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Recycling Technologies for Lithium-Ion Batteries in Electric Vehicles: A Critical Review

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Highlights

- Evaluates three major LIB recycling methods: hydro-, pyro-, and direct routes
- Direct recycling offers 40–60% lower environmental impact than other methods
- Hybrid recycling enhances recovery rates and reduces energy and emissions.

Abstract

One important element of international efforts to reduce carbon emissions is electric vehicles, or EVs. However, the management of lithium-ion batteries (LIBs) after their service life is becoming a bigger challenge due to their quick adoption. The need for effective and scalable recycling solutions is growing as millions of EV batteries approach retirement. The three main recycling pathways: hydrometallurgical, pyrometallurgical, and direct recycling, are examined in this review paper along with their advantages, disadvantages, and sustainability. Hydrometallurgy can recover precious metals like cobalt and lithium at high rates, but there are complications with chemical use, wastewater production, and process complexity. Pyrometallurgy is a well-established industrial process, but it conumes high energy, produces metal losses, and has a low lithium recovery rate. The variety of battery types and technological immaturity continue to limit the acceptance of direct recycling, despite the fact that it has emerged as a viable option that aims to recover usable elements with minimal processing. This review highlights the economic and legislative obstacles, including the absence of design-for-recycling guidelines, high operating costs, and volatile raw material markets. The management of hazardous waste, emissions from recycling activities, and the environmental impacts of battery manufacturing are also covered.The review concludes with an outlook on green solvents, hybrid recycling solutions, second-life uses, and legislative frameworks that promote the ideas of the circular economy. This study provides direction for researchers, policymakers, and industry stakeholders working toward sustainable lithium-ion battery recycling systems that are in line with resource security and climate goals by highlighting recent developments and highlighting important research needs.

Paper type: Review paper

Keywords: Lithium-ion batteries, battery recycling, electric vehicles, sustainable technologies, circular economy.

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1. Introduction

The worldwide transition to electric vehicles (EVs) is widely considered to be an important tactic for reducing climate change. Specifically when it comes to air pollution, the dependence on fossil fuels and greenhouse gas emissions are continuously rising (Harperet al., 2019). Lithium-ion batteries (LIBs) are essential for EV transition because they power battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). Additionally, manufacturers often tend to use LIBs (typically found beneath the vehicle

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floor) to improve weight distribution and enhance safety of EV by offering high density of energy and extending the battery's life cycle (M. Chen et al., 2019). This rapid increase in electric vehicle adoption presents substantial end-of-life (EOL) management challenges for lithium-ion batteries (LIBs).

Despite the possibility of recovering LIBs valuable metal content, which in return helps decrease the need for mining and saves resources, it is still anticipated that millions of retired EV batteries will enter waste streams by 2030. Thus raising serious environmental risks by endangering the ecosystem and human health (Golmohammadzadeh et al., 2022). Many batteries retain 70–80% of their capacity after average vehicle use proving that they are ideal for second-life applications (Amusa et al., 2024; Neumann et al., 2022). Yet, we face some limitations related to the extraction of lithium, nickel and cobalt, as well as deforestation and contamination of water bodies (Balázs Illés & Kékesi, 2023). However, by lowering the emission levels that are associated with battery production and lowering the dependency on mining, recycling can be a sustainable option (Biswal et al., 2024) where the efficiency of material recovery is directly affected by strategies like 'Design-for-Recycling' that are linked to the circular economy(Cerrillo-Gonzalez et al., 2024).

To address these problems, the European Union set a minimum standard, in its battery regulation policy, for the recycling efficiency and composition of the recycled material. Nowadays, Companies are legally required to maintain EOL management as part of their Extended Producer Responsibility (EPR) policy (Rolandi et al., 2024). On the other hand, there are still certain technological challenges such as the disassembly of LIBs due to their numerous design variants. Even though hydrometallurgical recycling is a good alternative, this problem needs more optimization to make it cost-effective (Fatima et al., 2024; Guo et al., 2024a). EVs are widely seen as a breakthrough in reducing carbon emissions from transportation. Still, their true environmental benefits depend on what happens to their batteries after use. Realizing the full green potential of EVs will require more than just adoption, it depends on supportive policies, effective recycling systems, and smarter reuse of battery components.

This review places strong emphasis on the main recycling technologies, including hydrometallurgical, pyrometallurgical, and direct recycling. It critically examines recent advances in the recycling of LIBs used in EVs. It explores the economic, regulatory, and environmental aspects of these methods, evaluating both their advantages and limitations.Our review builds on earlier studies by including the latest research and analysis of recycling technologies for LIBs up to 2025 ((M. Chen et al., 2019b; Lai et al., 2022; Larouche et al., 2020; A. Liu et al., 2024; Pražanová et al., 2022a; Samarukha, 2020). Earlier reviews mainly focused on specific topics like the environmental impact of battery life cycles (A. Liu et al., 2024), economic modeling (Samarukha, 2020), and technical details of recycling methods (M. Chen et al., 2019b; Larouche et al., 2020; Pražanová et al., 2022a). Our review combines these areas into a broader comparison. In addition to detailed technical analysis and strategic insights, it also discusses new trends such as hybrid recycling methods, green solvents, regulatory changes, and second-life uses.

