OPEN ACCESS

PERSPECTIVE

Journal homepage: www.the-innovation.org/energy-use

Energy Use

INNOVATION PRESS

Energy Use 1 (2026):100041

Contents lists available at INNOVATION PRESS

Recycling Spent Lithium-Ion Batteries: Recent Advances and Future Perspectives

Wenjing Deng,[1] Junhao Qin,[1] and Jie Tang[1,*]

[1]College of Materials Science and Engineering, Beijing University of Technology, Beijing 100124, China

*Correspondence: tangjie2024@bjut.edu.cn

Received: ; Accepted: March 22, 2026; Published Online: March 26, 2026; https://doi.org/10.59717/ipj.energy-use.2026.100041

Citation: Deng W., Qin J. and Tang J. (2026). Recycling Spent Lithium-Ion Batteries: Recent Advances and Future Perspectives. *Energy Use* **2**:100041.

With the rise of environmental awareness and emergence of energy crisis, lithium-ion batteries have gained widespread adoption as new energy storage solution for electric vehicles and mobile electronics. However, the shortage of raw materials and surge in the number of end-of-life batteries have intensified in recent years. Consequently, the recycling and reuse of spent lithium-ion batteries have become critically important for sustainable energy development. This perspective comprehensively outlines the current state of mainstream battery recycling and regeneration methods, along with associated advantages and challenges. It also offers corresponding guidance and insights for technical feasibility and regeneration efficiency for effectively recovering the physical and electrochemical properties of degraded battery materials. This perspective provides a possible focus for future research and technical pathways for the high-value recycling of spent batteries.

INTRODUCTION

Lithium-ion batteries (LIBs) represent one of the most successful energy storage systems and play a crucial role in modern life, offering clean and efficient energy solutions to address environmental challenges caused by the increasing depletion of fossil fuel resources. However, their performance gradually degrades with aging, leading to a sharp global increase in retired popularized lithium-ion batteries in the future. These batteries contain heavy metals, toxic electrolytes, and organic additives. Improper disposal not only results in the loss of critical metals such as nickel, cobalt, and lithium, but also poses severe environmental and ecological risks. Efficient recycling technologies represent a critical pathway for achieving resource circularity, reducing reliance on mineral extraction, and minimizing toxic emissions, which hold great significance for building sustainable energy technologies.[1]

However, recycling spent LIBs currently faces various technical challenges: the high heterogeneity of material conditions, the complexity of electrochemical degradation mechanisms, and the diversity in chemical/structural designs across different battery types. These factors necessitate systematic optimization of recycling processes to balance resource recovery rates, processing costs, and environmental impacts, driving the transition from existing energy-consumption recycling models toward low-carbon, precision-oriented upcycling approaches.[2] The summaries and assessments of development for spent battery recycling methods remain in their infancy. In this regard, the perspective first reviews pretreatment technologies that are crucial to recycling efficiency. Then it systematically discusses battery regeneration approaches, including evaluations of established recycling routes such as pyrometallurgical and hydrometallurgical processes, as well as emerging technologies like direct regeneration with low-energy, low-pollution features. Finally, this perspective provides insightful research directions for key methods in efficient metal extraction and direct recycling that significantly enhance metal recovery rates and electrochemical performance of recycled materials. This perspective aims to inspire researchers in selecting appropriate recycling methods and developing more advanced recycling technologies to fulfill the market demands, thereby advancing the regeneration technologies for the valorization of spent lithium-ion batteries.

ANALYSIS FROM COMPARISON OF RECYCLING METHODS

Currently, the mainstream recycling strategies for degraded lithium-ion batteries can be categorized into pyrometallurgical, hydrometallurgical, and direct recovery methods (Figure 1).[3] Traditional pyrometallurgical and hydrometallurgical processes typically rely on high-temperature treatment or chemical leaching to convert battery materials into metallic compounds. While these methods can enhance overall metal recovery rates to some extent, they are generally characterized by high energy consumption, complex process flows, and poor economic viability. Particularly when lithium carbonate prices are low, applying conventional methods to recover batteries, such as lithium iron phosphate batteries, may even incur net losses. In contrast, direct recycling technologies employ innovative physicochemical approaches to achieve upgrading and regeneration of spent battery materials, demonstrating significant technical and economic advantages.[4] The lithium storage capacity can be effectively restored and enhanced through ion re-intercalation, defect repair, and crystal phase structure reconstruction. This approach not only bypasses material decomposition steps in conventional recycling methods but also yields regenerated electrochemical capacities that surpass certain commercial materials. Of note, most direct regeneration strategies are still at the laboratory stage and should be scaled up for large-scale production to fully validate their potential for material upgrading and performance optimization.

