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EVALUATION OF CURRENT Li-Ion BATTERY RECYCLING TECHNOLOGIES

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Abstract

Lithium-ion batteries dominate electrochemical energy storage due to their high charge–discharge efficiency, thermal stability, and safety. With an average lifespan of 3-5 years, their growing end-of-life volume poses environmental and resource management challenges. While recycling efforts have focused on high-value metals, electrolyte recovery remains underdeveloped. This review compares pyrometallurgy, hydrometallurgy, and direct recycling based on literature from 2015–2025, evaluating metal recovery efficiency, energy demand, CO_2 emissions, environmental impact, and technological readiness. Hydrometallurgy emerges as the most viable current method (>90% recovery, ~800 kWh/ton energy use), while pyrometallurgy, though industrially established, has high energy requirements (~2,200 kg CO_2/ton) and poor lithium recovery. Direct recycling shows strong sustainability potential by preserving active material structures yet faces scalability challenges from feedstock variability and process standardization. Advancing sustainable recycling will require innovation in automation, standardized materials, and robust policy frameworks to support a circular economy for critical raw materials.

Key words: *battery, direct recycling, hydrometallurgy, pyrometallurgy.*

INTRODUCTION

In the context of the global transition toward sustainable technologies and electric mobility, lithium-ion batteries (Li-Ion) have become the cornerstone of energy storage for applications such as electric vehicles (EVs), portable electronics, and stationary storage systems. As this sector rapidly expands, the generation of waste from spent Li-Ion batteries has grown exponentially, exerting pressure on both the environment and the supply chains of critical materials such as lithium, cobalt, and nickel.

Recycling Li-Ion batteries is not only an ecological necessity but also a strategic opportunity to reduce dependence on primary resources, enhance the security of critical raw materials, and close the materials loop within a circular economy framework. However, not all recycling methods offer the same level of efficiency, sustainability, or industrial feasibility. Currently, three major technologies are employed or under investigation for battery recycling: pyrometallurgy, hydrometallurgy, and direct recycling. Each of these presents specific advantages and limitations, both from a technical standpoint and in terms of environmental impact and operational costs.

The objective of this study is to provide a comparative evaluation of the three primary recycling technologies, focusing on material recovery efficiency, greenhouse gas emissions (CO_2), energy consumption, and practical applicability within the European and Asian contexts, with particular emphasis on China. This paper offers a critical appraisal of the current landscape of battery-recycling technologies and maps plausible development pathways, emphasizing implications for environmental policy and industrial practice. It addresses three questions: (1) Which recycling method offers the best balance between efficiency, cost, and environmental impact? (2) What are the differences in application between the EU and China? (3) What is the long-term potential of emerging technologies?

The article is structured as follows: Section 2 outlines the methodology used for selecting the

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reviewed studies; Section 3 provides a detailed overview of each recycling technology; Section 4 presents the comparative and regional analysis; Section 5 discusses the implications for policy and industry; and Section 6 includes the conclusions and future research directions.

MATERIALS AND METHODS

This review paper was conducted based on a systematic selection of scientific articles from the Scopus, Web of Science, and ScienceDirect databases, covering the period 2015-2025.
The selection criteria included technological relevance, the presence of quantitative data on recovery efficiency, emissions, and technological maturity. Articles without comparable data or those focusing solely on battery reuse were excluded.
The comparative analysis was performed according to five criteria: metal recovery efficiency, energy consumption, CO_2 emissions, environmental impact, and level of industrial maturity.