2. Technologies for Recycling Lithium-Ion Batteries

The first step toward effective recycling is understanding the complex material composition as the components of modern lithium-ion batteries (LIBs) directly affect the selection and efficiency of the appropriate recycling technology. Recent studies have shown that hydrometallurgical methods are among the most efficient approaches for processing nickel-manganese-cobalt (NMC) cathodes. However, in some cases, direct recycling may be preferred due to its ability to preserve the original structure of the cathode (Azimi & Chan, 2024; Huang et al., 2024). It is also worth noting that cathodes and anodes make up the majority of the complex components in currently used lithium-ion batteries. Cathodes, which have a high material recovery value, are typically made from layered oxides such as NMC or phosphates like LFP (Gerold et al., 2022). Anodes, on the other hand, are commonly made of graphite and may include a few unstable additives (Jenis et al., 2024). Furthermore, flammable electrolytes that include $LiPF_6$ might be extremely dangerous if they're handled improperly (Chrétien et al., 2023). Separator membranes that are typically composed of microporous polymers, permit ionic transport while avoiding electrode contact (Lan et al., 2024), knowing that protective containers and conductive metal foils are used to protect the cell components (Z. Liu et al., 2024).

Batteries' degradation makes recycling even more challenging. Recoveries and yields decrease when the metal lithium and solid electrolyte interphase (SEI) layer form, and processing explosion hazards grow (Luo et al., 2023; Pražanová et al., 2022b). Therefore, before choosing the best pretreatment approach, battery characterization is necessary. Pretreatment, being the initial stage in battery recycling, incorporates three key processes:

1. Any residual energy is eliminated when the cell is discharged to zero volts (Premathilake et al., 2023).
2. The components are separated mechanically by sorting and shredding (Rolandi et al., 2024).
3. Stabilization of reactive materials by thermal or chemical means (Gao et al., 2022).

When these pre-treatment procedures are established properly, they can improve recovery rates afterwards and minimize the energy needed for all recycling pathways (Peris Sastre et al., 2023). For example, complete electrolyte removal reduces emissions in pyrometallurgical processes (Maritz, 2024). However, temporarily removing current collectors from the bulk leachate can increase recovery efficiency by around 15–20% due to enhanced leaching performance (Al-Asheh et al., 2024).

2.1 Hydrometallurgical Process

Hydrometallurgical processing is progressively becoming the best method for recycling LIBs, due to its high recovery rates of lithium, cobalt, nickel, and manganese (Biswal et al., 2024; Cao et al., 2024a). In this process, metals are selectively leached from battery materials using aqueous solutions. The actual leaching procedure typically employs inorganic acids (such as sulfuric acid with hydrogen peroxide as the oxidizing agent) or organic acids (such as citric acid with ascorbic acid) under carefully controlled reaction parameters, which involve temperature, concentration, and duration (Du et al., 2023). In addition, by reducing Co^{3+} to Co^{2+}, hydrogen peroxide promotes the cobalt species interaction and optimizes total metal extractions (Balázs Illés & Kékesi, 2023).

After successful leaching, complex separation techniques can be modified using the strategies that follow:

1. Selective solvent extraction for nickel and cobalt recovery using chelating agents like Di-(2-ethylhexyl) phosphoric acid (D2EHPA) (Gupta et al., 2024).
2. Lithium can be chosen as a carbonate or fluoride species using precipitation techniques (Davis, 2023).
3. new solvent systems with minimal environmental hazards and great selectivity include deep eutectic solvents (DES) (Paul et al., 2024).

Based on the latest advances in technology, the optimal temperature range for hydrometallurgical processing can improve metal purity and accelerate reaction kinetics (Lan et al., 2024). Despite its advantages, the process can be affected by contaminants and degradation products like Solid Electrolyte Interphase (SEI) layers, making downstream purification more difficult. A simplified flowchart of the hydrometallurgical recycling process is presented in **Figure** 1, which explains the main steps from leaching to final recovery techniques.

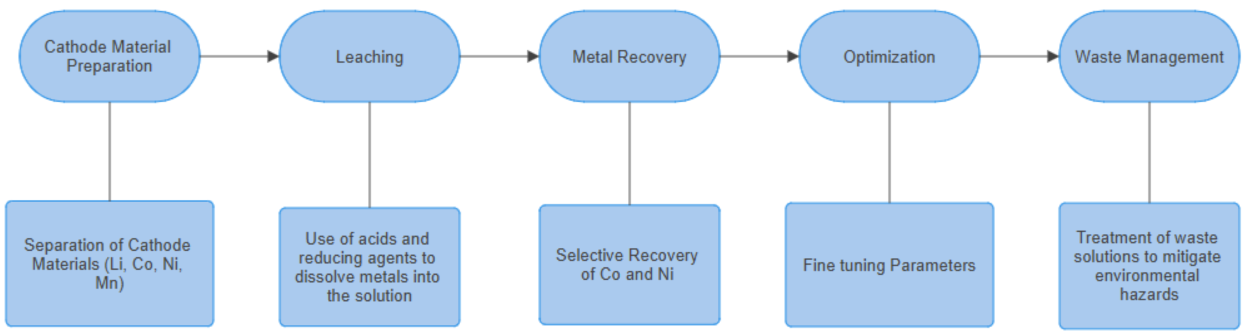

Fig. 1. Flowchart of the Hydrometallurgical Recycling Process *Adapted from (Fatima et al., 2024; Gupta et al., 2024; Jenis et al., 2024; Rolandi et al., 2024).*

