energy than extracting and refining new raw materials from ores. (Niščáková et al., 2024; Zanoletti et al., 2024) |
| 4. | **Economic Value** | Extracted metals from used batteries have considerable market value, supporting the development of a circular economy and lowering production costs. (Pražanová et al., 2024) |
| 5. | **Waste Reduction** | Reduces the volume of electronic waste ending up in landfills or incinerators, aligning with sustainable waste management practices. (Wiechers et al., 2024) |
| 6. | **Supply Chain Stability** | Ensures a more stable and localized supply of critical battery materials, especially important in times of geopolitical tension or trade restrictions. |
| 7. | **Compliance with Regulations** | Helps manufacturers and importers adhere to environmental regulations and extended producer responsibility (EPR) laws in many countries. (Baum et al., 2022) |
| 8. | **Sustainable Industry Growth** | Facilitates the development of green industries, supporting innovation in recycling technologies and sustainable battery production. (Patwa, 2024) |
| 9. | **Carbon Footprint Reduction** | Contributes to lower greenhouse gas emissions by reducing the need for high-emission mining and refining operations. |
| 10. | **Public Awareness & Responsibility** | Promotes consumer and corporate accountability in managing e-waste, fostering an environmentally conscious culture. (Chen, 2022) |

***Lithium-ion Battery Components***

Lithium-ion batteries (LIBs) are sophisticated electrochemical systems made up of several interdependent components, each playing a crucial role in the storage and release of electrical energy (Depmeier, 2012). The performance, safety, cost, and recyclability of these batteries are significantly influenced by the composition and design of their components. At the core, a typical LIB consists of a cathode, anode, electrolyte, separator, and various additives such as binders and conductive agents (Zinkevych et al., 2024). The cathode is the positive electrode during discharge and determines much of the battery's capacity and voltage (Thompson et al., 2020). Common materials include lithium cobalt oxide (LCO), lithium iron phosphate (LFP), lithium nickel manganese cobalt oxide (NMC), and lithium nickel cobalt aluminum oxide (NCA), each with unique trade-offs in terms of energy density, thermal stability, and cost (Bae & Kim, 2021). The anode, usually made from graphite, serves as the host for lithium ions during charging. Emerging materials like silicon composites are also being explored due to their high theoretical capacity (Davis & Demopoulos, 2023). The electrolyte, typically a lithium salt dissolved in a solvent, allows ionic movement between electrodes. It may be in liquid, gel, or solid-state form, depending on the battery type. The separator is a microporous membrane that keeps the anode and cathode physically apart while allowing ions to pass through (Rinne et al., 2025). It is critical for safety, as any failure can lead to short circuits. Finally, binders and conductive additives are used to hold the electrode materials together and facilitate electron flow within the electrodes. (Benaabidate et al., 2022)

**Table 2 Essential Components of Lithium-ion Batteries and Their Functions**

| Component | Material Examples | Primary Function |
|---|---|---|
| Cathode | LCO, NMC, LFP, NCA | Stores lithium ions and determines energy density and voltage |
| Anode | Graphite, Silicon-Graphite Composites | Hosts lithium ions during charge; affects capacity and cycle life (Lai et al., 2025) |
| Electrolyte | $LiPF_6$ in EC/DMC (liquid), solid electrolytes | Enables ionic conductivity between electrodes |
| Separator | Polyethylene (PE), Polypropylene (PP) | Physically separates anode and cathode while allowing ion flow (Roy et al., 2024) |
| Binder & Additives | PVDF, Carbon Black, CNTs | Provides structural integrity and improves electrical conductivity within electrodes (Pražanová et al., 2022) |

***Lifecycle and Environmental Impact of Lithium-ion Batteries***

Lithium-ion batteries (LIBs) follow a distinct lifecycle, beginning from raw material extraction to manufacturing, use, and eventual disposal or recycling. Each phase carries environmental implications, especially when sustainability practices are not adhered to. A comprehensive Lifecycle Assessment (LCA) evaluates the environmental footprint associated with energy use, emissions, and resource consumption throughout the battery's lifespan.

The raw material extraction phase is energy-intensive and often associated with significant ecological degradation (Xiaodong & Ishchenko, 2024). Mining of lithium, cobalt, and nickel leads to soil erosion, water contamination, and social issues in regions like the Democratic Republic of Congo and South America’s Lithium Triangle (Singh, 2025). The manufacturing stage further contributes to emissions due to high energy requirements in material processing and cell assembly.

Once deployed, the usage phase is relatively clean in terms of emissions, especially when used in electric vehicles or renewable energy systems (Shim, 2025). However, performance degradation over time leads to battery replacement. If not handled properly, the disposal of end-of-life batteries becomes a critical concern (Zhou et al., 2020). LIBs can release toxic substances like HF gas, heavy metals, and organic solvents, leading to soil and water pollution.