Li-Ion battery recycling methods

Pyrometallurgical Recycling
Pyrometallurgy represents one of the most established and industrially applied methods for the recycling of spent lithium-ion batteries (LIBs), particularly in the European Union. This technique involves high-temperature processing, typically above 1,200°C, to smelt battery materials and recover valuable metals. The process generally includes thermal pre-treatment (e.g., drying, deactivation), followed by smelting in a furnace where the electrode materials decompose and separate based on their physical and chemical properties.
During smelting, organic components such as electrolytes, binders, and separator materials are combusted, while transition metals like cobalt (Co), nickel (Ni), and copper (Cu) are recovered in a metallic alloy or slag phase. These metals can then be refined through additional hydrometallurgical steps to meet battery-grade purity levels.
One of the primary advantages of pyrometallurgical recycling lies in its process simplicity and robustness, making it suitable for mixed and unclassified battery waste streams. Moreover, the technique ensures relatively high recovery rates for cobalt and nickel, which are among the most economically valuable elements in LIBs.
However, this approach also presents several notable disadvantages. Most importantly, lithium is largely lost during the process, often ending up in the slag and becoming unrecoverable without additional complex treatments. In addition, the high energy demand of the smelting process contributes to significant greenhouse gas emissions, particularly when fossil fuels are used as the energy source. The combustion of electrolyte components can also release toxic gases, such as hydrogen fluoride (HF), which necessitates strict environmental controls and gas scrubbing systems.
Despite these limitations, pyrometallurgy continues to be widely used due to its maturity, scalability, and compatibility with existing metallurgical infrastructure. Nevertheless, in light of increasing environmental regulations and the need to recover lithium and other light elements more efficiently, this method is gradually being complemented or replaced by alternative recycling strategies, such as hydrometallurgy and direct recycling.
We have the following chemical reactions that take place during melting:
Cobalt reduction: $CoO + C \rightarrow Co + CO \uparrow$
Nickel reduction: $NiO + C \rightarrow Ni + CO \uparrow$
Decomposition of $LiPF_6$ from electrolyte:
$LiPF_6 \rightarrow LiF + PF_5 \uparrow$ (at > 60°C).
At high temperatures, PF_5 turns into HF (extremely toxic), and LiF ends up in the slag.
Depending on the chosen pyrometallurgical recycling method, batteries may require a pretreatment stage to extract the active cathode material for subsequent recovery, or they can be directly fed into a furnace, as in smelting processes. Thermal pretreatment techniques used for recovering cathode materials include incineration, calcination, and pyrolysis. The resulting metal-rich fraction is then processed through roasting or smelting. A major technical challenge in these pyrometallurgical processes has been the emission of toxic gases. However, recent advancements in pyrometallurgy have led to the development of integrated gas treatment systems such as the one implemented by Umicore which ensure the complete

removal of volatile organic compounds, effective dust capture, and a significant reduction in gas emissions.

Depending on the chosen pyrometallurgical recycling method, batteries may require a pretreatment stage to extract the active cathode material for subsequent recovery, or they can be directly fed into a furnace, as in smelting processes. Thermal pretreatment techniques used for recovering cathode materials include incineration, calcination, and pyrolysis. The resulting metal-rich fraction is then processed through roasting or smelting.

Regarding pyrometallurgy, its advantages consist of: mature technology that is already used on an industrial scale (e.g. Umicore, Glencore), high tolerance to mixtures where precise sorting of batteries is not necessary, but also efficient recovery of Co, Ni and Cu (over 85-90%).

Analyzing the disadvantages, there are certain limitations such as: lithium losses: Li ends up in the slag and is not economically recovered, high energy consumption: >4,000 kWh/ton processed in some cases, significant CO_2 and HF emissions: high climate impact and need for advanced gas treatment, requires advanced metallurgical infrastructure and large initial investments.

Hydrometallurgical recycling

Hydrometallurgy is an advanced method for recycling lithium-ion batteries that involves the chemical transformation of solid electrode materials into soluble forms, followed by the selective recovery of valuable metals. This process is structured in several stages: leaching (dissolution), separation of metal ions, purification and final recovery of salts or metals in solid form.

Acid leaching stage

The active materials (e.g. $LiCoO_2$, $LiNi_{1-x-}yMn_xCoyO_2$) are treated in an acidic solution, usually sulfuric acid (H_2SO_4) or hydrochloric acid (HCl), in the presence of a reducing agent (usually hydrogen peroxide, H_2O_2), which helps to oxidize the transition metals and solubilize them in the form of ions.