2.2 Pyrometallurgical Process

The pyrometallurgical process is the favored method for industrial LIB recycling. It utilizes high-temperature smelting, often at 900 - 1400 °C, to recover metal values (Makuza et al., 2021a). Mechanical pre-treatment by shredding batteries during the pre-treatment process, is the first step in the recovery process. It optimizes smelting efficiency and is considered to be one of the safest ways to dispose flammable electrolytes and separators(Islam & Iyer-Raniga, 2022). Carbon reductants will break down metal oxides into an elemental form in furnace processing (most frequently rotary kilns or electric arc furnaces). These elemental forms have several distinct states, including a valuable alloy phase that contains Co, Ni, and Cu (Velázquez-Martínez et al., 2019). In addition, a lithium-rich slag is generated, which can be handled as a secondary process(Vest et al., 2010). An overview of the pyrometallurgical recycling stages, from mechanical pre-treatment to smelting and slag handling, is provided in **Figure 2**.

Some the major limitations of the processes would be:

1. Lithium loss: around 80% of stable species are converted to slag (Van Hoof et al., 2023a).
2. Energy demand: 5-8 kWh/kg input (Van Hoof et al., 2023a).
3. Improving flue gas cleaning is necessary for emissions management (Tong et al., 2024).

Hybrid pyro-hydrometallurgical flowsheets (Harper et al., 2019a), recovering and promoting the slag back into material for construction, or microwave-induced smelting are some of the newer technologies that address and enhance the mentioned problems.

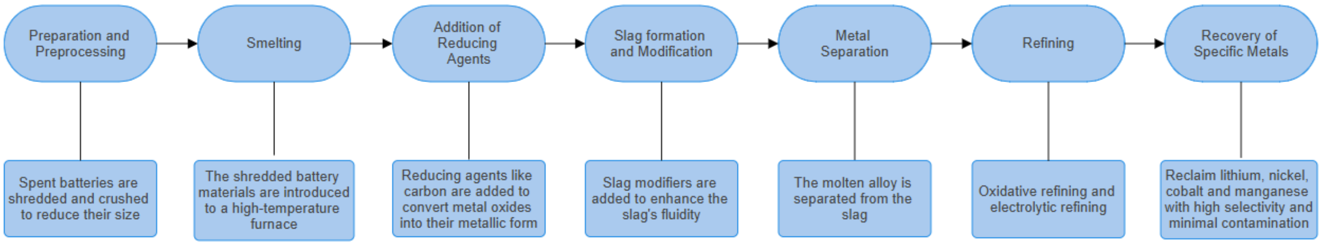

Fig. 2. Flowchart of the Pyrometallurgical Recycling Process. *Adapted from (Gerold et al., 2022; Rolandi et al., 2024; Wang et al., 2025).*

2.3 Direct Recycling Process

Direct recycling is a promising method that enables the recovery and reuse of valuable battery components, particularly cathode materials, while preserving their structure. This process has several advantages over traditional recycling methods (Huang et al., 2024). In comparison to standard hydrometallurgy routes, it uses 60–80% less energy. In addition, by using solid-state relithiation and hydrothermal regeneration, this method enables cathodes like NMC and LFP to be relithiated as solids while preserving their crystalline structure (Cao et al., 2024a; Lan et al., 2024). For example, regeneration techniques that apply electrochemical methods demonstrate recovery percentages more than 95% for moderate electrode degradation (Gao et al., 2022; Tong et al., 2024). Nevertheless, there are other obstacles to direct recycling, including the requirement to continuously monitor battery chemistry (Heimes et al., 2023; Neumann et al., 2022).

This approach is ineffective for regenerating materials that have degraded by more than 30% of their initial ability. Furthermore, changes in feedstock quality can greatly complicate the process and limit its scalability for large-scale disposal of batteries, given that direct recycling is highly sensitive to contamination (e.g., iron or aluminum impurities exceeding 0.1%) (Jenis et al., 2024; Zhou et al., 2024). Regardless of these drawbacks, lifecycle evaluations show that, when paired with automated sorting systems, direct recycling reduces environmental impact by 40–60% compared to regular recycling techniques (J. Chen et al., 2023). The workflow of direct recycling, including relithiation and regeneration steps, is outlined in **Figure 3**.

