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Research Article

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A Comparative Evaluation of Lithium-Ion Battery Recycling Technologies: Pyrometallurgical, Hydrometallurgical, and Direct Recycling Approaches

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Abstract

The rapid development of electric vehicles, renewable energy storage systems and other electronic devices has led to a dramatic increase in battery production and consumption, particularly Lithium-Ion batteries (LIBs). The current situation emphasizes the need for proper management of spent LIBs, which is challenged by environmental and economic barriers and is very rich in valuable materials such as lithium, nickel, cobalt, and copper. To overcome this problem, recycling technologies have been developed to recover these valuable materials, which help to establish the principles of a circular economy. This paper presents a comparative analysis of sustainable lithium-ion battery recycling technologies, specifically focusing on pyrometallurgical, hydrometallurgical, and direct recycling methods. The various methods are compared and analyzed based on their technical efficiency, metal recovery efficiency, and other factors. Finally, this study emphasizes the significance of recycling in establishing a circular economy and also presents future outlooks to further improve the efficiency of recycling.

Keywords: Pyrometallurgical Recycling, Hydrometallurgical recycling, Direct Recycling, E-Waste management, Battery Recycling and Sustainability

Abbreviations

LIB	Lithium-ion Battery
E-waste	Electronic Waste
EOL	End of Life
EV	Electric Vehicle
LFP	Lithium Iron Phosphate
NMC	Nickle Cobalt Manganese Oxide
NCA	Nickle Cobalt Aluminum Oxide
MMT	Matric Million Ton
CAGR	Compound Annual Growth Rate

1. Introduction

The increasing trend towards electrification and the use of renewable energy sources has created a huge demand for efficient and reliable energy storage solutions. Among the various alternatives, LIBs have emerged as the most sought-after option due to their remarkable energy density, long cycle life, low weight, and efficiency in performing well in different applications [1]. LIBs are already being used in electric vehicles, consumer electronics, renewable energy storage systems, and portable power tools. As these sectors are growing at a rapid pace, the manufacturing of lithium-ion batteries is experiencing unprecedented growth, resulting in a substantial increase in the number of LIB that have reached the end of their life [2].

According to recent projections in the industry, millions of tons of lithium-ion batteries are expected to be disposed of in the next twenty years, mainly because of the increasing use of electric vehicles [3]. Although LIB make transportation cleaner and reduce the emission of greenhouse gases during their use, their disposal poses serious environmental, economic, and health hazards. The disposed lithium-ion batteries contain dangerous materials such as flammable electrolytes and toxic heavy metals, which can cause problems such as soil and water pollution, as well as pose health hazards to humans if not disposed off properly [4]. Moreover, the disposal of lithium-ion battery waste by landfilling or incineration means that valuable resources are being lost.

Lithium-ion batteries are composed of "key metals such as lithium, cobalt, nickel, manganese, copper, and aluminum." These metals have been identified as key materials because of their relative scarcity and geopolitical issues surrounding their supply [5]. The mining and refining of these materials are not only energy- and resource-intensive, but they also cause environmental degradation in the form of greenhouse gas emissions, water pollution, and destruction of the ecosystem. With the increasing demand for lithium-ion batteries for electric vehicles, traditional mining is no longer environmentally sustainable or economically feasible.

Recycling lithium-ion batteries at the end of their life cycle is therefore becoming increasingly important. Battery recycling helps us extract precious metals that can be recycled for the production of new batteries, thereby reducing the need for mining. Studies have shown that the use of recycled battery materials can lower carbon emissions by 40-70% compared to materials obtained by conventional mining processes [6]. Moreover, recycling helps us overcome the risks associated with the disposal of batteries and also helps us comply with new environmental regulations. To address this issue, governments worldwide are enforcing stricter policies, such as Extended Producer Responsibility (EPR), recycling targets, and battery return programs, thereby emphasizing the need for the development of efficient battery recycling technologies [7]. Currently, different recycling technologies are being employed for lithium-ion batteries, while the industrial sector is mainly using pyrometallurgical and hydrometallurgical processes. Pyrometallurgical recycling involves high-temperature smelting to separate valuable metals, being the common recycling technology owing to its robustness and adaptability to different battery Chemistry. This recycling technology is expected to consume high amounts of energy, generate high greenhouse gas emissions, and have low lithium recovery rates [8].