Recycling addresses many of these concerns by recovering valuable materials and reducing the need for new resource extraction. It also mitigates greenhouse gas emissions and electronic waste (Bej & Zhimomi, 2022). Despite these advantages, the economic viability of recycling remains a challenge due to complex separation techniques and the fluctuating market value of recovered metals. (Kovačević et al., 2024)

**Table 3 Environmental Impact at Different Stages of Lithium-ion Battery Lifecycle**

| Lifecycle Stage | Key Activities | Environmental Impact |
|---|---|---|
| 1. Raw Material Extraction | Mining of lithium, cobalt, nickel | Deforestation, water contamination, energy consumption, habitat loss (Roychowdhury & Mohanty, 2023) |
| 2. Material Processing | Refining and chemical preparation | Emissions, chemical waste, air and water pollution |
| 3. Cell Manufacturing | Electrode production, cell assembly | High energy use, carbon emissions |
| 4. Battery Usage | Powering devices, vehicles, storage systems | Minimal direct emissions; indirect impact depends on energy source (P. Manikandan, 2025) |
| 5. End-of-Life Disposal | Landfilling, incineration (if unrecycled) | Toxic leachate, fire hazard, long-term environmental damage (Hu & Xu, 2021) |
| 6. Recycling/Reuse | Mechanical, thermal, or chemical processing | Resource recovery, reduced need for mining, lower environmental footprint |

***Recycling Methods of Lithium-ion Batteries***

The global rise in the consumption of lithium-ion batteries (LIBs), especially in electric vehicles and portable electronics, has brought with it a significant challenge: managing end-of-life batteries in an environmentally responsible and economically viable manner. Recycling is a key solution to this issue (Trends & Future, 2025). There are several methods currently employed or under development to recycle LIBs, each with its own merits and constraints. The following points outline the major methods used: (Heimes et al., 2023; Sloop et al., 2020)

**1. Pyrometallurgical Recycling**

This is one of the oldest and most commonly practiced techniques. It involves high-temperature processing, where batteries are smelted to recover metals like cobalt, nickel, and copper (Rajaeifa & Raugei, 2021). The process is relatively simple and well-established in industry. However, it comes with serious downsides high energy requirements, emission of greenhouse gases, and limited recovery of lighter metals like lithium and aluminum.

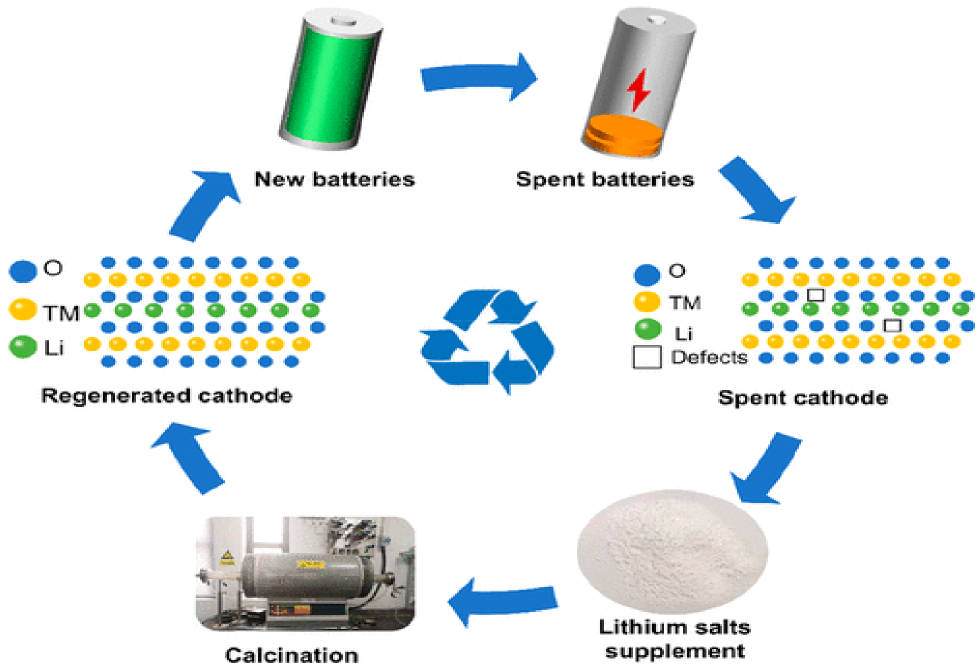


**Figure 1 Pyrometallurgical Recycling**
***https://pubs.acs.org/cms/10.1021/acsestengg.1c00067/asset/images/medium/ee1c00067_0006.gif***