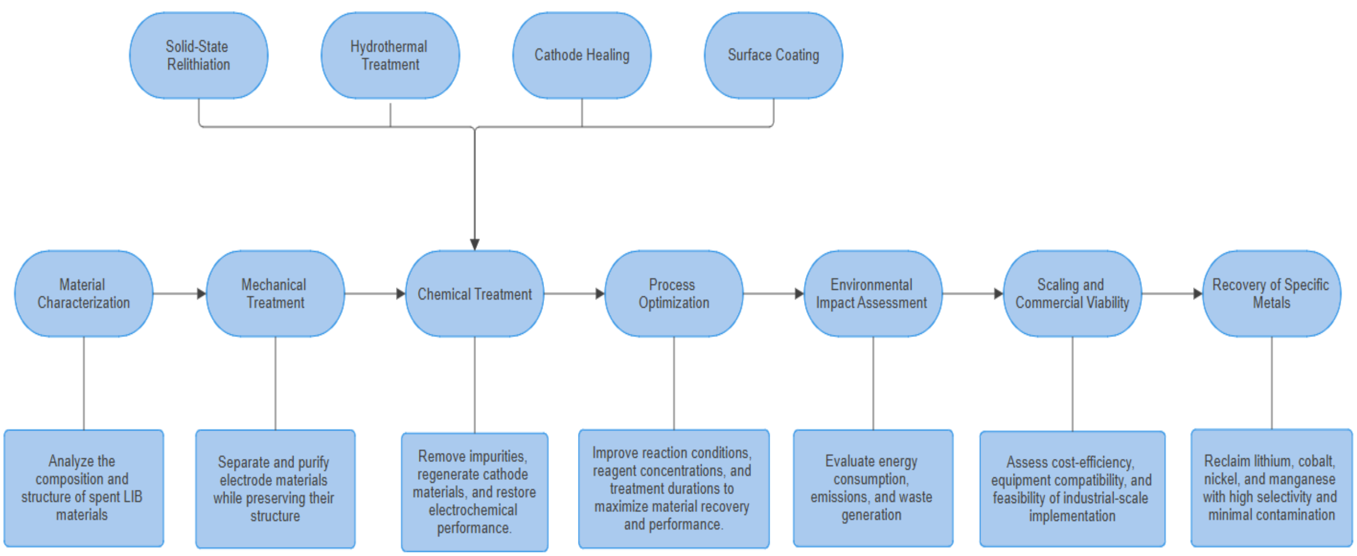

Fig. 3. Flowchart of the Direct Recycling Process. *Adapted from (Harper et al., 2019a; Joshi & Gaines, 2021)*

3. Technical Challenges in Battery Recycling

End-of-life LIBs have gone up dramatically as a result of the sudden increase in EV adoption and renewable energy storage, underlining the urgent need for reliable recycling techniques to recover vital components and limit environmental effects (Harper et al., 2019a). Despite major advancements, current recycling techniques, including pyrometallurgical and hydrometallurgical procedures still have a number of difficulties that hinder wider application and high energy consumption, limited recovery rates for specific metals, as well as ongoing issues with sustainability and scalability (Joshi & Gaines, 2021; Velázquez-Martínez et al., 2019). Alternative strategies, such as direct recycling and bioleaching, are needed as indicated by recent studies overcome these challenges and align with the principles of the circular economy.

3.1 Gaps in the Hydrometallurgical process

Given its advantages, that mainly consist of processing low-grade ores and producing less pollutants into the atmosphere, hydrometallurgy has several serious disadvantages.

i. Use of hazardous chemicals:

When LIBs are recycled using traditional methods, they use hazardous chemicals like strong acids and organic solvents like N-Methyl-2-pyrrolidone (NMP), which are harmful for both the environment and people's health (Davis & Demopoulos, 2023). Accordingly, people are becoming more interested in safer options like deep eutectic solvents (DESs) and ionic liquids (ILs) because they are not toxic, biodegradable, and can be reused. DESs, in particular, are a better way to get metals back from used LIBs at room temperature because they don't need heat or strong acids (Zheng et al., 2024). They have also been shown to work better than traditional methods for recovering nickel, cobalt, and lithium back (H. Yang et al., 2025). ILs also how significant potential because they are chemically stable and don't evaporate easily (Dar et al., 2025). However, both solvents have their problems. For example, some DESs can release harmful byproducts when they are heated.

ii. Process complexity and selectivity issues:

Selective leaching of metals during hydrometallurgical recycling of LIBs remains a significant difficulty because there are numerous cathode chemistries that complicate the leaching process. Target metals and non-target (contaminant) elements sometimes dissolve at the same time in traditional leaching, making further purification processes harder (Shi et al., 2025). In line with recent studies, the use of DESs and ILs can greatly improve leaching selectivity while minimizing the potential hazards connected with typical acids and bases. Particularly, DESs have shown that they may leach important metals like Ni, Co, Mn, and Li, often achieving high recovery rates. Certain DESs don’t have specific limitations and have dual functionality by acting as reducing agents along with leaching agents. Water or solvent decomposition can make them harder to recycle and impede process effectiveness (Svärd et al., 2024). More gains in leaching efficacy and selectivity have been demonstrated by modified solvent systems, such as ternary DESs or DES-extractant hybrids (Schiavi et al., 2022). To achieve scalable and sustainable battery recycling, these concepts need to be further developed and optimized.