On the other hand, hydrometallurgical recycling involves the use of chemical leaching and separation processes, which enable high recovery rates, especially for lithium and transition metals. However, this technology also faces different challenges owing to its complex chemical processes and waste products. In recent years, direct recycling has appeared as a promising method that aims to preserve the crystal structure of cathode materials rather than decomposing them into their respective components. Through the recycling of cathode materials via relithiation and thermal processes, this method holds promise for reduced energy consumption and environmental effects [9].

This paper offers a thorough comparative analysis of pyrometallurgical, hydrometallurgical, and direct recycling processes for lithium-ion batteries. It focuses on important factors such as the efficiency of material recovery, energy consumption, environmental concerns, maturity of technology, Cost and sustainability. By pointing out the challenges and looking at the opportunities in the future, this research aims to improve the development of effective recycling approaches to facilitate sustainable battery production.

2. Overview: Lithium- ion Battery

Lithium-ion batteries (LIB) are rechargeable batteries that work by moving lithium-ions between the two electrodes of the battery: the anode (negative) and the cathode (positive). Such batteries are commonly known as secondary batteries due to their rechargeable property.

Lithium-ion batteries are the best when it comes to storing a large amount of energy. This makes them suitable for use in different applications [10]. LIB powering two-wheeled and three-wheeled vehicles, consumer electronics such as smartphones and laptops, and industrial applications involving robots and manufacturing equipment. There are different types of lithium-ion batteries. These batteries are classified depending on size, shape, and the materials used in the electrodes. For example, MaxVolt Energy Industries Ltd. produces lithium-ion batterie pack which are not only have a long lifespan but also charge very fast, have excellent power performance, work well in low temperatures and most suitable to use in all conditions.

A typical LIB consists of:

- Cathode: $LiCoO_2$, NMC ($LiNiMnCoO_2$), NCA ($LiNiCoAlO_2$), LFP ($LiFePO_4$)
- Anode: Graphite
- Electrolyte: $LiPF_6$ in organic solvents
- Separator: Polyolefin membrane
- Current collectors: Copper (anode), Aluminum (cathode)

The cathode represents the highest economic value, particularly in cobalt-rich chemistries.

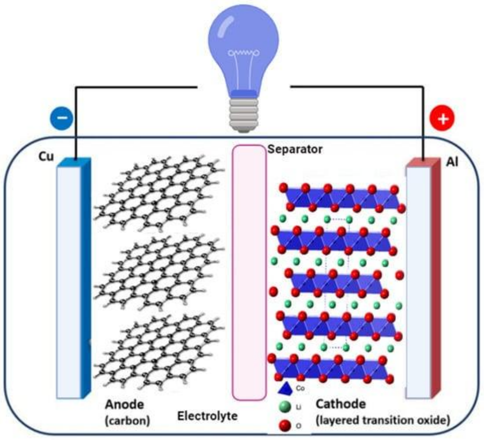

Figure 1: Components of LIBs: Cathode, Anode, Electrolyte, and Separator

The figure 1 illustrates the working principle and structure of the Lithium-Ion Battery cell. This diagram illustrates how electrical energy is generated through the flow of lithium ions and electrons between the anode and cathode.