EVALUATION OF LITHIUM-ION BATTERIES RECYCLING

1. LIBs recycling commences with the pre-treatment stage, where end-of-life battery packs are transported from collection points to locations. The secondary materials, such as cathodes, anodes, current collectors, electrolytes, and separators, are subsequently refined and transported into recovery processes. Initially, spent batteries undergo electrochemical testing for various key parameters, including impedance and capacity derived from information provided by the battery management system. Following pre-testing, the spent batteries undergo pre-processing via one of two treatment pathways: shredding or disassembly. For shredding way employed in industrial processes, battery materials are pulverized, resulting in component mixing prior to separation. To enhance recovery rate of materials in spent batteries, cleaner separation of materials into waste streams is required. This can simplify subsequent recycling routes and provide scope for redesigning spent batteries to facilitate their remanufacturing and reuse. Current innovations in pretreatment technology primarily focus on the following directions: (1) Green solvent methods replacing traditional systems: To substitute highly toxic organic solvents such as N-methyl-2-pyrrolidone (NMP), researchers have developed bio-based or environmentally friendly solvents represented

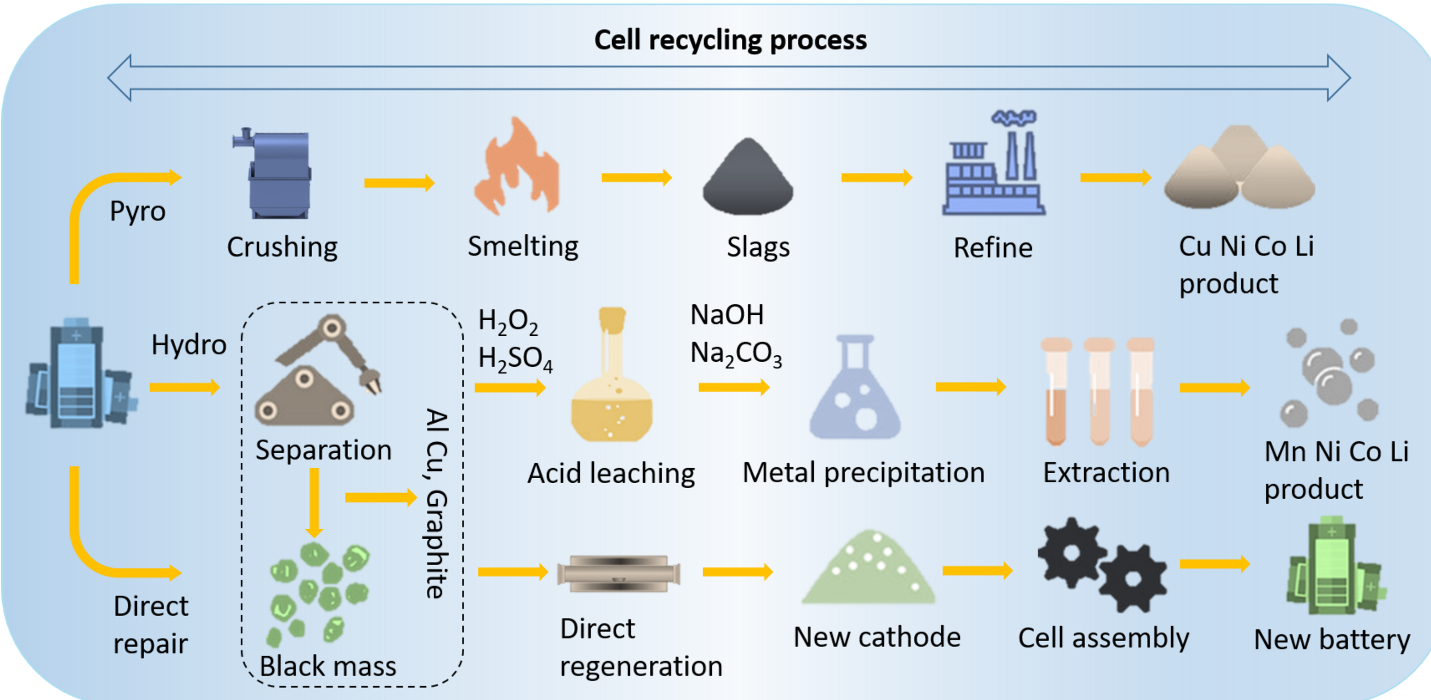

Figure 1. Simplified battery recycling processes of pyrometallurgical (Pyro) and hydrometallurgical (Hydro), and direct recycling.