iii. High water and chemical consumption:

Hydrometallurgical recycling of LIBs involves substantial use of water and chemicals, which has adverse impacts on the environment and the economy. The process often involves acidic or alkaline leaching agents, which often include sulfuric acid or hydrochloric acid, to recover critical metals from older used batteries (Al-Asheh et al., 2024). These chemical processes take a lot of water and produce wastewater with hazardous byproducts since the leachants must be diluted, applied, and then cleaned. This has a substantial negative impact on the environment and rises operating expenses (Cerrillo-Gonzalez et al., 2024). For instance, leaching NMC cathodes with sulfuric acid and hydrogen peroxide (H_2O_2) results in sulfate-rich effluents that are frequently challenging to neutralize and properly dispose of (Balázs Illés & Kékesi, 2023). Furthermore, the chemically harsh solvent extraction and precipitation methods that are frequently used in metal recovery greatly raise the total chemical footprint. Other agents, such chelating compounds, help with the selective extraction of metals, but they also make the chemicals used more complicated (Azimi & Chan, 2024). Promising substitutes are provided by ILs and DESs, that use less water and leave behind fewer harmful residues. However, further research is needed to evaluate their scalability, cost-effectiveness, and long-term stability before they can be widely implemented at the industrial level (Gupta et al., 2024).

iv. Incomplete lithium recovery and purity issues:

Since lithium is trapped in stable silicate or aluminate phases inside the slag, hydrometallurgical processes have low lithium recovery. These substances reduce the amount of lithium available for extraction because they are extremely resistant to disintegration under mild leaching conditions (T. Zhao et al., 2023). In addition, co-extraction during the leaching process may result from the presence of contaminants including iron, aluminum, and manganese, which also lowers the purity of lithium and needs expensive purification to satisfy quality requirements (B. Yang et al., 2025). However, new methods like membrane-assisted solvent extraction and mechanochemical activation have improved effectiveness and product quality by achieving lithium recovery rates of over 92% while drastically reducing contaminant levels (F. Liu et al., 2021).

3.2 Gaps in the Pyrometallurgical Process

Despite pyrometallurgy's benefits, that include its high rate of processing and ability to process diverse battery chemistries without pre-treatment, there are also major drawbacks.

i. High energy consumption and carbon footprint:

Extremely high manufacturing temperatures, generally between 900°C and 1,400 °C, are necessary for pyrometallurgy recycling. This process is highly energy-intensive and leaves a big ecological footprint, especially when fossil fuels are used (Premathilake et al., 2023; Zhou et al., 2024). When these pyrometallurgical processes are used extensively, their high energy consumption raises operating costs and diminishes the positive environmental effects of adopting EVs (Rolandi et al., 2024). Furthermore, the heat breakdown of electrolytes and polymer binding agents in smelting, produces hazardous gases that pose significant risks to both the atmosphere and people's health (Azimi & Chan, 2024). These disadvantages emphasize the need for more environmentally friendly or hybrid recycling strategies that provide lower energy costs and better fit the circular economy (Neumann et al., 2022; Paul et al., 2024).

ii. Lithium and aluminum loss:

Due to their thermodynamic nature at high processing conditions, lithium and aluminum extraction is a significant barrier to the pyrometallurgical recycling of LIBs. For lithium, its recovery rates are severely limited by the stable compounds that it tends to produce (like fluorinated lithium salts and lithium silicates), which are stuck in the slag and do not reduce to their metallic state (Pan & Shen, 2023). On the other hand, since aluminum has a higher possibility to create complicated alloys with transition metals or oxides of high melting temperatures, it therefore reduces selective recovery and makes extraction challenging (Amusa et al., 2024). The viscous nature of slag further complicates these recovery issues because of its ability to trap important metals, requiring extra post-treatment processes to liberate them (Qu et al., 2024). Although pyrometallurgy remains inefficien at extracting lithium and aluminum, it is still useful for recovering metals like nickel and cobalt. However, a more practical way to boost yield and achieve sustainable recovery of these crucial components is to combine hydrometallurgical processes with pyrometallurgical pretreatment (Al-Asheh et al., 2024).

iii. High operational costs:

Because it needs significant energy to melt battery materials at temperatures between 900 and 1400 °C, pyrometallurgical recycling necessitates a large capital investment, which raises material and manufacturing prices considerably. Operational costs are a significant concern because the process also depends on expensive equipment that requires constant maintenance (Reinhart et al., 2023). Furthermore, the initial investment and ongoing maintenance expenses are increased by the required specialist equipment, such as electric arc furnaces and rotary kilns. Even though innovative processes like the chlorination and sulfation of salt-assisted roasting have shown promise for lithium recovery, they still require stringent environmental controls to minimize the production of hazardous or corrosive gases and rely on costly chemicals (Gutsch & Leker, 2024). These financial obstacles limit the expansion of current recycling technologies and highlight the need for more affordable, effective, and energy-efficient substitutes (Cornelio et al., 2024).