3. Recycling Market Overview

The market for LIBs Recycling is expected to grow extensively, with a projected value of US$10.7 billion by 2025, with a CAGR of 24.8% from 2020-25 [11]. This is mainly due to the rising demand for electric and hybrid electric vehicles, which are heavily dependent on Lithium-ion batteries. As the demand for these vehicles increases, so the price of essential battery components such as cobalt and lithium, making Lithium-ion battery recycling a more profitable business. Additionally, the scarcity of raw materials required for Lithium-ion battery manufacturing, coupled with the rapidly increasing demand in different industries, drives the recycling market forward [12].

Based on the Global E-waste Monitor 2025 and the latest forecasts for the period 2025-2026, the top five countries that generate electronic waste are mainly those that use and produce electronics in large quantities. It is important to note that China and the United States are major contributors to global electronic waste [13]. Here is a list of the top five countries, based on the latest information available about their expected position by 2026:

- China (~12–15+ MMT): As the largest producer, fueled by extensive manufacturing and fast consumption rates.
- United States (~7–8 MMT): The second-largest contributor, characterized by high per-capita e-waste generation.
- India (~3–4+ MMT): An emerging producer experiencing rapid growth but currently facing low formal recycling rates, with predictions indicating a substantial increase.
- Japan (~2.5–3 MMT): A significant electronics consumer generating a noteworthy volume of waste.
- Brazil (~2+ MMT): A key producer in South America with a notably low rate of formal recycling.

a. Indian Battery Recycling Market

The battery recycling market in India is projected to reach a value of $530.80 million by 2025 and is estimated to grow to $1,996.03 million by 2030, registering a stupendous compound annual growth rate (CAGR) of 16.95% from 2025 to 2030. This is due to the rising use of electric vehicles, in addition to the strict implementation of regulations regarding the use of extended producer responsibility (EPR) [14]. As of May 2025, the Battery Waste Management Rules will be fully implemented, which will enforce EPR on original equipment manufacturers (OEMs) of electric vehicles and battery manufacturers, with the target of recovery rising from 70% in FY 2025 to 90% in FY 2027 for lithium-ion batteries used in electric vehicles. This is completely turning around the market dynamics by implementing a legal system for the collection and processing of spent batteries in the country [15].

The policy will impact all the stakeholders involved in the battery life cycle, as recyclers are required to register with the state pollution control boards. Electric two-wheelers lead the charge in adoption, contributing 60% of EV sales in 2024, with around 1.2 million units sold [16]. Leading companies such as Ola Electric, TVS Motor Company, and Ather Energy are leading the charge in this segment, creating huge demand for new batteries. Moreover, electric three-wheelers (E3Ws) contribute around 57% of the total three-wheeler sales in India as of FY2025, showing a swift shift from internal combustion engines (ICE) [17].

Government support for the manufacturing of Advanced Chemistry Cells batteries under Production-Linked Incentive schemes is driving downstream demand for recycled battery materials. This has led to recyclers aligning capacity expansion with the growth of domestic battery manufacturing, establishing the circular supply chain [18]. State governments are establishing dedicated EV and material recovery parks to promote recycling investments, assisted by infrastructure development and facilitation of approval procedures. These industrial estates are battery disassembly, chemical processing, and material refining units [19].

The constantly shifting environment is also driven by the involvement of start-ups and existing conglomerates, which is resulting in the rapid growth of lithium-ion battery recycling capacity in various parts of the world. Various entities such as Attero Recycling, Lohum Cleantech, and MaxVolt ReEarth Pvt. Ltd. are also increasing their recycling capacity to meet the growing demand.

The battery recycling market in India is divided into various types, such as chemistry, application, recycling process, and source. In the application type, one can distinguish various types such as transportation, consumer electronics, and industrial applications, among others [20]. The key players in this market are Attero Recycling, Lohum Cleantech Private Limited, and MaxVolt ReEarth Pvt. Ltd.

Attero Recycling is at the forefront of electronic waste and lithium-ion battery recycling in the Indian industry. Based in Uttarakhand, the company has enormous processing capacities and is dedicated to the recovery of critical materials from waste batteries, consumer electronics, and industrial waste through advanced hydrometallurgy processes.