by methanol-citric acid composite systems. These novel solvents efficiently dissolve polyvinylidene fluoride (PVDF) binders while enabling damage-free recovery of aluminum foil; (2) Upgrading thermal treatment technologies: Innovative thermal separation techniques like pulsed direct current flash, Joule heating, and shock-induced rapid heating can utilize instantaneous high temperatures to induce rapid binder decomposition.[5] This achieves efficient separation of cathode materials from current collectors while significantly reducing energy consumption and processing time. The ongoing development of pretreatment technologies requires achieving a systematic balance among multiple quantitative metrics, including processing costs and separation efficiency.

2. Pyrometallurgical recovery processes feature relatively straightforward operational procedures and moderate equipment requirements, rendering them suitable for large-scale industrial implementation. Pyrometallurgical recovery also demonstrates broad applicability across various electrode materials. The smelting process, carried out at temperatures exceeding 1000 °C, transforms the waste material into an alloy containing various metallic elements and produces lithium-bearing slag. When starting from waste LIBs, the casing, conductive carbon, electrolyte, anode, and binder are consumed as fuel in the smelting step. In contrast, directly starting with black mass allows for separation of current collector and casing during pre-treatment, inducing trace amounts of aluminium or copper into resulted metal alloy and slag product. In subsequent hydrometallurgical stages, the intermediate metal alloy is refined to recover high-purity metal resources. However, pyrometallurgical processes are constrained by their reliance on high-temperature smelting for material decomposition and elemental extraction, acting as a high-energy approach that triggers significant HF or CO_2 emissions. The economic viability of this method is also restricted to high-value elements like cobalt and nickel. The novel heating methods, such as carbon thermal shock, remain at laboratory scale, whereas industrial pyrometallurgical recovery processes have been commercialized to yield metals, metal salts, and metal alloys.[6]

In hydrometallurgical recovery processes, high-value metals are extracted from waste batteries during the leaching step. This occurs through chemical reactions with leaching and reducing agents within reactors operating at temperatures typically below 200 °C. Following pretreatment, the resulting black material undergoes hydrometallurgical recovery, which generally comprises two primary stages: leaching and separation.[7] During leaching, leaching agents extract valuable metal ions from the black material into solution. These agents are typically strong inorganic acids, such as hydrochloric acid and nitric acid. Subsequently, the valuable metal source in leachate can be separated using various methods, including chemical precipitation and solvent extraction. Chemical precipitation involves adjusting the leachate pH to precipitate various metals. In contrast, for solvent extraction, metal ions are selectively separated and extracted based on differences in their solubility between formulated aqueous solution and organic solvent.

3. Direct recycling technology effectively restores the electrochemical performance of lithium cathodes by repairing lattice defects and replenishing lost lithium sources, thereby avoiding the energy-intensive metal synthesis process in traditional recycling methods.[8] Current mainstream regeneration methods primarily include: (1) Solid-phase sintering: High-temperature heat treatment replenishes lithium sources while simultaneously repairing crystal structures. This method offers advantages of simplicity and lower cost, but faces challenges such as slow reaction kinetics, uneven particle contact, and grain growth due to high temperatures; (2) Eutectic molten salt method: Utilizing low-melting-point molten salts to promote ion migration can enable efficient regeneration at lower temperatures. Challenges include molten salt recovery difficulties and relatively high overall energy consumption and costs; (3) Hydrothermal method: It combines liquid-phase lithiation with thermal treatment to precisely control material composition and suppress particle agglomeration. However, it faces challenges of complex process and high chemical reagent costs; (4) Liquid-phase reduction method: It utilizes a reducing lithium source, such as ascorbic acid, in a liquid-phase environment to replenish lithium and repair phase-separated structures. The reaction conditions are mild, but the multi-step operation and solvent system incur higher costs; (5) Electrochemical regeneration method: This utilizes a functionalized electrochemical lithium-replenishing reaction to achieve in situ lithium compensation within the battery. However, the electrode restructuring process is complex and poses significant engineering challenges. Regarding industrial applicability, the solid-state sintering method holds the greatest potential for widespread adoption. Yet its repair capacity is limited, often requiring solvent-assisted techniques to enhance regeneration effects on severely degraded materials. Liquid-phase methods enable precise control over lithium spatial distribution, yet their complex workflows necessitate streamlining wet-processing steps to reduce costs. While electrochemical and chemical methods offer high selectivity and low-temperature advantages, they face constraints in equipment integration and reagent recycling bottlenecks. Future efforts should focus on multi-technology convergence, such as combining thermal treatment with chemical reduction, or synergizing electrochemical regeneration with structural regulation to establish low-energy, broadly adaptable integrated regeneration systems. Furthermore, optimizing energy consumption and environmental footprint during regeneration will strengthen economic competitiveness, serving as the key driver for advancing direct recycling technologies toward industrialization.

