The Journal of Green Energy and Environmental Engineering

Review Paper

Research Advances in Recycling Technologies for Valuable Components from Spent Lithium-Ion Batteries

María Bakera[1], Pablo V. Bustamante[1,*]

[1] Universidad Politécnica de Madrid. Escuela Superior Agronómica, Alimentaria y de Biosistemas. Departamento de Ingeniería Agroforestal. Unidad de Proyectos, Avenida Puerta del Hierro nº 2-4, 28040, Madrid, Spain
*Corresponding author: mBakera@upm.es; PVB@upm.es

Abstract. With the rapid expansion of the new energy industry, lithium-ion batteries have witnessed explosive growth in production and deployment, driven by broadening applications in electric vehicles, consumer electronics, and grid-scale energy storage. Consequently, the volume of retired batteries is increasing annually. Spent lithium-ion batteries contain high concentrations of strategic metals—notably nickel, cobalt, and lithium—that hold substantial economic value. Inadequate recycling not only results in significant resource depletion but also triggers severe environmental risks, including soil and groundwater contamination from heavy metal leaching, threatening both ecological systems and human health. Current recycling technologies for spent lithium-ion batteries are broadly classified into three categories: physical methods, chemical methods, and biological methods. This review analyzes each technology based on its fundamental operating principles, systematically evaluating key performance indicators including metal recovery efficiency, economic feasibility, and environmental footprint, while discussing their respective technical strengths and application limitations. To address existing bottlenecks, we propose an integrated strategy: employing intelligent sorting technologies for pre-separation and enrichment of compositionally uniform fractions, followed by conventional physical and chemical recycling processes. Future recycling systems are expected to evolve toward intelligent, green, and short-process paradigms, minimizing energy consumption and environmental impact across the entire recovery chain.

Keywords: *lithium-ion batteries; physical methods; chemical methods; biological methods; recycling*

Received on 15 Feb 2026, Accepted on 15 May 2026, Published on 22 July 2026

1 Introduction

The trajectory of modern technological civilization is inextricably linked to the development of efficient energy storage systems. Over the past three decades, the lithium-ion battery (LIB) has emerged as the undisputed cornerstone of the portable electronics revolution and the ongoing global transition toward electrified transportation. Since the pioneering work of Whittingham on intercalation electrodes in the 1970s and the subsequent breakthrough discovery of the $LiCoO_2$ cathode by Goodenough in 1980, the energy density and cycle life of LIBs have improved exponentially [1,2]. The commercialization of the first LIB by Sony in 1991 marked a paradigm shift, enabling the miniaturization of consumer electronics and, eventually, serving as the primary power source for electric vehicles (EVs) and grid-scale energy storage systems [3]. This proliferation has been fueled by global decarbonization policies aimed at mitigating climate change and reducing dependence on fossil fuels. However, as the installed base of LIBs surpasses hundreds of gigawatt-hours annually, the industry faces a formidable and unavoidable challenge: the management of end-of-life batteries. Unlike the relatively small volumes of consumer electronics waste in the 1990s, the retirement of EV batteries—typically after 5 to 8 years of service—is generating a tidal wave of spent lithium-ion cells. Projections indicate that by 2025, China alone will contend with 1.37 million tonnes of retired power batteries, a figure that is expected to grow exponentially as the first generation of EV owners replaces their vehicles [4]. Globally, the cumulative volume of spent LIBs is forecast to exceed 11 million tonnes by 2030, presenting both an unprecedented environmental liability and a unique resource opportunity [5].

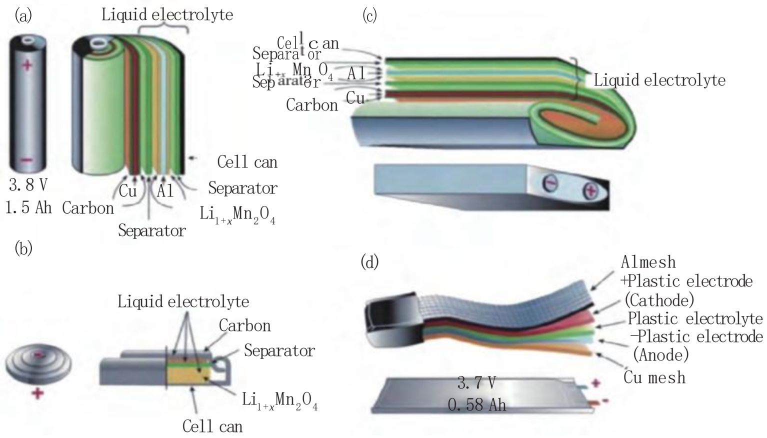

Figure 1 Schematic diagram of lithium-ion battery structure:(a)cylindrical shape;(b) button shape;(c)prismatic shape;(d) strip shape[9]

Spent LIBs are often mischaracterized as mere hazardous waste; in reality, they constitute a high-grade "urban mine" of critical raw materials. As illustrated in Table 1, the intrinsic value of a spent battery lies primarily in its cathode composition, which accounts for 30% to 35% of the total battery cost. Cathode materials such as lithium cobalt oxide (LCO), nickel cobalt manganese (NCM), and nickel cobalt aluminum (NCA) contain concentrated quantities of strategic metals: lithium (2–7 wt%), cobalt (5–20 wt%), and nickel (10–30 wt%) [6]. These elements are classified as Critical Raw Materials by geopolitical entities such as the European Union and the United States due to their extreme supply chain vulnerability. For instance, over 70% of the world's cobalt supply is sourced from the Democratic Republic of Congo, while China controls approximately 60% of global lithium refining capacity [7]. This geographical concentration creates significant risks of supply disruption. Moreover, the virgin extraction of these metals is environmentally destructive; hard rock lithium mining consumes vast quantities of water and generates substantial CO_2 emissions, while nickel and cobalt mining often result in severe habitat destruction and heavy metal pollution [8]. Therefore, the efficient recycling of spent LIBs is not merely an exercise in waste management—it is a strategic imperative for national resource security and for closing the loop in a circular economy. By recovering these metals, we reduce the pressure on primary mining, stabilize commodity prices, and decrease the carbon footprint of battery manufacturing.