## 2. Hydrometallurgical Recycling

This process involves the use of chemical solutions (acids or bases) to leach metals from shredded battery components. The dissolved metals are then separated and purified using various chemical and electrochemical techniques (Jena et al., 2021). This method allows for high recovery rates, including lithium, and is more selective and environmentally controlled than pyro-methods. Nevertheless, handling toxic chemicals and waste effluents remains a major concern. (Ali et al., 2022)

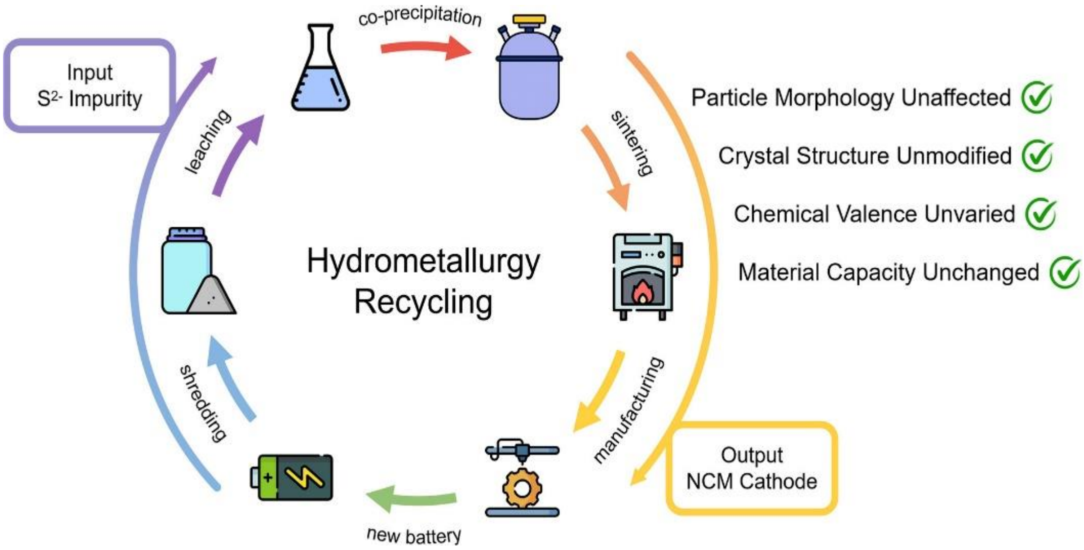


**Figure 2 Hydrometallurgical Recycling**
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## 3. Direct Recycling

Direct methods aim to recover and restore the original electrode materials, such as cathode powders, without breaking them down into individual elements (Gaines, 2020). The idea is to regenerate these materials through chemical treatments, such as relithiation. While this process uses less energy and maintains material quality, it is highly sensitive to battery type, chemistry, and contamination making sorting and preprocessing crucial.

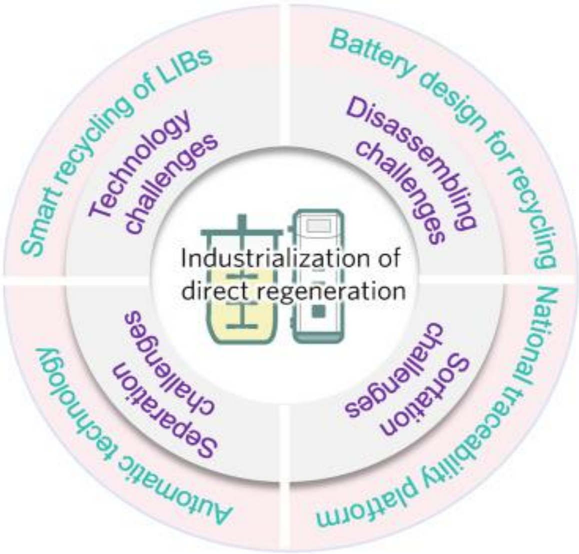


**Figure 3 Direct Recycling**
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**Table 4 Comparison of Lithium-ion Battery Recycling Methods**

| S. No. | Method | Process Description | Key Advantages | Main Limitations |
|---|---|---|---|---|
| 1 | Pyrometallurgical | High-temperature smelting to extract metals | Established, treats mixed chemistries | High energy use, low lithium recovery, $CO_2$ emissions (Li et al., 2024) |
| 2 | Hydrometallurgical | Acid or base leaching followed by purification | High metal recovery, selective processing | Chemical waste generation, complex procedures |
| 3 | Direct Recycling | Material regeneration without full decomposition | Energy efficient, retains cathode structure | Requires clean, sorted input; still in development |
| 4 | Biological Recycling | Microbial extraction using bioleaching organisms | Environmentally friendly, minimal chemical usage | Slow processing, not yet commercially scalable |

***Challenges in Recycling Lithium-ion Batteries***

While the recycling of lithium-ion batteries (LIBs) offers environmental and economic benefits, it also faces several critical challenges that hinder its widespread implementation. These challenges arise from technical limitations, safety concerns, economic uncertainties, and regulatory gaps (Zhan, 2021) (Sarma, 2024) (Pagliaro & Meneguzzo, 2019) (Brückner et al., 2020). Understanding these obstacles is essential to improving the efficiency, safety, and viability of LIB recycling systems (Sarma, 2024).