Typical dissolution reactions:

- $LiCoO_2 + 2H^+ + H_2O_2 \rightarrow Li^+ + Co^{2+} + O_2 + 2H_2O$
- $LiNiO_2 + 2H^+ + H_2O_2 \rightarrow Li^+ + Ni^{2+} + O_2 + 2H_2O$
- $MnO_2 + 4H^+ + 2e^- \rightarrow Mn^{2+} + 2H_2O$

Li^+ remains dissolved as a soluble ion, without further redox reaction.

The leaching process is generally carried out at temperatures between 60-90°C, for a time of 1–3 hours, in a slightly agitated environment, with a pH < 2.

Metal separation and recovery stage

After complete dissolution, the metal ions (Co^{2+}, Ni^{2+}, Mn^{2+}, Li^+) are separated by sequential techniques such as:

Selective precipitation – e.g. $Co(OH)_2$, CoC_2O_4;

Solvent extraction – D2EHPA, Cyanex 272;

Lithium recovery – e.g. $Li^+ + CO_3^{2-} \rightarrow Li_2CO_3 \downarrow$

The yields are over 90-95% for Co and Ni and between 80-90% for Li, depending on the cathode formulation and process conditions.

The limitations and challenges of this method would be: the generation of liquid waste rich in non-recoverable ions, significant consumption of acidic reagents, the need for rigorous control of process parameters.

The method is applied by companies such as Fortum (Finland), Li-Cycle (Canada), Recupyl (France), all using hydrometallurgical variants adapted for the efficient recovery of strategic metals.

Direct recycling

Direct recycling is an emerging technology with significant potential in the field of circular economy, which aims to recover and directly reuse active materials from used lithium-ion batteries, especially cathode ones, without completely decomposing them into basic chemical elements. Unlike pyrometallurgical and hydrometallurgical methods, which involve the complete destruction of the material structure, direct recycling preserves or regenerates the crystalline structure of transition metal oxides (e.g. $LiCoO_2$, NMC), allowing their direct reuse in the manufacture of new cells.

During charge-discharge cycles, the active material undergoes electrochemical and structural degradation caused by: interstitial lithium loss; phase changes and distortions of the crystal lattice; surface contamination. However, the basic structure of the cathode often remains relatively intact, especially in the case of post-industrial waste or batteries with a low number of cycles.

Stages of the direct recycling technological process:

1. Battery deactivation and disassembly;
2. Mechanical separation of the active material;
3. Binder and contaminant removal (thermal or chemical);
4. Stoichiometric replenishment with Li_2CO_3 or LiOH;
5. Recrystallization at 700-900°C;
6. Testing and characterization (XRD, SEM, electrochemical cycling).

Representative reaction: $Li_{1-x}MO_2 + xLi_2CO_3 + \Delta T \rightarrow LiMO_2 + xCO_2\uparrow$.

Performance and efficiency:

Material recovery efficiency is up to 95%;

Electrochemical capacity restoration: 85-95%;

Costs: 30–50% lower than in classical methods;

CO_2 emissions: reduced by up to 90%.

Limitations for this method are represented by: the need to sort materials; the lack of a mature industrial infrastructure; sensitivity to contaminants; the need for automation and standardization.

RESULTS AND DISCUSSIONS

Pyrometallurgy is widely adopted due to its simplicity and robustness but suffers from high emissions and energy consumption, with poor lithium recovery. Hydrometallurgy offers a more environmentally friendly alternative with high recovery rates, though it generates liquid waste and involves complex chemical separation. Direct recycling, while still emerging, shows the greatest potential for low-impact, high-efficiency recovery by preserving cathode materials, yet it requires high feedstock purity and standardized battery formats (Table 1).