Beyond resource security, the improper disposal of spent LIBs poses severe environmental and safety hazards. A lithium-ion battery is a complex chemical reactor containing multiple hazardous components. The electrolyte, typically composed of lithium hexafluorophosphate ($LiPF_6$) dissolved in organic carbonates (dimethyl carbonate, ethyl methyl carbonate), is highly flammable and toxic [9]. Upon exposure to atmospheric moisture, $LiPF_6$ hydrolyzes to form hydrofluoric acid (HF), a highly corrosive substance capable of causing irreversible environmental damage and severe health issues [10]. The polyvinylidene fluoride (PVDF) binder, widely used to adhere active materials to current collectors, releases HF upon thermal decomposition. Furthermore, the leaching of heavy metals such as cobalt, nickel, and manganese from landfilled batteries can contaminate soil and groundwater aquifers, posing long-term ecotoxicological risks to flora, fauna, and human populations [11]. Physically, spent LIBs retain residual voltages and are prone to internal short circuits, thermal runaway, and fire if mechanically damaged during disposal, creating significant risks for waste management facilities. Consequently, developing safe, efficient, and environmentally benign recycling technologies is a prerequisite for mitigating these risks and aligning with global "carbon peaking and carbon neutrality" (Dual Carbon) goals.

Historically, the industrial response to battery recycling has evolved through three distinct generations. The first generation, dominated by the 1990s and early 2000s, relied almost exclusively on pyrometallurgical processes. Companies like Umicore pioneered high-temperature smelting (>1400 °C) in electric arc furnaces to recover cobalt and nickel in the form of alloys [12]. While robust and capable of handling diverse battery formats, pyrometallurgy suffers from significant drawbacks: it is extremely energy-intensive, results in the near-total loss of lithium (which ends up in slag or off-gas), and emits hazardous dioxins and furans if not properly controlled [13]. In response, the second generation of recycling technologies emerged, centered on hydrometallurgical processes. These involve the leaching of shredded battery "black mass" using strong inorganic acids (HCl, H_2SO_4,

HNO_3) combined with reducing agents, followed by sophisticated solvent extraction and precipitation steps to recover high-purity metal salts [14]. Although hydrometallurgy achieves high recovery rates (>95%) and allows for lithium recovery, it generates large volumes of acidic wastewater, requires extensive chemical consumption, and often involves complex, multi-step purification processes that increase operational costs [15].

Currently, the field stands at the cusp of a third generation of recycling technologies. There is a growing consensus that single-process approaches are insufficient. The industry is moving toward hybrid strategies that integrate physical, chemical, and biological methods to maximize efficiency and minimize environmental impact. Physical methods—including crushing, sieving, magnetic separation, eddy current separation, and photoelectric sorting—serve as crucial pre-treatment steps to safely dismantle batteries and concentrate valuable materials without generating chemical waste [16]. However, as detailed in subsequent sections of this review, challenges remain in the precise separation of mixed metal fractions and the removal of organic coatings. Biological methods, utilizing microorganisms such as Acidithiobacillus ferrooxidansor Aspergillus niger, offer a low-energy, ambient-temperature alternative for metal leaching, though kinetics remain slow and industrial scalability is unproven [17]. Furthermore, innovative approaches such as direct recycling—which aims to repair and regenerate cathode materials without breaking them down to their elemental constituents—have gained significant attention as a means to preserve the embedded energy and value of the original material [18].

Despite the wealth of research in this field, a comprehensive review that systematically connects the fundamental physical properties of battery components (Table 1) to the selection and optimization of specific recycling technologies is lacking. Many existing reviews focus solely on chemical leaching efficiencies or economic models, often overlooking the critical role of physical separation in determining the success of downstream metallurgical processes. This review seeks to fill that gap. By analyzing the technical principles, recovery efficiencies, and economic costs of physical, chemical, and biological methods, we provide a holistic perspective on the state-of-the-art in LIB recycling. Special attention is paid to the integration of intelligent sorting technologies as a means to pre-enrich specific components, thereby reducing the complexity of subsequent chemical treatments. Finally, we discuss the future trajectory of the industry, emphasizing the need for green, short-process, and intelligent recycling systems that can meet the demands of a circular economy and ensure the sustainable growth of the global new energy industry.

2 Physical Methods

2.1 Gravity Separation

Huang Weixin [10] employed the Knelson centrifugal concentrator for recycling spent $LiFePO_4$ batteries, addressing the separation challenge of copper from $LiFePO_4$ and graphite. The process leverages density differences between copper (heavy) and $LiFePO_4$/graphite (light). As shown in Figure 2, during separation, slurry flows upward along the cone wall under high-speed centrifugal force; light minerals discharge from the upper cone as tailings, while heavy minerals migrate downward and accumulate in the bottom mold, achieving effective material separation.

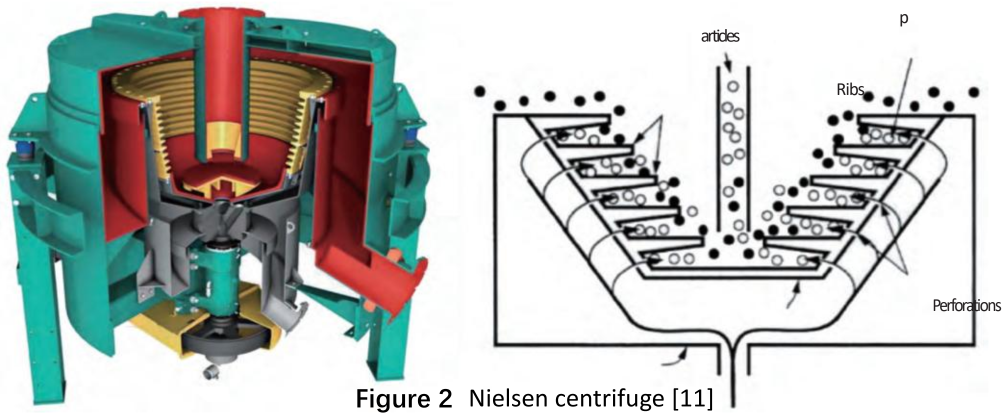

Figure 2 Nielsen centrifuge [11]

2.2 Pneumatic Separation

Pneumatic separation utilizes differences in particle density and size to achieve classification or impurity removal under aerodynamic forces. Lu Shijie et al. [12] analyzed material characteristics and key factors affecting liberation efficiency, constructing a fine-crushing test system comprising a fine crusher, cyclone collector, star discharger, and centrifugal fan (Figure 3). Optimal parameters were identified as: feed size (−9.5 mm accounting for 91.6%), hammer rotor speed (3141 r·min^{-1}), and centrifugal fan speed (2300 r·min^{-1}). Under these conditions, the −74 μm product achieved the highest cumulative negative yield, with peak cobalt content and superior product quality.