**Table 5 Major Challenges in Lithium-ion Battery Recycling**

| S. No. | Challenge | Description |
|---|---|---|
| 1 | Material Complexity | Diverse battery chemistries require specific treatment and separation processes |
| 2 | Safety Concerns | Risk of fire or explosion during transport and dismantling |
| 3 | Low Economic Returns | Declining cobalt content reduces profitability |
| 4 | Poor Lithium & Graphite Recovery | Technological limits prevent full resource utilization |
| 5 | Inadequate Infrastructure | Lack of organized collection and recycling systems |
| 6 | Chemical Waste Generation | Some methods create hazardous by-products needing treatment (Pagliaro & Meneguzzo, 2019) |
| 7 | Weak Regulations | Absence of strong legal framework or enforcement in many regions (Brückner et al., 2020) |
| 8 | Low Consumer Awareness | Public ignorance hinders battery return and recycling rates |

**Table 6 Challenges in Lithium-ion Battery Recycling**

| Category | Specific Challenges | Explanation |
|---|---|---|
| **5.1 Technical and Material Complexity** | • Diverse chemistries (NMC, LFP, LCO, etc.)<br>• Battery design variation<br>• Sorting and dismantling difficulties | The wide variety in battery types and compositions makes uniform recycling processes inefficient and costly. |
| **5.2 Economic and Logistical Barriers** | • Low value of some recovered materials<br>• High cost of collection and transportation<br>• Lack of large-scale plants | Recycling is often economically unviable, especially in regions lacking infrastructure or subsidies. |
| **5.3 Safety and Environmental Concerns** | • Risk of fire, explosion, and toxic exposure<br>• Chemical waste generation<br>• Environmental leakage from improper disposal | Improper handling or disposal can lead to safety hazards and pollution, negating recycling benefits. |
| **5.4 Regulatory and Policy Issues** | • Absence of EPR enforcement<br>• Lack of global recycling standards<br>• Poor consumer participation and awareness | Weak regulation and limited awareness hinder effective collection and systematic recycling efforts. |

**LITERATURE REVIEWS**

(Windisch-Kern et al., 2021) Although pyrometallurgical recycling technologies are very advantageous, they are unable to extract lithium from dark matter because of lithium's slagged affinity for oxygen. Because it avoids this drawback and is very adaptable with respect to the input material's chemical makeup, the proposed InduRed reactor idea may be a fruitful new strategy. Heating microscope experiments, thermogravimetric analysis, and differential scanning calorimetry were used to characterize the behaviour of nickel rich cathode materials ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ and $LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$) and black matter from a pretreatment process under reducing conditions, in order to prove its basic suitability for black matter processing. The metals of interest were further investigated by conducting another set of experiments in a lab-scale InduRed reactor to determine feasible transfer coefficients. High recovery potentials for manganese, cobalt, and nickel were shown, along with reaction temperatures ranging from 800 to 1000 degrees Celsius that were considered technically viable. In addition, we were able to remove up to 90% of the lithium's original mass and significantly reduce the slagging of the lithium.

(Lee et al., 2024) The reviewers analyzed current pyrometallurgical recycling methods and noted that they excel at processing enormous quantities without pre-treatment, which is a major benefit. However, these technologies face obstacles to their competitiveness because to the high-temperature smelting process's energy consumption, greenhouse gas (GHG) emissions, element loss (Li and Mn included), and so on. Economic studies, laws, and regulations pertaining to lithium-ion batteries and recycling technologies all reflect these concerns. There has been a rise in the amount of lithium-ion battery recycling due to the fact that recycling is becoming more of a legal requirement in many nations. Although this has the potential to have a beneficial impact on pyrometallurgical recycling technologies, they will need to undergo more innovation to meet the demands of minimum recovery rates for particular material components and the obligatory reduction of carbon footprints.