iv. Limited scalability for newer battery chemistries:

The development of viable, scalable, and affordable recycling systems is severely hindered by the growing popularity of newer battery chemistries like solid state and sodium ion batteries. Nevertheless, LIBs are still expected to remain the dominant technology of the energy storage market. The material compositions of these advanced batteries are usually incompatible with the LIB recycling system that is now in place (Al-Asheh et al., 2024). For instance, metallic lithium, that is commonly in solid state batteries, is very reactive and presents major safety issues during any mechanical or chemical processing, despite offering improvements in safety and energy density. Additionally, unique technical challenges that current recycling methods are not designed to handle are introduced from their usage of electrolytes (Azimi & Chan, 2024). However, as sodium ion batteries apply complicated chemistries including vanadium, iron, or phosphorus compounds, they create recovery issues even when they have cost and supply gains (Chayambuka et al., 2020). Too many diversity of materials and the absence of standardized designs for both traditional and developing battery types present significant challenges to recycling efforts (Gupta et al., 2024).

3.3 Recurring Issues

The environmentally friendly nature and effectiveness of recycling EVBs continue to be restricted by persistent gaps, especially in the hydrometallurgical and pyrometallurgical processes. In response to the ongoing use of dangerous chemicals, scientists are looking at alternative techniques like direct recycling, to preserve functioning materials without total chemical breakdown, and bioleaching, (Gerold et al., 2022). Moreover, economic viability is a significant obstacle as well, high-purity recovery of metals like lithium and nickel sometimes needs extra procedures and expensive reagents. Additionally, battery chemistries are changing quickly, so that new kinds containing less high-value metals such as solid state batteries and LFP, diminish the economic motivation for traditional recycling methods (Neumann et al., 2022). Significant improvements are required to handle future recycling needs since the current infrastructure is unable to handle the expected spike in end-of-life EV batteries. Hybrid recycling procedures are showing promise as a solution for these issues. Base metals such as nickel and cobalt can be efficiently extracted via pyrometallurgy (Zhang, 2022). Conversely, hydrometallurgy recovers more lithium through solvent extraction and selective leaching, but it uses an extensive amount of chemicals and generates potentially hazardous waste (Y. Liu et al., 2024). For instance, chlorination or sulfation can convert lithium in slag into more recoverable forms such as lithium chloride or lithium sulfate, which can subsequently undergo hydrometallurgical treatment (Makuza et al., 2021a). Hybrid recycling is found to be better at recovering metals and is a more cost-effective and environmentally beneficial option than using just one process (Skeete et al., 2020). This is because it helps the goals of the circular economy by recovering valuable metals and making the most of resources ((Neumann et al., 2022)). **Table 1** highlights the main approaches and shows how they affect the environment and technology.

Table 1. Summary of advantages and disadvantages of major lithium-Ion Battery recycling technologies

Technology	Advantages	Disadvantages	References
Hydrometallurgy	- Low energy consumption - High selectivity - Low air emissions	- Generates wastewater - Uses corrosive chemicals - Slower processing time	Cao et al., 2024a; Chalaris et al., 2023; Nakhaie & Asselin, 2025; Ullah et al., 2024
Pyrometallurgy	- Suitable for large-scale operations - Handles mixed chemistries - Fast processing	- High energy consumption - High greenhouse gas emissions - Low lithium recovery	Birloaga et al., 2014; Harvey et al., 2022; Premathilake et al., 2024; Rinne et al., 2021; Sabia et al., 2022
Direct regeneration	- Energy efficient - Maintains cathode structure - Low chemical usage	- Limited purity and material quality - Lack of standardization in battery Designs - Challenging separation and processing	Birloaga et al., 2014; Harvey et al., 2022; Premathilake et al., 2024; Rinne et al., 2021; Sabia et al., 2022

3.4 Comparative Performance and Global Data Insights

Table 2 provides a comparative summary across crucial performance parameters to address significant discrepancies between the primary recycling methods and enhance the analytical depth of this analysis. These consist of recovery efficiency, energy consumption, CO_2 emissions, economic cost, and technology readiness. The values are compiled from peer-reviewed studies and technical assessments.

Key findings that were previously presented in this study are reaffirmed in Table 2. Although cost and chemical waste are still issues, hydrometallurgy provides the most effective recovery of cobalt and lithium with minimal energy needs. Although pyrometallurgy is commonly employed in industry, it has a high energy consumption and a reduced lithium recovery rate, which results in significant carbon emissions. Notwithstanding these limitations, it is a good option for mixed or deteriorated batteries due to its resilience to feedstock variability.

Although it is still in its infancy, direct recycling has great promise because of its low environmental effect and high recovery rates. By maintaining cathode structure, it avoids high-temperature procedures and uses fewer chemicals. Technical obstacles, such as the requirement for standardized battery forms and exact feedstock separation, now restrict its scalability.