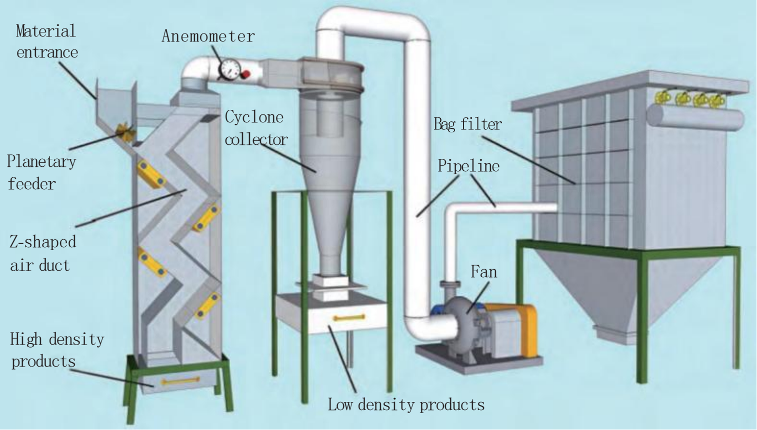

Figure 3 Structure diagram of pneumatic separator

Zhang Yu [14] exploited the density difference between copper (8.96 g·cm^{-3}) and aluminum (2.7 g·cm^{-3}) in spent battery current collectors, adopting active pulsating airflow separation. Airflow velocity—controlled by adjusting magnitude and frequency to regulate particle drag force—was identified as the key parameter governing separation efficiency. Narrower particle size distributions and finer materials enhanced differential settling velocities, improving separation performance. Although minor shape variations and residual graphite/$LiCoO_2$ impurities slightly reduced efficiency, optimal conditions (−0.5+0.25 mm particle size, airflow velocity 6.10 m·s^{-1}, pulsation frequency 7.15 Hz, feed rate 0.5 g·s^{-1}) achieved a copper-aluminum separation efficiency of 68.19%, with copper and aluminum recoveries of 83.82% and 84.37%, respectively.

Under the "Dual Carbon" policy context, environmentally benign pneumatic separation has garnered increasing attention. However, limitations persist regarding fine-particle separation efficiency and equipment scale-up. Zhu Xueshuai et al. [15] reviewed progress from theoretical, technological, and application perspectives. Theoretically, beyond gravity and drag, particles experience additional forces such as fluid gradient forces during pneumatic separation; numerical simulation further elucidates these force dynamics. Technological improvements encompass optimized air supply (e.g., pulsating airflow) and equipment structure (e.g., Z-type configurations, vibrators). Future development will advance toward intelligent online monitoring and control, large-scale equipment, refined efficiency, and process integration, supported by thermal runaway simulation [16].

2.3 Magnetic Separation

Magnetic separation exploits differences in magnetic susceptibility between ferromagnetic and non-magnetic materials, presenting high potential for $LiFePO_4$ battery recycling. Gan Tao's team [17] measured the magnetic properties of mainstream electrode active materials, natural spherical graphite, and artificial spherical graphite. Positive electrode materials exhibited paramagnetism and were adsorbed by a custom high-gradient magnetic separator, while negative electrode graphite displayed diamagnetism and remained non-adsorbed, establishing the theoretical basis for magnetic separation (Figure 4). Using high-gradient magnetic separation to purify mixed positive/negative electrode materials from spent $LiFePO_4$ batteries reduced carbon grade in the magnetic product to 12.0%–13.0% and increased carbon grade in the non-magnetic product to 91.0%–92.0%; adjusting pulsation frequency further enhanced carbon grade in the non-magnetic fraction.

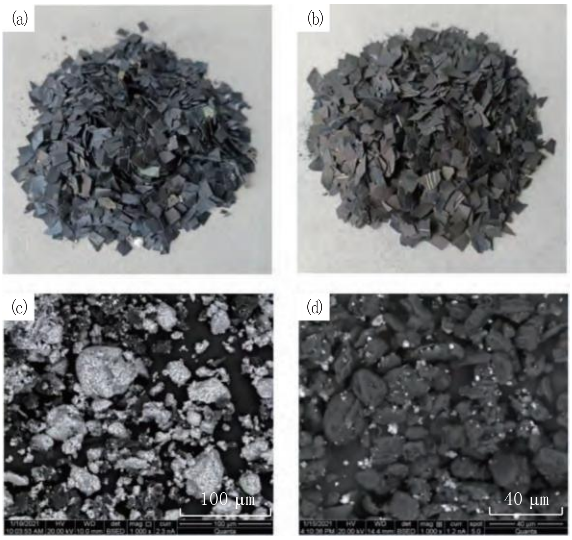

Figure 4 (a)Cathode;(b)Anode;(c)SEM image of lithium iron phosphate;(d)SEM image of graphite

Huang Weixin [10] investigated the magnetic separation of waste $LiFePO_4$ electrode powder, revealing magnetic field intensity as the dominant parameter governing efficiency. Increasing field intensity from 1 T to 2 T raised $LiFePO_4$ recovery from 72% to 94.23% (grade: 79.66%); further increasing to 2.38 T reduced efficiency due to fine-particle entrainment. Feed concentration and residence time exerted minimal influence.

2.4 Eddy Current Separation

Eddy current separation operates based on Faraday’s law of electromagnetic induction. A rapidly rotating magnetic roller generates an alternating magnetic field, inducing eddy currents in conductive materials. The induced magnetic field opposes the roller’s field, generating Lorentz repulsion. If the vertical repulsive force exceeds gravitational force, conductors are ejected, while non-conductors follow parabolic trajectories, directing materials into separate collectors (Figure 5).