(Etude et al., 2024) The study's authors looked into a variety of recycling processes, including the most recent innovations in hydrometallurgy, pyrometallurgy, direct recycling, and pretreatment. A mountain of wasted LIBs has been dumped into landfills due to the proliferation of electric vehicles and other electrical gadgets. Just in 2019, 500,000 tons of LIB trash were produced by EVs. At the current rate, it will reach 8,000,000 tons by the year 2040. At the now, recycling accounts for only 5% of the world's waste used LIBs. The necessity to recycle LIBs is a result of the need to save money and save raw resources. It is important to recycle LIBs since they include heavy metals (Ni, Li, Co, Cu, Mn, Fe, and Al) and dangerous compounds that pose a harm to both the environment and human health.

(Islam & Iyer-Raniga, 2022) According to the research, there has been a meteoric rise in the number of publications covering the subject, with the majority of these articles concentrating on recycling and recovery while giving less space to discussions of policy and regulation. According to the classifications created, the majority of the research consisted of conducting trials, then evaluating and planning the next steps. There was a lot of talk on pre-treatment procedures, which are essential in hydrometallurgy and DPR. DPR is an exciting new recycling method that needs further research and development. Safe reverse logistics, a worldwide evaluation of electric vehicles that shows material recovery potential, and a lifecycle evaluation of experimental procedures (in hydrometallurgical and pyrometallurgical processes) are some of the matters that need additional investigation. Further attention is required on the following topics: material tracking and identification; the expanded producer responsibility implications; the circular business model and its related stakeholders' participation; clear and definite policy guidelines; and the execution of the model.

(Wiszniewski et al., 2025) To ensure that the black mass produced is free of contaminants and suitable for use in the InduRed reactor, a well-planned pre-treatment strategy must be put into process. In order to customize the chemical composition to meet the reactor's unique process needs, a carefully planned series of pre-treatment steps was devised. In particular, efforts were made to reduce the amounts of phosphorus, aluminium, copper, and carbon, which are known to have a negative impact on the reaction kinetics and the final product quality. We suggested a sequential process chain after thoroughly analyzing technologies at both industrial and laboratory scales. Beginning with the sorting of battery chemistries, which makes use of instruments like the battery passport to efficiently separate LFP batteries from other types of trash, is the first step in the chain. After that, there are thermal pre-treatment procedures to get rid of organic binders and electrolytes for good, sieving procedures to get rid of any remaining Cu and Al, and a flotation process to get the best possible carbon content. For the InduRed reactor's pyrometallurgical settings, the complete process was designed to generate black mass with an optimum impurity profile. Maintaining experimental validation of the suggested method will reveal how well it regularly achieves the desired black mass quality.

(Heelan et al., 2016) Commercial recycling of Li-ion batteries allows for the extraction of valuable raw materials and the safe disposal of a hazardous waste product. To deal with the annual influx of used batteries into landfills, a number of businesses have emerged, mostly in the European and North American markets. Electric and hybrid cars, as well as consumer gadgets, are the main consumers of lithium-ion batteries. Among the several methods for recycling Li-ion batteries, pyrometallurgical and hydrometallurgical procedures stand out. To extract nickel and cobalt as alloys, pyrometallurgical treatment employs high-temperature smelting techniques. Hydrometallurgical methods enable the recovery of materials via the application of chemical leaching.

(H. Wang & Friedrich, 2015) An effective and product-oriented hydrometallurgical recycling method, including pre-treatment, was devised by the researchers to deal with used Li-ion batteries from automobiles. It is being explored if high-grade graphite, cathode metal salts, and lithium carbonate can be recovered. The method that was created incorporates procedures such as solution refining, leaching, precipitation of cathode metals, and crystallization of lithium carbonate. In ideal circumstances (80oC, 50 g/L of hydrogen peroxide, 2 mol/L of sulphuric acid or 4 mol/L of hydrochloric acid) the leaching efficiencies of precious metals (Co, Ni, Cu, and Li) vary from 98.6% to 99.9%. Meanwhile, the filtered graphite is obtained with a purity level of 99.8 percent. As shown below, the optimal temperature for Cu cementation is 60oC, and the activation energy of the cementation process is determined to be 12.9 kJ/mol. For the elimination of aluminium and iron in hydroxide precipitation, a pH of 3.5–4 is recommended, whereas a pH of 10 is sufficient for the precipitation of salts of cathode metals (Col, Ni, and Mn). It is also shown that the carbonate and sulphide precipitation procedures work similarly. A number of commercially viable byproducts are produced, including graphite, copper powder, salts of cathode metals, and lithium carbonate.

(Tembo et al., 2024) Using a standard baseline that clearly shows the costs of each operation helps simplify economic assessments of LIB recycling and waste management by diverse ways. To emphasize this advantage, this study presents the cost-conversion figures for several end-of-life LIB and waste LIB treatment procedures. The cost per ton of LIB is used to normalize the costs. The findings demonstrate that, when it comes to processing LIB, pyrometallurgy offers the most cost-effective option, while hydrometallurgy is the most expensive. The feedstock and the method's complexity are the primary factors that affect costs. When thinking about distinct hydrometallurgical processes that call for different processing chemicals, or when thinking about the energy source in relation to direct or indirect pyrometallurgy, this impact becomes apparent.