Table 1. Comparative analysis of Lithium-Ion battery recycling technologies

Criteria	Pyrometallurgy	Hydrometallurgy	Direct Recycling
Recovery Efficiency	~60%	~90%	~95%
Materials Recovered	Co, Ni, Cu (Li, Al lost in slag)	Co, Ni, Li, Mn, Cu	Intact cathode material (e.g., NMC, LFP)
CO_2 Emissions	~2200 kg/ton	~1200 kg/ton	~300 kg/ton
Energy Consumption	~1500 kWh/ton	~800 kWh/ton	~500 kWh/ton
Process Temperature	>1500°C	<100°C	Room temperature to 150°C
Technology Maturity	Industrial	Commercial	Emerging
Feedstock Flexibility	High	Medium	Low
Capital & Operating Costs	High	Medium	Low (with automation)
Environmental Impact	High	Medium	Low
Challenges	Low Li recovery, high CO_2	Chemical waste, separation complexity	Sorting, disassembly, standardization

The European Union and China are the two leading regions implementing large-scale lithium-ion battery recycling programs, each reflecting unique industrial strategies and regulatory frameworks.

In the EU, the recycling landscape is shaped by strong environmental directives such as the EU Battery Regulation (2023), which mandates minimum recycled content and high recovery targets for lithium (35%), cobalt (95%), and nickel (90%) by 2030.

The EU supports direct recycling research through initiatives like the Horizon Europe program, but most commercial plants still use hydrometallurgical techniques, balancing efficiency and sustainability.

China, in contrast, leads the world in both battery production and recycling volume, processing over 600,000 tons of spent LIBs annually. Chinese companies leverage vertical integration and economies of scale, with a strong emphasis on hydrometallurgical recovery.

Recent pilot projects also explore direct recycling, driven by the government's 2021 guideline on battery recycling and reuse, which supports second-life applications and material loop closure. Key differences lie in the policy focus: the EU prioritizes sustainability and traceability, while China emphasizes scale, speed, and economic return. Technologically, both regions are advancing direct recycling, but with different paces of standardization and investment.

Figure 1 illustrates a comparative assessment between the European Union and China regarding lithium-ion battery recycling, based on key indicators such as recycling volume, recovery efficiency, CO_2 emissions, regulatory strength, and investment in direct recycling technologies.

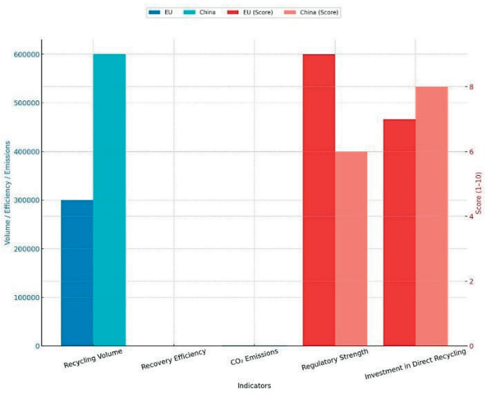

Figure 1. UE vs China in Li-Ion battery recycling (Source: European Commission (2023). Regulation (EU) 2023/1542 of the European Parliament and of the Council on batteries and waste batteries. Official Journal of the European Union. https://eur-lex.europa.eu)

China processes approximately 600,000 tons of lithium-ion batteries annually - about twice the EU's recycling volume of 300,000 tons - reflecting its significant industrial capacity and the high domestic demand for battery reuse and material recovery. In terms of efficiency, the EU achieves an estimated 90%, slightly surpassing China's 85%, a performance advantage attributable to stringent environmental regulations that mandate elevated recovery standards for critical raw materials such as lithium, cobalt, and nickel. From an environmental impact perspective, the EU generates lower carbon emissions, averaging around 800 kg per ton, compared to China's approximately 1,000 kg per ton, largely due to its reliance on cleaner hydrometallurgical processes, while China employs a broader range of technologies, including more carbon-intensive methods. Regarding governance, the EU attains a regulatory strength score of 9/10, underpinned by comprehensive legislative frameworks such as Regulation (EU) 2023/1542, whereas China scores 6/10, with a still-developing and more flexible regulatory environment that prioritizes industrial agility and rapid execution. Finally, in the domain of technological investment, China leads with a score of 8/10, driven by substantial funding for direct recycling initiatives from major industrial actors such as CATL and GEM, while the EU follows with 7/10, primarily through Horizon Europe programs, focusing on scientific validation and regulatory harmonization but progressing more slowly in large-scale commercial deployment.