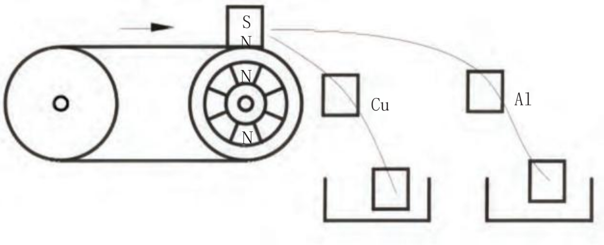

Figure 5 Principle of eddy current separation[19]

Li Jianbo [20] leveraged electrical conductivity differences: at a belt speed of 0.8 $m \cdot s^{-1}$ and magnetic roller speed of 1200 $r \cdot min^{-1}$, positive electrode material recovery reached 88.19%, with copper foil mixing at only 12.33%. The high resistivity of the cathode prevented eddy current repulsion, directing it to the conductor collector. In the non-conductor fraction, copper foil recovery was 63.13%, attributable to strong eddy current repulsion from its high conductivity, confirming effective separation of aluminum and copper foils.

2.5 Photoelectric Sorting

Photoelectric sorting identifies and separates materials based on optical property differences (color, reflectivity, fluorescence) and electromagnetic characteristics, integrating sensor technology, image recognition, and artificial intelligence. As an advanced evolution of manual sorting [21], optical systems dynamically scan materials via dual-sided sensors; image recognition generates discrimination signals synchronized with particle drop timing, triggering high-speed air jets to eject target particles into dedicated collectors (Figure 6).

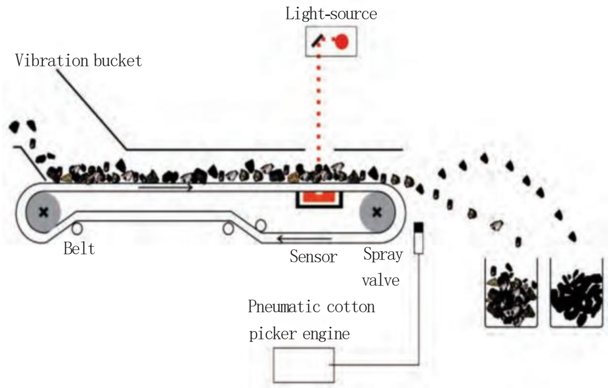

Figure 6 The schematic diagram of photoelectric sorting

Zhong Xuehu [13] applied photoelectric sorting to separate copper and aluminum current collectors, achieving yields of 31.74% and 68.26%, respectively. Copper purity reached 99.95%, and aluminum purity reached 99.94%, with total recoveries of 99.78% and 99.94%, demonstrating excellent separation performance (Figure 7).

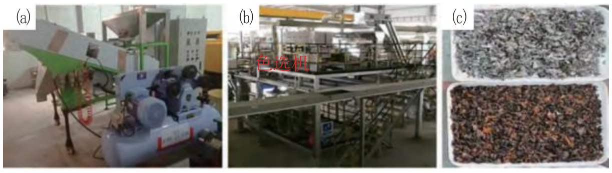

Figure 7 (a) Color sorter;(b) Color sorter on pilot scale experiment;(c)Aluminum foil and copper foil [13]

3 Chemical Methods

3.1 Hydrometallurgy

Hydrometallurgical processing of spent cathode materials involves acid [24] or alkali [25] leaching to dissolve target metal ions into solution, followed by solvent extraction and purification to produce high-purity products [26]. Shentu Huajian [27] focused on regenerating spent $LiFePO_4$ batteries, using ammonium persulfate as an oxidant to convert $LiFePO_4$ into $FePO_4$ with identical crystal structure in an aqueous solution at 40 °C, transferring lithium to the solution and achieving 99% preferential lithium leaching. Alternatively, using CO_2 as both lechant and precipitant under weakly alkaline conditions with H_2O_2 achieved 97% lithium recovery, replacing conventional strong acids/bases and significantly reducing reagent consumption and wastewater generation (Figure 8).

Figure 8 Schematic diagram of hydrometallurgy

Tsinghua University's Li Jinhui team proposed a galvanic leaching strategy leveraging the spontaneous battery effect [29]. As shown in Figure 9, spent battery cathodes and aluminum current collectors self-assembled into a system with a 3.84 V potential difference, eliminating pretreatment. Aluminum foil facilitated directional electron transfer, reductively decomposing cathode materials without disrupting battery structure, reducing process entropy. Compared to conventional methods, lithium recovery exceeded 99%, while fluorine-containing binders were immobilized in tailings within an organic framework, lowering secondary wastewater treatment difficulty.

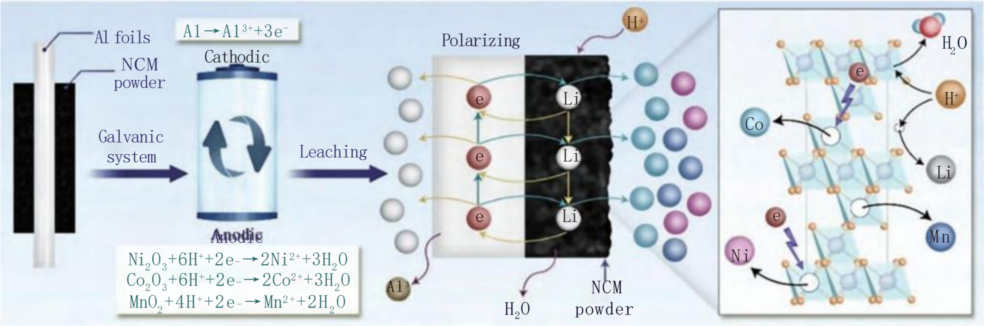

Figure 9 Galvanic cell leaching system for spent lithium-ion batteries[29]

3.2 Pyrometallurgy

Pyrometallurgy involves high-temperature reactions between spent cathode materials and reducing agents/additives to form metal alloys and oxides [30] (Figure 10). High-temperature smelting utilizes carbon and aluminum reduction reactions to form molten layers for metal separation:

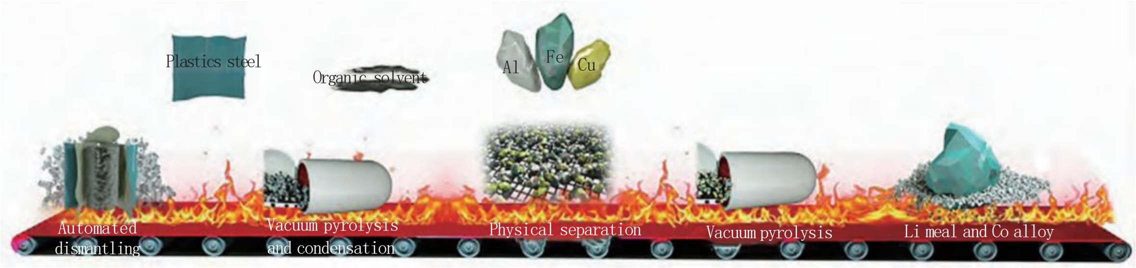

Figure 10 Schematic diagram of pyrometallurgy[28]

$$2LiCoO_2 + 2Al \rightarrow Li_2O + 2Co + Al_2O_3$$

$$2LiCoNiO_2 + 3C \rightarrow Li_2O + 2Co + 2Ni + 3CO(g)$$

$$2LiCoNiO_2 + 2Al \rightarrow Li_2O + 2Co + 2Ni + Al_2O_3$$

Salt-assisted roasting combined with carbothermal reduction preferentially extracts lithium, avoiding lithium loss in conventional smelting. Huang Cheng [26] mixed crushed spent cathode materials with $LiOH$–$LiNO_3$ molten salt as precursors, varying roasting temperature and holding time. Ex-situ XRD and FESEM analyses (Figure 11) indicated that elevated temperatures altered cathode morphology, reconstructing nanoscale particles into micron-sized aggregates.

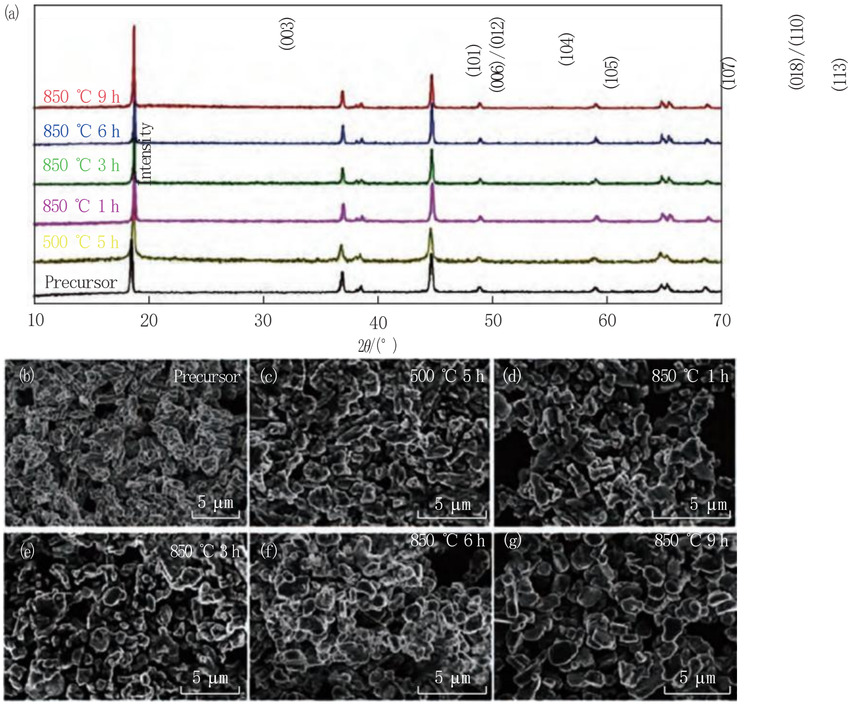

Figure 11 Changes in structure and morphology of cathode materials at different calcination temperatures and holding times [26]:(a) XRD patterns;(b-g) FESEM images

3.3 Integrated Hydrometallurgy-Pyrometallurgy Process

Conventional hydrometallurgy suffers from long lithium leaching durations and low recovery rates, while pyrometallurgy incurs high energy consumption, cost, and pollution. An integrated approach combines the advantages of both, overcoming individual limitations to reduce energy/cost, enhance comprehensive efficiency, and improve environmental performance. Long Guangwu [31] developed a "reductive roasting–water leaching–acid leaching" short-process using graphite from spent batteries as a reductant (Figure 12). In-situ reductive roasting converted lithium in ternary cathodes into water-soluble Li_2CO_3, achieving 97.86% lithium leaching; nickel, cobalt, and manganese remained largely unleached. Subsequent H_2SO_4 acid leaching of the residue yielded Ni, Co, and Mn leaching rates of 99.41%, 99.92%, and 98.35%, respectively, enabling efficient separation and recovery.

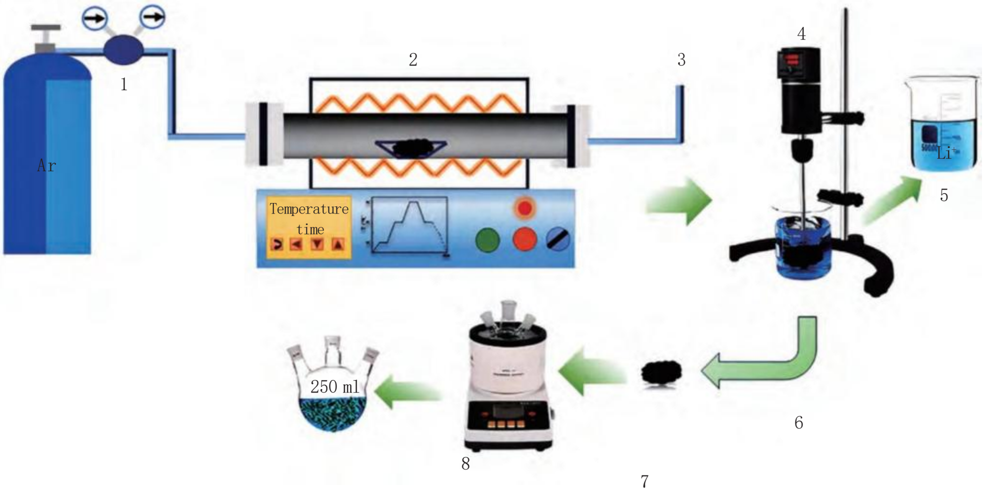

Figure 12 Synergistic process of hydrometallurgy-pyrometallurgy [31]

Zheng Rujuan [32] adopted a multi-process integration model for whole-battery recycling. Aluminum foil was dissolved using alkali solution to separate active materials, enhanced by ultrasonic assistance. For spent $LiFePO_4$ batteries, discharge, crushing, and 600 °C heat treatment removed binders and carbon coatings; Fe^{2+} was oxidized to Fe^{3+}, followed by leaching with 2.5 $mol \cdot L^{-1}$ sulfuric acid to recover iron and lithium. Adding nonionic surfactants and adjusting pH to 2.0 precipitated $FePO_4$, while Na_2CO_3 precipitated Li_2CO_3, yielding high-purity products meeting battery-grade standards. Recovered materials were reprocessed into $LiFePO_4/C$ via carbothermal reduction, exhibiting electrochemical performance comparable to commercial products. Similar pretreatment of spent $LiFePO_4/Li_3V_2(PO_4)_3$ batteries, with elemental ratio adjustment, enabled resynthesis of $xLiFePO_4$–$yLi_3V_2(PO_4)_3$ composite cathodes combining both materials' properties. Mixed batteries were acid-leached to remove Fe, Cu, and Al impurities, followed by coprecipitation of Ni-Co-Mn precursors and solid-state synthesis of $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ with excellent cycling stability.