This comparative evaluation highlights the need for technology-specific deployment strategies and the potential for hybrid systems that leverage the strengths of each method while addressing their limitations.

Table 2. Comparative metrics of LIB recycling methods

Technology	Lithium Recovery (%)	Cobalt Recovery (%)	Energy Use (kWh/kg battery)	CO_2 Emissions (kg CO_2/kg battery)	Cost (USD/ton battery)	Technology Readiness
Hydrometallurgy	80–95% (Gaines, 2018), (Makuza et al., 2021b)	95–98% (Gaines, 2018), (Makuza et al., 2021b)	8–20 (Dai et al., 2019)	2–6 (Dai et al., 2019)	1,800–2,500 (Gaines, 2018), (Harper et al., 2019b)	High (commercial scale) (Harper et al., 2019b; Makuza et al., 2021b; Swain, 2017)
Pyrometallurgy	<50% (Gaines, 2018), (Makuza et al., 2021b)	70–90% (Gaines, 2018), (Makuza et al., 2021b)	30–50 (Dai et al., 2019),	8–12 (Dai et al., 2019)	3,400–4,500 (Harper et al., 2019b), (Swain, 2017)	High (widely applied) (Gaines, 2018; Harper et al., 2019b; Swain, 2017)
Direct Recycling	~90% (Cao et al., 2024c), (Zeng et al., 2014)	~90% (Cao et al., 2024c), (Zeng et al., 2014)	2–10 (Dai et al., 2019), (Cao et al., 2024c)	1–3 (Dai et al., 2019), (Cao et al., 2024c)	1,000–2,000 (Harper et al., 2019b), (Cao et al., 2024c), (Zeng et al., 2014)	Low (pilot/demo stage) (Cao et al., 2024c; Harper et al., 2019b; Zeng et al., 2014)

4. Economic and Technical Barriers

Recycling LIBs is crucial to limit environmental damage and guarantee the longevity of resources. However, the implementation of a completely circular economy in this area is hindered by some considerable obstacles. Through smelting procedures that need for extraordinarily high temperatures, pyrometallurgical recycling techniques provide a practical way to recover metals like cobalt, nickel, and copper. Energy use represents a major portion of operating costs in pyrometallurgical recycling, reflecting the high energy demands of the process.

Whilst the hydrometallurgical method uses less energy, it has its own disadvantages, which include the costly nature of multi-step processes (like leaching, solvent extraction, and precipitation) as well as the high price of reagents (like sulfuric acid and organic solvents). Because of fluctuating metal prices, economic viability is still unclear. For example, the price of cobalt changes, which may have a significant impact on how profitable recycling operations are. Yet, lithium is typically recycled at a low market value in relation to its amount (Guo et al., 2024b).

Other obstacles include finance and equipment. In order to fulfill environmental regulations, constructing a large-scale recycling plant needs a significant investment, particularly when integrating materials that resist corrosion and wastewater treatment facilities (Lee et al., 2019). This is made worse by the absence of standardized collecting methods and the reliance on worker labor for battery dismantling (Harper et al., 2019a). From a technical perspective, several recovery methods are needed for the different battery chemistries, including NMC, LFP, and lithium cobalt oxide (LCO). Since LFP batteries do not contain cobalt, traditional is often economically unfeasible unless alternative approaches, such as direct recycling, are employed. In contrast, NMC batteries are more compatible with selective leaching techniques. (M. Chen et al., 2019a; Roy et al., 2024).

Furthermore, the majority of new techniques concentrate on renewing cathode materials instead of completely disassembling them, which limits the effectiveness of sorting and material separation (Golmohammadzadeh et al., 2022; Huang et al., 2024) . Additionally, because it is hard to standardize disassembly for systems that contain bonded or welded components, battery variability also hinders automation (Zhan, 2021). While automating recycling is still an interest, they have difficulty adapting to a wide range of battery types (Harper et al., 2019a).

Green solvents are being promoted by researchers as a potentially safer and more economical option to overcome these restrictions (Zhang, 2022). Hybrid recycling processes have shown increased yields and decreased emissions (F. Liu et al., 2021) with the European Union's Battery Regulation establishing goals like a 70% lithium recovery rate by 2030, in return policy assistance is also increasing (Tan et al., 2020).

5. Environmental Impact

LIB recycling has a variety of environmental effects, including those related to the extraction of raw materials, manufacturing procedures, recycling techniques, and disposal at the end of life. The process of producing LIBs, starts with extraction of critical minerals including lithium, cobalt, and nickel, this leads to deforestation and waterways contamination (Guo et al., 2024b; Su et al., 2022). In lithium mining for example, especially brine extraction, can release harmful compounds into the environment and deplete freshwater supplies (Q. Zhao et al., 2024, E. Zhao et al., 2021). According to life cycle studies, the production of LIBs may produce around 187.26 kg of CO_2 equivalent for every kWh of battery capacity, since they heavily depend on fossil fuels and are highly energy intensive (Neumann et al., 2022).