Maxvolt ReEarth Pvt. Ltd., a specialized division of Maxvolt Energy Industries Ltd, is transforming the very idea of a circular economy with its emphasis on resource recovery. With expansion plans on the horizon, the company is all set to begin its operations with an initial processing capacity of 2-5 ton per day, with special emphasis on the highly efficient recycling of lithium-ion batteries.

4. Lithium-ion Battery Recycling Overview & Technologies

Battery recycling is an important process that focuses on the recovery of valuable materials from used or discarded batteries. In other words, battery recycling is the process that involves the collection, sorting, and processing of used battery materials for the purpose of recovering valuable materials to be reused in the production of new products [21]. With the increasing demand for batteries, especially LIBs, due to their increasing applications in EVs, electronic products, and energy storage systems ESS, recycling processes are becoming more important for the sustainable use of resources.

a. Steps for battery recycling

Battery Recycling is a technique of extracting valuable materials from used or discarded batteries. Some of the basic steps involved in battery recycling are as follows, focusing on the most widely used batteries such as Lithium Ion (Li-ion), Lead-Acid, and Nickel-Cadmium (Ni-Cd) batteries [22].

- Deactivation or Discharge of the battery
- Disassembly of the battery system
- Mechanical Process like sorting, crushing, etc.
- Electrolyte Recovery
- Metal Recovery process i.e. Hydrometallurgical, Pyrometallurgical & Direct recycling Process
- Purifications & Refining

Figure 2: Battery Recycling Pathways

The above figure 2 shows the circular life cycle of a Lithium-Ion Battery and how materials flow through its life cycle from raw material extraction to production, usage, end of life, recycling, and then back into production again. This is referred to as the circular economy in lithium-ion battery technology.

b. Battery Recycling Technologies

Battery recycling technologies play a critical role in the efficient recycling of valuable materials from used or discarded batteries. Various batteries call for different recycling technologies, but the most prevalent ones include pyrometallurgical processes, hydrometallurgical processes, and direct recycling [23]. There are also new technologies being developed to enhance efficiency and the recovery of valuable materials such as lithium, cobalt, and nickel. Some of the overviews of the dominant recycling technologies are highlighted below.

i. Pyrometallurgical Process

Pyrometallurgy is a technique that involves the use of high temperatures to melt and separate metals. The technique is mostly used to treat spent batteries that contain metals like cobalt, nickel, and copper. These batteries include lithium-ion batteries, nickel-cadmium batteries, and lead-acid batteries. Pyrometallurgical techniques mostly involve heating the materials in a furnace at high temperatures above 1000°C [24].

The process starts with mechanical pre-treatment, where the batteries are first discharged, disassembled if necessary, and then fed into a furnace. In some designs, whole batteries can be directly treated without much disassembly. The materials are then heated to temperatures ranging from 1200°C to 1500°C in a smelting furnace. At high temperatures, organic materials such as electrolyte and plastic separators undergo combustion, producing heat that partly satisfies the energy requirements of the process. The metals melt and separate according to density [25]. A metal alloy layer is created at the bottom of the furnace, consisting of cobalt, nickel, copper, and iron. A slag layer is also created above the metal alloy layer, consisting of lithium, aluminum, manganese, and silicon compounds. The metal alloy is further refined through hydrometallurgical processes to separate cobalt, nickel, and copper into high-purity materials.

ii. Hydrometallurgical Process

Hydrometallurgy battery recycling is an environmentally friendly and efficient method that uses aqueous chemistry to recover high-purity metals such as lithium, cobalt, nickel, and manganese from shredded battery "black mass [26]." The method involves acid/base leaching, purification, and solvent extraction, which consumes less energy and has higher metal recovery rates compared to conventional smelting. Hydrometallurgy is carried out at temperatures usually below 100°C, which consumes significantly lower energy compared to smelting. Lithium, cobalt, nickel, and manganese metal recovery rates are often above 90-95% efficiency.