3.4 Flotation

Flotation separates materials based on differences in surface physicochemical properties. By modifying target particle surfaces, hydrophobic materials attach to bubbles and float, achieving separation from hydrophilic materials. Liu Jiangshan [33] applied low-temperature selective crushing and grinding to rapidly remove organic coatings from electrode particles, increasing the contact angle difference between graphite and $LiCoO_2$ from 10° to 40°, significantly enhancing flotation efficiency. This yielded a $LiCoO_2$ concentrate with 91.75% grade and 89.83% recovery, improvements of 36.39% and 17.03% over unground processes, respectively (Figure 13).

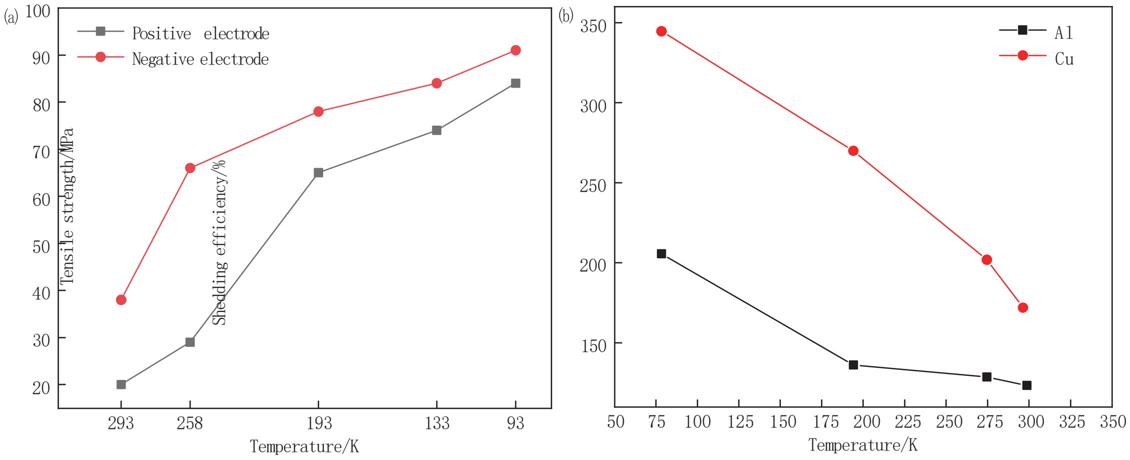

Figure 13 (a)Effect of crushing temperature on coating delamination efficiency of electrode materials;(b) Relationship between impact strength and temperature for current collector materials [33]

Gan Tao [34] used kerosene and n-dodecane as collectors and methyl isobutyl carbinol as a frother, increasing $LiCoO_2$ grade from 69.9% to 87.2%. Thermal treatment (550 °C pyrolysis or 450 °C roasting) removed surface organics, further raising $LiCoO_2$ concentrate grade to 98.0%, achieving efficient separation of cathode and anode materials.

4 Biological Methods

Biological methods typically employ chemoautotrophic acidophilic bacteria, utilizing elemental sulfur and Fe^{2+} as energy sources to metabolically produce H_2SO_4 and Fe^{3+}. These metabolites leach metals via chemical dissolution, highlighting the unique synergy between biotechnology and hydrometallurgy [35]. Certain microorganisms (e.g., Aspergillus niger, Acidithiobacillus ferrooxidans) achieve high leaching rates for lithium, cobalt, and nickel—with lithium leaching reaching up to 100%—though manganese leaching remains low (~20%). Biological leaching selectively recovers valuable metals from spent batteries at ambient temperature, offering advantages of low energy consumption and low pollution. Key influencing factors are summarized in Figure 14.