(Wagner-Wenz et al., 2023) With the goal of conducting a comprehensive assessment of lithium-ion battery recycling, the researchers looked at the three main methods, comparing their development status, process performance, and life-cycle environmental consequences. Specifically, 209 articles covering the three distinct recycling processes—the direct physical, the pyro-metallurgical, and the hydro-metallurgical—were combed through for this objective. After reviewing the available literature, we were able to identify several holes in the present study methodology that make it impossible to rank the three recycling methods with any degree of certainty. We will address these deficiencies in detail below. Interviews with industry professionals and impartial field reports would greatly enhance the current body of literature on commercial plants. But that's not what a literature review is about. First and foremost, we learned that owing to a lack of definitions or ambiguous or inconsistent use of key terms, the literature lacks comprehensive information. To start with, this is relevant to the very definition of recycling or recycling route. The following is our well-defined concept of a comprehensive recycling route: From the (end-of-life) batteries, a complete recycling pathway proceeds to either the active material, the alloy, or the salt of the transition metal as its constituent products.

(ELIBAMA project, 2014) The design of the battery should make it easier to access the modules and cells; standardizing the connections will also aid in this endeavour. In order to optimize energy consumptions, some researches are required with respect to the thermal process. Investigation into the possibility of recouping process energy is necessary. According to battery technology, the off-gas treatment differs based on the first trials. In the bag house filter, some elements (Li, Zn) may be recovered. The goal is to operate with a low-temperature, continuous process at first, and then ramp it up using the energy in the battery. The development of the battery's second life should occur concurrently with materials recovery. Lots of things have to be ironed out. Packaging and electrical wire connection standardization. Entry into the BMS space. Repairing broken components, cells, and modules is a breeze.

(S. Wang et al., 2020) The method of recycling LIBs is new, but it's gaining popularity fast. Most of the value in the wasted LIBs comes from cobalt and lithium. Almost every business is primarily involved in lithium and cobalt recovery. However, iron, manganese, copper, and aluminium are also recovered by certain businesses. Refining this metal could be more lucrative in the future, since experts predict that the price of lithium will rise in the next years. Efficiency gains and cost reductions for recovered metals are driving forces behind the evolution of recycling systems. Among the several methods put out is the employment of microbes to break down substances. It is a novel way to recycle used LIBs. By reducing demand for minerals and conserving natural resources, it has a good chance of becoming a reality in the not-too-distant future.

(Padmanabhan et al., 2024) Infrastructure for electric vehicles in India is still in its early stages of development, but it is picking up steam. Approximately 2.5 billion metric tons, or about 7% of the world's total carbon emissions, come from India at the moment. Nearly 40% of India's air pollution comes from cars and other vehicles powered by internal combustion engines. Given these facts, it is critical to immediately initiate a major campaign to encourage the use of electric cars to reduce the increasing pollution levels. There has been a change in international climate policy as a result of the worldwide movement towards a low-carbon economy that is required to reduce the effects of climate change. In an effort to hasten the country's overall shift away from ICE cars and toward EVs, over 20 Indian states have developed all-encompassing EV policies at the state level. The buildup of trash in public spaces, which might cause landfills to leak dangerous chemicals, is a direct outcome of insufficient regulations for the proper waste management.

(Ahuis et al., 2024) Using wet mechanical processing, the researchers proved that electrode manufacture could directly recycle scrap. The effort included developing a production approach that utilizes wet sieving, de-coating the black mass in an appropriate solvent (water for the anode and NMP or TEP for the cathode), and then cutting the electrode debris. Reusing the anode coating in the electrode manufacturing process achieves very high recycling yields (>95%) in this process chain. In order to get high enough recovery yields, more shear stress is necessary since the PVDF binder increases the adherence of the cathode coating. Mechanical stress on the coating is one of the driving factors in cathode de-coating, along with the solvent and its temperature. A high solids concentration hinders wet screening and leads to reduced recycling yields, hence it's important to employ an adequate solids content. Anode recovery yields of 97% and cathode recovery yields of 85% are achievable in total. To find a greener alternative to the harmful solvent NMP, we evaluated the recycling, resuspension, and coating capabilities of three other solvents: dimethyl isocyanate (DMI), acetone, and TEP. Solvent TEP is the only one that shows promise for a high enough recovery yield; nevertheless, it operates at hotter temperatures than NMP, necessitating more energy for the procedure. Furthermore, recycling yields are always lower than NMP recycling yields. The fact that the method can be easily scaled up makes it a good fit for commercial applications.