Table 2 presents a comparative analysis of the three major Li-Ion battery recycling methods: pyrometallurgy, hydrometallurgy and direct recycling, based on energy efficiency, metal recovery yield, environmental impact, costs and technological maturity.

Table 2. Comparative analysis of Li-Ion battery recycling methods

Criterion	Pyrometallurgy	Hydrometallurgy	Direct Recycling
Energy efficiency	Low – requires very high temperatures (>1000°C)	Medium – energy needed for chemical processes and separation	High – low-temperature processes, more efficient
Metal recovery rate	Low–medium – recovers only valuable metals	High – can recover most metals (Li, Co, Ni, Mn)	Very high – preserves the structure of active materials
Environmental impact	High – CO_2 and other toxic gas emissions	Medium – uses acidic chemical substances	Low – fewer emissions and waste
Costs	High – significant energy costs	Medium – chemicals can be reused	Potentially low – but technology is still developing
Technological maturity	Very mature – used at industrial scale	Mature – being optimized for large-scale application	Immature – still under research, limited applications

The comparative analysis of the three primary methods for recycling Li-Ion batteries - pyrometallurgy, hydrometallurgy, and direct recycling indicates that there is no universally optimal solution. Rather, the selection of the recycling method should be guided by specific process objectives, including energy efficiency, cost-effectiveness, environmental sustainability, and scalability. Nevertheless, an integrated assessment of the key criteria yields the following insights:

From the perspective of energy efficiency and environmental impact, direct recycling appears to be the most promising approach. This method enables the preservation of active materials with minimal energy consumption and produces significantly lower amounts of hazardous waste. However, its limited technological maturity and the absence of a well-established industrial infrastructure currently constrain its large-scale deployment.

Direct recycling stands out for its low energy consumption and minimal CO_2 emissions, as it preserves active cathode materials without fully breaking them down. Recovery rates can exceed 90% for certain materials, and the environmental footprint is significantly lower than that of other methods. However, its industrial application is currently limited due to low technological maturity and the lack of a standardized recycling infrastructure.

Hydrometallurgy offers a balanced trade-off between performance and sustainability. It enables high recovery rates - often above 95% - for critical metals such as lithium, cobalt, nickel, and manganese. The energy demand is moderate, and the technology is already being implemented in pilot and commercial-scale facilities. Its adaptability to different battery chemistries makes it the most viable and scalable solution in the medium term.

Pyrometallurgy, while technologically mature and widely industrialized, presents several drawbacks: high energy requirements (often exceeding 5–8 MJ/kg), relatively low lithium recovery (below 50%), and significant CO_2 emissions. These limitations increasingly position it as a transitional or last-resort method, better suited for mixed or contaminated battery waste streams but misaligned with future regulatory and sustainability goals.

The comparative performance chart (Figure 2) clearly illustrates the strengths and limitations of each method across five key criteria: energy efficiency, metal recovery rate, environmental impact, cost-effectiveness, and technological maturity. This multidimensional evaluation supports the discussion and highlights where each method currently stands and what future developments may be needed.

Hydrometallurgy is therefore increasingly favored by researchers and industry stakeholders for integration into large-scale circular economy initiatives.

Although pyrometallurgy is a well-established and industrialized recycling method, it presents significant disadvantages, including high energy consumption, relatively low recovery rates for certain elements (particularly lithium), and major environmental concerns. As a result, pyrometallurgy is increasingly regarded as a transitional or last-resort option, especially in the context of tightening environmental regulations in the European Union and other regions.

In summary, hydrometallurgy currently represents the most efficient and balanced approach for Li-Ion battery recycling, combining high metal recovery rates with proven technical feasibility. However, direct recycling holds substantial long-term potential to become the industry standard, provided that future technological advancements improve its scalability and standardization.

Accelerating the transition toward sustainable battery recycling requires coordinated action from both policymakers and the industry. On the policy side, investments in research, fiscal incentives for emerging technologies, and clear regulations on battery ecodesign (such as standardization of formats and materials) are essential. From an industrial perspective, companies are encouraged to adopt circular business models, develop local recycling infrastructure, and establish strategic partnerships to facilitate the transition from innovation to commercial deployment. International cooperation, particularly between the EU and China, can further support the harmonization of standards and accelerate widespread adoption.