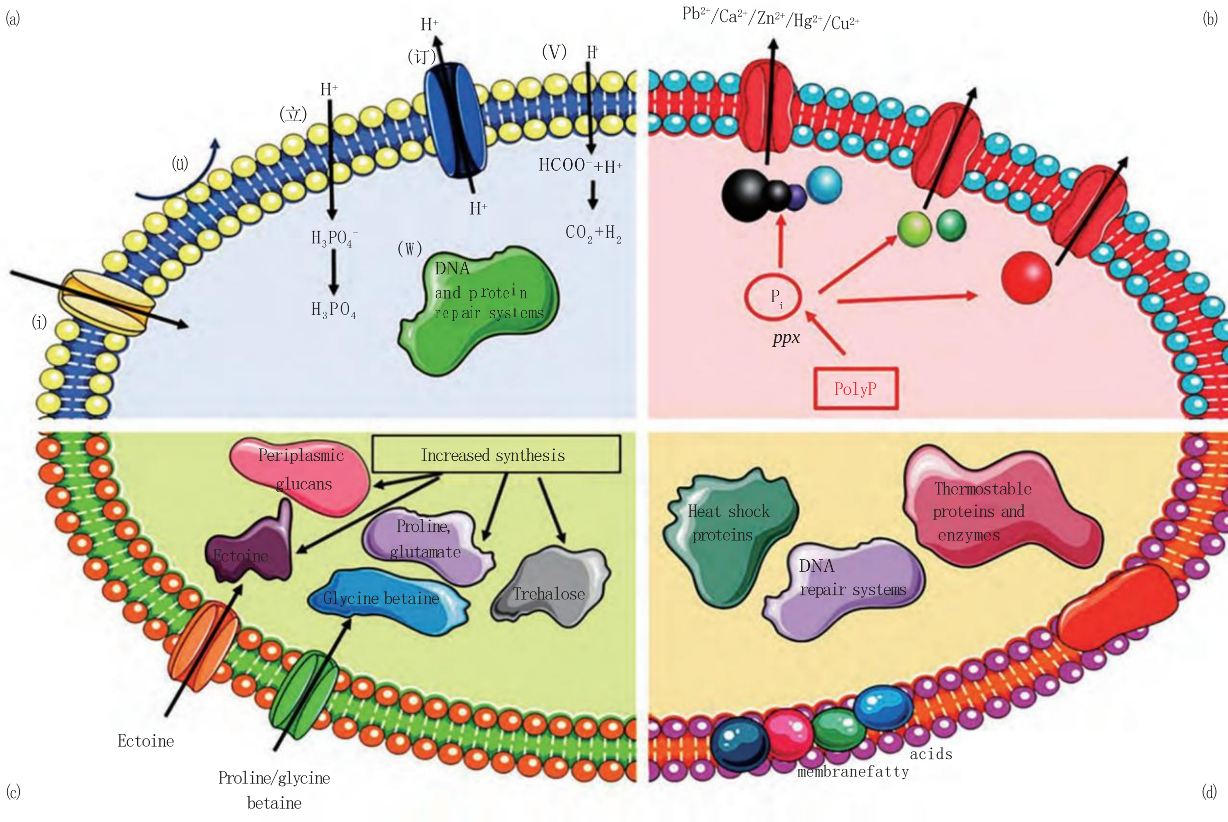

Figure 14 Influencing factors of bioleaching:(a)Acidity;(b)Metal toxicity;(c)Temperature;(d)Permeability [36]

5 Conclusions and Future Outlook

The exponential growth of the lithium-ion battery (LIB) industry, driven by the global transition to electrified transportation and renewable energy storage, has precipitated an unprecedented challenge: the management of end-of-life batteries. As detailed in this review, spent LIBs are not merely hazardous waste but a high-concentration "urban mine" of strategic metals, including lithium, cobalt, and nickel. The efficient recovery of these resources is paramount for ensuring supply chain security, mitigating the environmental impact of primary mining, and achieving global carbon neutrality goals. This review has systematically examined the technical principles, process routes, and performance metrics of physical, chemical, and biological recycling methods, highlighting the evolution from rudimentary smelting to sophisticated, multi-stage recovery systems. While significant progress has been made, the transition from linear economic models to a truly circular battery economy remains incomplete.

Summary of Current Technologies

Physical separation methods constitute the critical gateway for all recycling operations, transforming hazardous, heterogeneous battery packs into safer, more homogeneous streams. As discussed, techniques such as crushing, sieving, and density-based separation (e.g., Nelson centrifugal concentration) are effective for coarse liberation. However, the true advancement lies in the precision of modern sorting. High-gradient magnetic separation (HGMS) exploits the paramagnetic nature of cathode materials versus the diamagnetic nature of graphite, achieving carbon purification levels exceeding 91%. Similarly, eddy current separation and photoelectric sorting have demonstrated remarkable efficacy in reclaiming high-purity copper (99.95%) and aluminum (99.94%) from shredded mixtures. These processes significantly reduce the entrainment of impurities that would otherwise complicate downstream metallurgical operations.

Chemical methods remain the backbone of metal recovery, bridging the gap between concentrated black mass and high-purity battery-grade materials. Pyrometallurgy, despite its robustness, is increasingly viewed as unsustainable due to high energy consumption and the irreversible loss of lithium into slag. Conversely, hydrometallurgical processes dominate current industrial practice due to their high selectivity and recovery rates (>95%). Innovations such as galvanic leaching leverage the residual energy within spent batteries to drive reductive dissolution, achieving lithium recovery rates exceeding 99% without external reagents. Furthermore, integrated "pyro-hydrometallurgical" short-flow processes—specifically reductive roasting followed by water leaching—have proven effective in preferentially extracting lithium while leaving nickel, cobalt, and manganese in the solid residue for subsequent acid leaching. This synergistic approach optimizes energy use and minimizes reagent consumption.

Biological methods represent the frontier of green recycling. By harnessing chemoautotrophic bacteria (e.g., Acidithiobacillus ferrooxidans) or fungi (e.g., Aspergillus niger), these processes operate at ambient temperature and pressure, drastically reducing the carbon footprint. While promising, the industrial deployment of bioleaching is currently hindered by slow kinetics, sensitivity to pulp toxicity, and the challenge of scaling up bioreactors.

Future Outlook and Strategic Directions

To realize a sustainable and economically viable battery recycling ecosystem, future research must transcend incremental improvements and pursue transformative innovations. The following strategic directions are recommended:

1. Intelligentization and Digital Integration.

The current recycling chain is largely fragmented, with limited feedback between sorting stages. The future lies in fully automated, AI-driven facilities. Machine vision and deep learning algorithms should be deployed to identify battery chemistries and states of health in real-time, allowing robotic systems to execute adaptive disassembly strategies. Digital twin technology should be utilized to create virtual replicas of the recycling plant, simulating material flows and optimizing process parameters (e.g., magnetic field intensity, airflow velocity) dynamically. This shift from "experience-driven" to "data-driven" operations will maximize resource efficiency and minimize operational costs.

2. Direct Regeneration and Short-Flow Processes.

The conventional route of breaking down materials to the molecular level and resynthesizing them is energy-intensive and costly. A paradigm shift toward direct regeneration is imperative. Instead of leaching metals, future technologies should focus on repairing the crystal structure of spent cathodes. Techniques such as solid-state sintering with replenished lithium sources, or hydrothermal relithiation, can heal cracks and restore the layered structure of NCM or LFP materials. This preserves the embedded energy of the original material and reduces the carbon footprint of remanufacturing. Concurrently, research into green leaching agents—such as deep eutectic solvents (DES) or bio-based organic acids—should replace conventional inorganic acids to eliminate secondary pollution.

3. Compatibility and Flexibility for Diverse Battery Streams.

The market is flooded with a diverse array of battery formats (prismatic, cylindrical, pouch) and chemistries (LFP, NCM, NCA, LMO). Existing recycling lines are often rigid and chemistry-specific. Future infrastructure must be flexible ("flex-factories") to handle this heterogeneity. This requires universal pre-treatment platforms capable of automatically adjusting crushing and sorting parameters based on incoming feedstock. Special attention should be given to the low-value, high-volume LFP batteries. Novel processes must be developed to either upgrade iron phosphate into high-value products or to recover lithium selectively while converting phosphorus into benign, stable compounds, thereby solving the current problem of iron-phosphate slag disposal.