(Vaccari et al., 2024) The research extensively examined the modelling of LIB recycling using a quantitative process simulator based on Python. It focused on two routes, one based on pyrometallurgy and the other on hydrometallurgy, with co-precipitation of the precursor of cathode active materials. Instead of making direct comparisons between these fundamentally different processes, the main objective was to assess how resilient their performance was. The primary results show that the study's goal was to provide quantitative insights to supplement the debate in a recent review article (Latini et al., 2022). Recognizing that the numerical outputs of recycling performance indicators are strongly related to these definitional decisions, the research first highlighted the critical importance of defining who is and isn't liable for recycling. Second, a crucial component was the establishment of Purity Levels (PLs), which stand for mass fraction cutoffs for materials that should not be considered contaminants in a stream. The research found that PLs had a stronger effect on the hydrometallurgical route compared to the pyrometallurgical one, highlighting the need to take these limits into account when assessing recycling efficiency. Thirdly, hydrometallurgical process performance is less affected by the ratio of big format LIBs to small format LIBs than pyrometallurgical route performance. To improve process performance and decrease utility consumption, it is essential to optimize operational parameters based on spent battery feed composition. However, altering the chemistry of spent LIBs entering recycling routes has no discernible effect on recycling indices for either process.

(Reinhart et al., 2023) From a techno-economic standpoint, the article compared two pyrometallurgical recycling routes—one that is direct and another that involves many steps—for various compositions of lithium-ion battery cells (NMC333/C, NMC811/C, LFP/C, NMCLMO/C). Using lifetime inventories per recycling method and battery type, a total cost of ownership study for typical pyrometallurgical recycling facilities on a pre-industrial size is conducted to assess the viability of these two recycling processes. The findings demonstrated that cell chemistry significantly affects recycling profitability. It seems especially challenging to run a recycling operation successfully for low-nickel and low-cobalt battery types under present circumstances. The limits and potential benefits of various levers for improving the process profitability of recycling various systems of lithium-ion battery cells are shown in a sensitivity study.

(Dobó et al., 2023) The researchers provided an overview of LIB structure and discussed potential solutions for LIB disposal, such as recycling and reusing, to reduce the amount of used batteries sent to landfills or incinerators. Remanufacturing and repurposing are part of the re-use strategy, which is favoured in the hierarchy of waste management practices. Nevertheless, these choices just postpone the inevitable recycling horizon and increase the battery lifetime. There are three primary methods for recycling used lithium-ion batteries: direct recycling, hydrometallurgical recycling, and pyrometallurgical recycling. The pyrometallurgy process involves heating waste LIBs and then separating them. Hydrometallurgy is a method that recovers metals from LIBs by dissolving them in a leaching solution and then recovering them via subsequent purification and separation steps. While keeping the battery structures intact, direct recycling involves retrieving LIB active ingredients directly.

(Srinivasan et al., 2025) The LIB composition was covered, with an emphasis on the significance of understanding cathode chemistry and common cathode materials for efficient LIB recycling. After looking at the previous research, it's clear that LIB recycling tactics are important for addressing environmental problems and making the most of the resources available to modern society. As the demand for LIBs increases, it is critical to establish effective recycling operations in order to decrease the negative environmental consequences, safeguard valuable resources, and promote a battery ecosystem that lasts. Mechanical, hydrometallurgical, and pyrometallurgical procedures are the primary steps in traditional lithium-ion battery recycling. Biometallurgical and direct physical recycling are two new approaches that might need some scalability. Looking into the situation in India, we can see how lithium-ion battery use is at the moment, what the recycling landscape is like there, what laws and policies are in place regarding recycling batteries, and who the main players are who are trying to get people to recycle their old batteries.

(Öztürk et al., 2023) Research on LIBs near the end of their useful lives has mostly concentrated on recycling techniques that aim to lessen pollution and cut down on the use of natural resources; this has helped advance the causes of environmental sustainability and the circular economy. Three distinct recycling processes were compared using MCDM in the research. After the criteria were weighted using the Entropy Method, two distinct approaches, ANP and TOPSIS, were used to assess the alternatives. The Entropy Method's weighing procedures revealed that wastewater creation and greenhouse gas emissions were the two most critical assessment criteria. poisonous gas production and the usage of similarly weighed poisonous reagents follow these standards. Overall, the ANP findings showed that Direct Recycling was the superior option. The hydrometallurgical process and the pyrometallurgical process are the two methods that follow the direct recycling method. The TOPSIS algorithm yielded ideal and negative ideal separation metrics, as well as ranking results and relative proximity to the optimal solution.