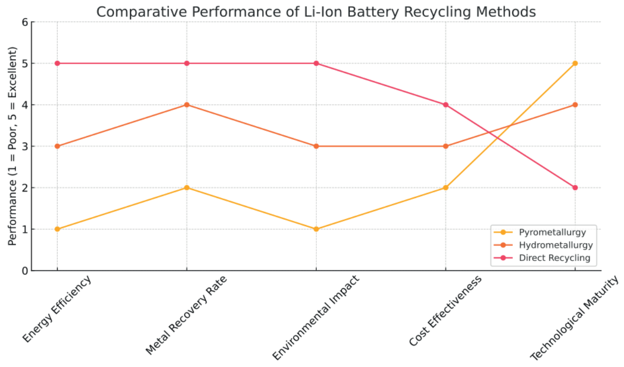

Figure 2. Comparative performance of Li-Ion battery recycling methods
(Source: Data compiled from Gaines, 2018; Xu et al., 2020; Fan et al., 2021; Harper et al., 2019; Zhao et al., 2021; Liu et al., 2021; Cornelio et al., 2024; Makuza et al., 2021)

CONCLUSIONS

As demand for Li-Ion batteries continues to rise - driven by the transition to electric mobility and renewable energy - the development of efficient recycling solutions has become a critical priority. Currently, three main technologies are emerging as viable options for recovering valuable materials from spent batteries: pyrometallurgy, hydrometallurgy, and direct recycling. Each method offers distinct advantages and limitations, and the optimal choice depends on balancing technical performance, environmental impact, and industrial readiness.

Among these, hydrometallurgy stands out as the most balanced and practical option at present. With recovery efficiencies of over 90% for critical metals such as lithium, cobalt, nickel, and manganese, moderate energy consumption (approximately 800 kWh per ton of processed batteries), and proven scalability, this method is already being deployed in commercial facilities. However, the intensive use of chemical reagents and the generation of liquid waste require advanced wastewater treatment solutions to mitigate environmental impact.

Pyrometallurgy, a long-established industrial method used by companies like Umicore and Glencore, offers the advantage of processing entire batteries without prior dismantling. Yet, it performs poorly from an environmental perspective: high CO_2 emissions (~2200 kg/ton), high energy demand (~1500 kWh/ton), and relatively low metal recovery (~60%), with significant lithium losses in the slag.

In contrast, direct recycling is increasingly viewed as the most promising long-term solution. By preserving the chemical structure of active materials - such as $LiCoO_2$ or NMC - it enables their reuse at lower costs and energy requirements. It also delivers excellent performance in key areas: up to 95% recovery efficiency, minimal CO_2 emissions (~300 kg/ton), and low-temperature processing. However, it is still in the early stages of development, facing major challenges such as material variability, the need for precise dismantling and separation processes, and the lack of industrial infrastructure.

To accelerate the advancement of direct recycling, research and innovation efforts should focus on battery standardization, the development of automated dismantling technologies, efficient separation and regeneration methods for cathode materials, and increasing tolerance to the variability of spent batteries. Additionally, integrating direct recycling into existing supply chains through public-private partnerships will be crucial.

From a policy perspective, accelerating the transition toward sustainable battery recycling requires coordinated action between authorities and industry. Key measures include investment in local recycling infrastructure, fiscal incentives for companies adopting emerging technologies, and clear regulations on battery ecodesign - especially regarding material and component standardization. Setting ambitious material recovery targets and fostering international cooperation - particularly between the European Union and China - could further harmonize technical standards and support the rapid deployment of the most efficient technologies globally.

In conclusion, hydrometallurgy currently offers the best trade-off between environmental responsibility, material recovery, and industrial feasibility, while direct recycling holds strong long-term potential. Unlocking this potential, however, will require a sustained, cross-sectoral effort in research, innovation, and policy development.

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