The hydrometallurgical recycling process typically begins with the mechanical shredding of batteries in an inert or controlled atmosphere to prevent the risk of fire. This produces a material called "black mass," which is a mixture of cathode and anode powders and fine metallic particles [27].

The black mass is subjected to acid leaching, a procedure that usually involves sulfuric acid (H_2SO_4) with hydrogen peroxide (H_2O_2) as a reducing agent. In the leaching process, metal oxides are dissolved into solution:

$$LiNiMnCoO_2 + \text{acid} \rightarrow Li^{+} + Ni^{2+} + Mn^{2+} + Co^{2+} + \text{solution species}$$

After the leaching process, the impurities such as copper and aluminum are separated by selective precipitation or cementation. Solvent extraction techniques are used to separate cobalt, nickel, and manganese one after the other. Finally, lithium is extracted in the form of lithium carbonate (Li_2CO_3) or lithium hydroxide ($LiOH$), which can be used for the production of new batteries [28].

iii. Direct Recycling Process

Direct recycling is a very innovative technique that aims at preserving the crystal structure of cathode materials rather than decomposing them into individual metals. This technology has been developed by research institutions such as Argonne National Laboratory. The initial step involves battery disassembly and cathode material separation. The cathode powder is separated from aluminum current collectors, and the polymer binder (such as PVDF) is removed using a solvent or heating method [29].

Rather than decomposing the metals, the cathode material undergoes relithiation. The lithium-ion loss that results from battery cycling is replenished by the addition of lithium salts at relatively low temperatures (600-900°C). This process is intended to restore the original layered crystal structure of materials such as NMC or LCO. The obtained cathode powder is then re-sintered and analyzed for electrochemical performance. Laboratory analysis has demonstrated that the re-manufactured cathodes can provide 95-100% of the original performance of the original material.