(Nyikes & Toth, 2025) The authors provided a concise overview of the most important mining and usage trends for chemical components in battery manufacture. Furthermore, there are environmental and ethical issues about the mining techniques in the Democratic Republic of the Congo and the distribution of cobalt, a critical component in battery production. The advent of lithium-ion batteries presents additional obstacles, in contrast to the well-established and widely used techniques for recycling lead-acid batteries. The technological and economic challenges of recycling lithium batteries are a result of the high prices and complexity of the procedures involved. Options for recycling batteries were laid forth by the writers. In order to establish a circular economy and guarantee environmental preservation, it is necessary to emphasize sustainable recycling techniques. Within the framework of current trends in battery manufacturing and use, the study highlighted the critical need of sustainable recycling techniques.

(Melin, 2018) Even while recycling is becoming more common, the quantity of materials actually recovered is still very little compared to the whole market. This is true for both manufacturing scrap and waste batteries. This partnership will last for quite some time, given the increasing need for raw materials to meet the burgeoning battery industry. Despite the growing trend of recycling lithium and its refining into battery quality material, the quantities involved are still insufficient to make a significant dent in the overall lithium market. Metals like copper, nickel, and aluminium are in the same boat. The metal cobalt is an exception. Since the majority of recyclable materials originate from long-standing LCO batteries which include more cobalt per kilogram than NMC and NCA the quantity of recovered cobalt is not negligible when contrasted with the amount now used in manufacture. More than 10% of the cobalt supply in 2018 will come from recycled materials, which is up to 14,000 metric tons. While LCO batteries are making a comeback, the percentage of recycled cobalt will fall due to the slow recovery of new cobalt-containing chemistries like NCA and NMC.

**Table 7 Key Findings from Literature on Lithium-ion Battery Recycling**

| Study | Focus Area | Key Findings | Relevance to Study |
|---|---|---|---|
| Windisch-Kern et al. (2021) | Pyrometallurgical innovation | InduRed reactor enables recovery of Ni, Co, Mn, and up to 90% lithium with reduced slagging; effective at 800–1000°C. | Demonstrates advanced pyro-recycling with improved lithium recovery. |
| Lee et al. (2024) | Environmental & policy challenges | High GHG emissions and energy usage of pyrometallurgy; regulatory push requires innovation for better recovery and lower footprints. | Highlights regulatory constraints driving technology development. |
| Wiszniewski et al. (2025) | Pre-treatment optimization | Developed sequential pre-treatment to reduce impurities (Cu, Al, P, C), enhancing pyro efficiency in InduRed reactor. | Shows importance of upstream purity control for downstream recovery efficiency. |
| H. Wang & Friedrich (2015) | Hydrometallurgical recovery | Efficient recovery of Co, Ni, Li, Cu and graphite using chemical leaching and precipitation methods; multiple marketable products. | Demonstrates commercial viability of hydro-based recycling with high purity outputs. |
| Tembo et al. (2024) | Economic comparison | Pyrometallurgy has lowest cost per tonne; hydrometallurgy is costlier due to chemicals and complexity. | Provides cost insights crucial for selecting feasible recycling strategies. |
| Öztürk et al. (2023) | Sustainability assessment | MCDM shows direct recycling as best environmentally, followed by pyro- and hydro-methods; wastewater and GHGs are top concerns. | Supports selection of low-impact technologies to meet environmental goals. |
| Srinivasan et al. (2025) | Circular economy & policy | Emphasizes need for scalable recycling plants, emerging technologies (bio-, DPR), and India's policy gap in LIB recycling. | Contextualizes challenges/opportunities in policy and infrastructure. |
| Vaccari et al. (2024) | Process modeling | Defined recycling performance indicators; hydromet’s performance more sensitive to purity thresholds; highlights robustness of pyro route. | Provides analytical framework to compare performance across recycling methods. |

## CONCLUSION

Lithium-ion batteries are now used in many areas like electric vehicles, mobile phones, and solar energy systems. As their use grows, the need to manage battery waste and recover valuable materials also increases. This review looked at the main parts of these batteries and the methods used to recycle them. There are three main recycling methods: pyrometallurgy, hydrometallurgy, and direct recycling. Pyrometallurgy uses high heat to extract metals but can cause pollution and uses a lot of energy. Hydrometallurgy uses chemicals to separate metals more efficiently, though it is more complex and costly. Direct recycling is still being developed and focuses on reusing battery parts without breaking them down completely, which could save time and resources.

However, recycling batteries is not easy. Each battery is made differently, which makes sorting and processing difficult. There are also problems with cost, safety, and rules. In many places, recycling systems are not fully in place, and public awareness is low. To solve these issues, better recycling technology, clear policies, and public support are needed. Building a proper recycling system will not only protect the environment but also help recover important materials needed for future energy use.

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