Improper disposal of spent LIBs can cause harmful substances, such fluorine-based chemicals, to seep into soil and water causing long-term pollution as well as direct impairment to human health (Gantenbein et al., 2019; Zanoletti et al., 2024). How much impact a certain recycling technique has over the environment varies, for example, pyrometallurgy uses substantial energy and releases hazardous fumes and particles (Mrozik et al., 2021). However, hydrometallurgy operates at lower temperatures but involves hazardous chemicals, requiring waste management practices to prevent secondary pollution (Golmohammadzadeh et al., 2022; Xiao et al., 2023). On the other hand, more recent direct recycling methods, like solid-state relithiation and hydrothermal processing, provide more ecologically friendly solutions by reducing energy and chemical use, as well as promoting circular economy projects (Lan et al., 2024; Roy et al., 2024). Green solutions, such as environmentally friendly solvents and biodegradable binders, are required to address these environmental problems (Van Hoof et al., 2023b).

6. Future Research Directions

Based on the critical assessment presented in this review, we recommend several further investigations to overcome the current problems in LIB recycling:

First, more research is needed on advancing cathode materials such as LFP and NMC to minimize cross-contamination and enable selective metal removal is essential. It was reported that combining pH-controlled leaching with citric acid and DESs an effectively separates metals from NMC and LFP cathodes (Balázs Illés & Kékesi, 2023; B. Yang et al., 2025). For example, a maleic acid–choline chloride DES can selectively recover key metals from spent cells (Biniaz et al., 2025).

Second, it is important to design flexible battery architectures that support universal disassembly, as this will streamline part recovery, improve material segregation, and cut waste. Standardizing component design and labeling further enhances traceability and material flow (Environmental Protection Agency, 2025; Golmohammadzadeh et al., 2022; Harper et al., 2019). Furthermore, when integrating renewable energy, such as solar or wind, into pyrometallurgical recycling, this can also slash greenhouse gas emissions from high-temperature operations (Van Hoof et al., 2023a; Cheng et al., 2024).

Finally, solvent-free and bio-based hydrometallurgy, like microbial recovery and mechanochemical leaching, advances circular-economy goals and cuts hazardous chemicals (Biswal et al., 2024). Bioleaching is considered a viable alternative to conventional chemical procedures, since it has shown promising results in utilizing microorganisms to extract valuable metals from discarded LIBs (Kityk et al., 2024). Together, these methods form a next-generation framework for sustainable LIB recycling (Rolandi et al., 2024).

7. Conclusion

The necessity for efficient and sustainable LIB recycling has grown as the use of EVs increases internationally. Three main recycling technologies with distinctive advantages and challenges were evaluated extensively in this study. For example, hydrometallurgy produces secondary waste due to high dependence on chemical reagents but has a high recovery rate and selectivity. However, for pyrometallurgy, despite its industrial maturity and suitability for large-scale processing, it is considered inefficient and energy-intensive for recovering lithium. Unlike direct recycling which is becoming a more energy-efficient option, but is still limited by issues with scale, degradation levels, and material compatibility.

There is potential for improving total recovery efficiency and reducing the negative environmental effects by incorporating these techniques into hybrid recycling strategies. Specifically, hybrid processes can use hydrometallurgy or direct recycling techniques for lithium recovery and cathode material maintenance but then take use of pyrometallurgy's high-throughput capability for base metal concentration. However, advancements remain constrained by technical obstacles like the need for standardized battery designs and variations in battery chemistries.

Scaling up battery recycling remains difficult due to both economic and environmental concerns. The use of harmful chemicals, rising capital costs, and constantly changing metal prices all point to the need for greener alternatives. Moving forward, efforts should focus on bio-based or solvent-free hydrometallurgical methods, along with using renewable energy to power high-temperature recycling processes.

CRediT Author Contribution Statement

Z. Abu El-Rub: Conceptualization, Writing – Review & Editing, Resources, Visualization, Supervision, Project Administration.
N. Nassar: Methodology, Investigation, Writing – Original Draft, Visualization.
N. Shuqum: Methodology, Investigation, Writing – Original Draft, Visualization.
R. Al-Junaidi: Methodology, Investigation, Writing – Original Draft, Visualization.

Declaration Statements

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Conflicts of Interest
The authors declare no conflict of interest.

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Nomenclature

Abbreviation	Full Term
BEV	Battery Electric Vehicle
DES	Deep Eutectic Solvent
EOL	End of Life
EPA	Environmental Protection Agency
EPR	Extended Producer Responsibility
EV	Electric Vehicle
EVB	Electric Vehicle Battery
IL	Ionic Liquid
LCO	Lithium Cobalt Oxide
LFP	Lithium Iron Phosphate
LIB	Lithium-Ion Battery
NCA	Nickel Cobalt Aluminum
NMC	Nickel Manganese Cobalt
NMP	N-Methyl-2-pyrrolidone
PHEV	Plug-in Hybrid Electric Vehicle
SEI	Solid Electrolyte Interphase

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