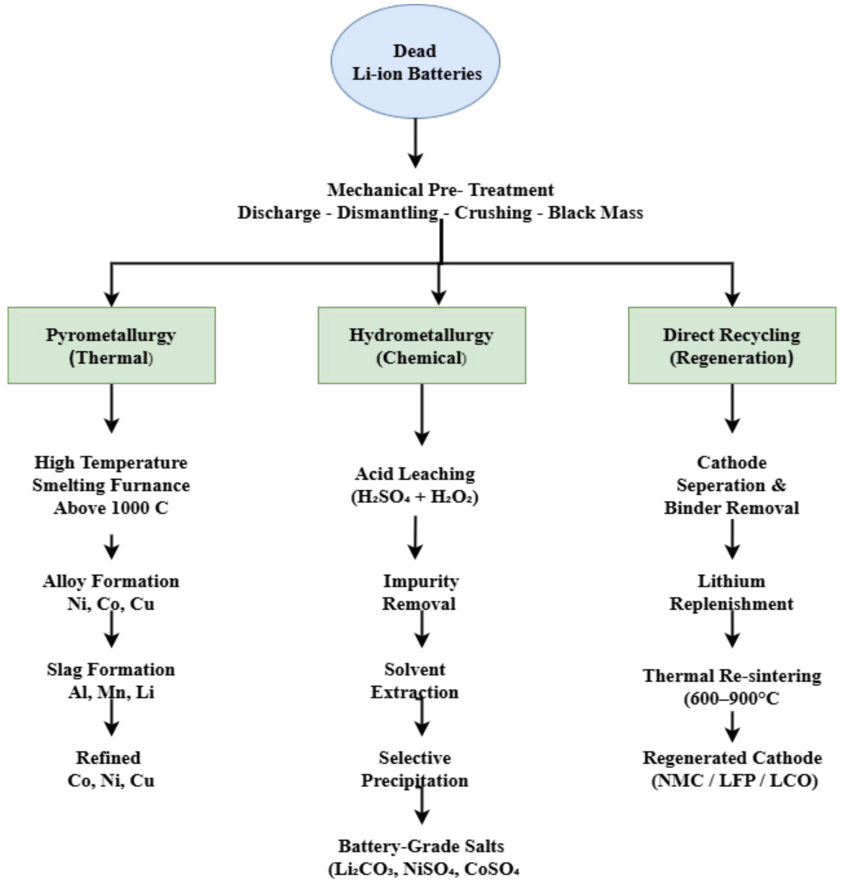

Figure 3: Flowchart of the Recycling Methods

Figure 3 above illustrates the major recycling routes for dead lithium-ion batteries. After the useful life of lithium-ion batteries is over, there are three major recycling routes available for recycling these lithium-ion batteries: Pyrometallurgy, Hydrometallurgy, and Direct Recycling.

c. Comparative Analysis

Pyrometallurgy is known for its robustness and scalability but is marked by high energy consumption and low lithium recovery. Hydrometallurgy is known for high recovery rates and low pollution although is complex in terms of chemical processing. Direct recycling is the most sustainable theoretical method, which retains cathode functionality but demands standardized battery streams and sophisticated separation methods.

In practice, there is a trend towards hybrid methods. For example, mechanical pre-treatment can be combined with hydrometallurgical extraction, while certain cathode materials can be directed to direct regeneration processes.

Parameters	Pyrometallurgy	Hydrometallurgy	Direct Recycling
Temperature	Very High (Above 10000C)	Low to Moderate	
(75 -1100C)	Moderate		
Lithium Recovery	Low (30-50%)	High (>95%)	Very High (=98%)
Energy Consumptions	High	Moderate	Low
CO2 emissions	High	Lower	Lowest
Process Complexity	Simple	Complex	Highly Specialized
Industrial Maturity	High	High	Emerging
Sorting Requirement	Minimal	Moderate	High

Table 1: Comparative Analysis of Recycling Process

The above table 1 compares three major recycling technologies used for end-of-life lithium-ion batteries: Pyrometallurgy, Hydrometallurgy, and Direct Recycling. Each method differs in temperature requirements, metal recovery efficiency, environmental impact, and industrial maturity.

5. Conclusions

The increasing demand for lithium-ion batteries (LIBs), particularly in electric vehicles and renewable energy technologies, has increased the need for efficient and sustainable approaches for their end-of-life treatment. This research performed a comparative study of the three primary recycling processes: pyrometallurgical, hydrometallurgical, and direct recycling, based on their recovery efficiency, environmental performance, and technological maturity.

Pyrometallurgical recycling processes remain prominent players in the sector due to their scalability and simple process operation that can accommodate different battery types. Nevertheless, their high energy consumption, increased greenhouse gas emissions, and low lithium recovery efficiency have sparked concerns about their long-term sustainability. In contrast, hydrometallurgical processes have the great advantage of recovering key metals such as lithium, cobalt, and nickel with high efficiency and at relatively lower temperatures, which improves their environmental sustainability. Nevertheless, these processes also have the disadvantages of requiring chemical agents and complex multi-step procedures that may cause wastewater treatment problems. However, direct recycling is a promising technique with long-term potential. It maintains the structure of cathode materials, which decreases energy consumption and environmental impacts. Additionally, it guarantees the quality of active materials, making it consistent with the principles of a circular economy. However, problems such as material separation, chemical selectivity, and the challenges of commercialization on a large scale need to be overcome to make it more suitable for implementation.

At present, there is no recycling technique that meets all the technical, economic, and environmental criteria. A hybrid technique that leverages the strengths of pyrometallurgical techniques, the high recovery rates of hydrometallurgical techniques, and the sustainability benefits of direct recycling may prove to be the most viable strategy. Research and development activities, as well as government initiatives, will play a crucial role in developing a sustainable infrastructure for lithium-ion battery recycling.

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