4. Previously, waste graphite generated from used lithium-ion batteries was incinerated or landfilled. The incineration process requires considerable energy input, which results in substantial greenhouse gas emissions, thus aggravating energy consumption and posing a barrier to the development of lithium-ion batteries. Due to the presence of metal elements remaining in waste electrodes derived from toxic electrolyte salts and cathode materials, direct disposal of spent graphite into water and soil sources causes severe pollution. Consequently, traditional waste graphite disposal methods conflict with the principles of the circular economy. In recent years, the reuse of graphite anodes from end-of-life lithium-ion batteries has attracted considerable attention, underscoring the necessity of developing efficient and sustainable recycling strategies for graphite anodes. Graphite materials recycling mainly follows two ways: direct repair of graphite or production of value-upgraded graphite materials.[9] Although graphite prices have remained relatively stable and low, its high-value derivatives, such as graphene, are characterized by their high market prospects.

5. Recycling of electrolyte in waste lithium batteries primarily employs mechanical, cryogenic, and extraction methods.[10] The mechanical method utilizes high-speed rotation to separate and collect electrolyte, requiring centrifuge speeds exceeding 20,000 rpm. Alternatively, high-pressure air nozzles can be used to separate the electrolyte. The cryogenic method rapidly freezes spent lithium batteries to collect electrolyte in solid form. This approach reduces safety risks in recycling but demands complex equipment and consumes high energy. The extraction method employs organic solvents to separate and purify electrolyte or utilizes supercritical fluids to isolate specific components. However, the former raises environmental pollution concerns, while the latter requires advanced equipment. Continued research into efficient and eco-friendly recycling methods is needed.

PERSPECTIVE OF LITHIUM-ION BATTERIES RECYCLING

The rapid proliferation of electric vehicles and renewable energy is driving innovation in lithium-ion battery recycling towards greater efficiency and lower carbon footprints. Current mainstream hydrometallurgical and pyrometallurgical processes face challenges such as secondary pollution and high energy consumption. Direct recycling technologies, however, demonstrate significant potential for cost reduction and low carbon emissions by repairing and regenerating cathode materials. Key development pathways are proposed below from the perspectives of technological optimization and industrial chain collaboration.

1. During the design and assembly of lithium-ion batteries, the layout of each component must be optimized to facilitate dismantling and separation in the pre-treatment process. Furthermore, more advanced techniques for the precise disassembly and separation of batteries should be developed. Leveraging machine learning and real-time sensing systems to achieve precise condition identification of end-of-life batteries, including mild/moderate/severe degradation, dynamically matching regeneration processes through physical characterization. Mild degradation may employ solvent or physical separation to preserve material structure, while severe degradation requires chemical modification or high-temperature sintering. Developing universal regeneration workflows is key to reducing process complexity.

2. Strengthening investigations into electrode material failure mechanisms, restoration processes, and underlying principles will accelerate advancements in battery recycling technology. For instance, the fundamental mechanisms governing lithium depletion and structural degradation, coupled with the lithiation kinetics during replenishment, still lack a comprehensive understanding. This ambiguity leads to suboptimal outcomes in restoration experiments. Elucidating failure mechanisms and restoration principles holds promise for developing a universal direct regeneration technique adaptable to diverse failed electrode materials, thereby enhancing recovery efficiency while simultaneously reducing cost inputs.

3. Deeply integrating cathode material preparation processes, such as solid-state mixing methods, hydrothermal synthesis methods, with regeneration workflows to establish a scalable, compatible production system. Employing elemental doping techniques or surface nanoengineering to improve the electrochemical performance of recycled materials. Integrating direct regeneration pathways with other electrochemical energy storage techniques achieves dual benefits. For instance, integrating redox reactions in electrode materials with changes of elemental valence state within redox flow batteries could design novel electrochemical devices that simultaneously promote spent electrode restoration and enhance battery performance.

4. Establish industry-wide testing benchmarks covering specific capacity, cycle life, and fast-charging capability. Developing traceable databases and large-scale validation platforms can define impurity content standards while optimizing online monitoring. The industry frequently handles multiple mixed cathodes simultaneously. Consequently, there is an urgent need to develop direct recycling strategies for mixed electrode materials to meet the demand. As commercial cathode performance standards continue to rise, the upgrading and remanufacturing of waste cathodes becomes increasingly vital.

5. Current direct recycling techniques primarily focus on spent electrodes while neglecting other lithium-ion battery components like electrolytes and separators. Only through the complete recycling of all lithium-ion battery components can a truly economic cycle be achieved. Consequently, direct recycling methods for residual battery components must also be considered. Furthermore, beyond lithium-ion batteries, novel energy storage systems such as sodium-ion batteries are emerging as prominent research areas. Designing recycling strategies for these emerging technologies should be prioritized to secure a competitive approach in the future energy storage recycling development.

CONCLUSIONS

This perspective outlines various recycling technologies, many of which have commenced large-scale demonstration and exerted tangible impacts on the closed-loop battery system. Pyrometallurgical and hydrometallurgical recovery methods have achieved commercialization, while direct regeneration remains confined to laboratory-scale operations. Despite the high efficiency and purity produced by direct recycling, the method faces significant hurdles, including stringent pre-processing protocols, inherent challenges of manual operation, and the risk of producing outdated materials. Scalability, flexibility, and safety are among the numerous factors determining which proposed method is adopted. Furthermore, standards concerning capital and operational costs, coupled with key environmental impact indicators such as water consumption, CO_2 emissions, and electricity usage, must be addressed to prevent the unsustainability of battery recycling. Thus, a comprehensive assessment of the technological, economic, environmental, and societal impacts of advanced recycling and upgrade processes must be undertaken for the industrialization of LIBs regeneration in the future.

REFERENCES

1. Zheng M., You Y. and Lu J. (2025). Understanding materials failure mechanisms for the optimization of lithium-ion battery recycling. *Nature Reviews Materials* **10**:355−368. DOI:10.1038/s41578-025-00783-5
2. Mao J., Ye C., Zhang S., et al. (2022). Toward practical lithium-ion battery recycling: adding value, tackling circularity and recycling-oriented design. *Energy Environ. Sci.* **15**:2732−2752. DOI:10.1039/D2EE00162D
3. Ma X., Meng Z., Bellonia M. V., et al. (2025). The evolution of lithium-ion battery recycling. *Nature Reviews Clean Technology* **1**:75−94. DOI:10.1038/s44359-024-00010-4
4. Sederholm J. G., Li L., Liu Z., et al. (2025). Emerging Trends and Future Opportunities for Battery Recycling. *ACS Energy Lett.* **10**:107−119. DOI:10.1021/acsenergylett.4c02198
5. Liu W., Peng L., Zeng Z., et al. (2025). Advanced direct recycling enables upcycling of spent lithium-ion batteries. *Science China Chemistry*. DOI:10.1007/s11426-025-2928-5
6. Jin Y., Zhang T. and Zhang M. (2022). Advances in Intelligent Regeneration of Cathode Materials for Sustainable Lithium-Ion Batteries. *Adv. Energy Mater.* **12**:2201526. DOI:10.1002/aenm.202201526
7. Zhang N., Xu Z., Deng W., et al. (2022). Recycling and Upcycling Spent LIB Cathodes: A Comprehensive Review. *Electrochemical Energy Reviews* **5**:33. DOI:10.1007/s41918-022-00154-6
8. Yang Q., Su Y., Wang X., et al. (2025). Emerging Strategies for Sustainable Holistic Recycling of Spent Lithium-Ion Batteries. *Adv. Funct. Mater.* **n/a**:e14524. DOI:10.1002/adfm.202514524
9. Shen J., Zhou M., Liu W., et al. (2025). Advanced direct recycling technology enables a second life of spent lithium-ion battery. *Energy Storage Mater.* **74**:103964. DOI:10.1016/j.ensm.2024.103964
10. Niu B., Xu Z., Xiao J., et al. (2023). Recycling Hazardous and Valuable Electrolyte in Spent Lithium-Ion Batteries: Urgency, Progress, Challenge, and Viable Approach. *Chem. Rev.* **123**:8718−8735. DOI:10.1021/acs.chemrev.3c00174

FUNDING AND ACKNOWLEDGMENTS

This work was supported by the Beijing Natural Science Foundation (25ISB003).

DECLARATION OF INTERESTS

The authors declare no competing interests.