4. Life Cycle Assessment (LCA) and Business Model Innovation.

Technical feasibility is no longer sufficient; economic and environmental viability must be quantified. Comprehensive LCA studies are needed to calculate the net carbon footprint of recycling processes, ensuring that the energy saved by recycling metals outweighs the energy consumed in the process. Policymakers should incentivize "Battery Passports" that track a battery's composition and carbon footprint throughout its life. Furthermore, business models such as "Battery-as-a-Service" (BaaS) should be promoted to standardize battery design for recyclability (Design for Recycling), creating a closed-loop ecosystem where materials flow seamlessly from production to reuse to high-value recycling.

In conclusion, the recycling of spent lithium-ion batteries stands at a critical juncture. By integrating intelligent automation, pursuing direct regeneration, ensuring process flexibility, and adhering to rigorous lifecycle standards, the industry can overcome current limitations. The ultimate goal is to transform the battery recycling sector from a waste management burden into a cornerstone of the green economy, securing the resources necessary for a sustainable energy future.

References

[1] Qiu Jiangen, Wang Chao, Li Yongqiang, et al. Progress in recycling technology of spent lithium-ion batteries under background of carbon peaking and carbon neutrality. Recycling Research, 2024, 17(12): 42–46.

[2] Wang Yi. Surface and interfacial properties of high voltage layered oxide cathode materials for lithium batteries. Beijing: University of Chinese Academy of Sciences (Institute of Physics, Chinese Academy of Sciences), 2019.

[3] Liu Yang, Liu Wenbo, Zheng Feng, et al. Three "godfathers" of lithium battery win the 2019 Nobel Prize in Chemistry. Chinese Journal of Nature, 2019, 41(6): 407–413.

[4] Xu Mao, Liu Dong, Wang Dezhao. Analysis on echelon utilization of retired lithium iron phosphate power battery. Chinese Journal of Power Sources, 2020, 44(8): 1227–1230.

[5] Zhao Dongmei, Li Zhenwei, Liu Lingdi, et al. Progress of preparation and application of graphene/carbon nanotube composite materials. Acta Chimica Sinica, 2014, 72(2): 185–200. (in Chinese)

[6] Jiang Kai, Li Haomiao, Li Wei, et al. On several battery technologies for power grids. Automation of Electric Power Systems, 2013, 37(1): 47–53.

[7] Zhao Siqi. Study on recycling of spent power lithium-ion batteries, and analysis on renovation process and mechanism of cathode materials. Shanghai: Tongji University, 2022.

[8] Wang Yanhong, Zhang Lei, Wang Chaoyue, et al. Recent progress of layered Ni-rich co-free positive electrode materials for high-performance lithium-ion batteries. Nonferrous Metals, 2025, 15(4): 544–555.

[9] Tarascon J M, Armand M. Issues and challenges facing rechargeable lithium batteries. Nature, 2001, 414(6861): 359–367.

[10] Huang Weixin. Fundamental research on multi-physical field separation and grading of waste LFP battery powder from retired $LiFePO_4$ batteries. Changsha: Central South University, 2022.

[11] Celep O, Yazici E Y, Deveci H. Recovery of silver and barite from the plant tailings of a refractory silver ore by knelson concentrator. In: 15th International Mineral Processing Symposium, Istanbul, Turkey, October 19–21, 2016.

[12] Lu Shijie, Zhou Hongxi, Lang Pingzhen, et al. Experimental research of spent traction battery broken materials fine crushing and powdering. Nonferrous Metals (Mineral Processing Section), 2021(3): 62–68.

[13] Zhong Xuehu. Fundamental research on recycling of spent $LiFePO_4$ batteries and regeneration of cathode active materials. Changsha: Central South University, 2023.

[14] Zhang Yu. Basic research on active pulsing airflow separation of current collectors from spent LIBs. Xuzhou: China University of Mining and Technology, 2018.

[15] Zhu Xueshuai, Sun Tao, Song Zhao, et al. Research progress on airflow separation technology. Clean Coal Technology, 2024, 30(1): 22–30.

[16] Zhao Lulu, Zhang Yukui, Wang Rong, et al. Thermal runaway mechanism of lithium ion batteries. Nonferrous Metals Engineering, 2024, 14(1): 23–31.

[17] Gan Tao, Song Weifeng, Liu Yong, et al. Magnetic separation mechanism and purification process of spent battery electrode materials. The Chinese Journal of Nonferrous Metals, 2021, 31(12): 3664–3674.

[18] Gan Tao, Song Weifeng, Liu Yong, et al. Separation process of mixed electrode materials for waste lithium iron phosphate power battery. Nonferrous Metals (Mineral Processing Section), 2022(3): 26–33. (in Chinese)

[19] He Shuanghua. Analysis and experimental study on the wind separation characteristics of shredded lithium iron phosphate battery waste. Hefei: Hefei University of Technology, 2018.

[20] Li Jianbo. Study on the physical separation and recovery process of spent lithium ion power batteries. Beijing: General Research Institute for Nonferrous Metals, 2018.

[21] Cui Guijin. Study on separation of wheat scab by photoelectric separation technology. Zhengzhou: Henan University of Technology, 2013.

[22] Zhang Xianmei. The design and implement of the photoelectric sorter measurement and control system. Dalian: Dalian University of Technology, 2006.

[23] Sotoudeh F, Nehrung M, Kizil M, et al. Integrated underground mining and pre-concentration systems; a critical review of technical concepts and developments. International Journal of Mining, Reclamation and Environment, 2021, 35(3): 153–182.

[24] Ding Siyi, Huang Kui, Zhai Ruijiao, et al. Extraction of valuable metals from waste ternary lithium-ion battery cathode materials using phospho-glutathione system. Nonferrous Metals, 2025, 15(3): 506–513.

[25] Chen Juan, Zhang Chenglong, Zhang Xihua, et al. Separation of waste lithium iron phosphate batteries and regeneration of positive electrode materials. Nonferrous Metals Engineering, 2024, 14(1): 151–159.

[26] Huang Cheng. Research on recycling and reusing the layered oxide cathode materials of spent lithium-ion batteries. Hefei: Hefei University of Technology, 2022.

[27] Shentu Huajian. Research on green recycling technology of $LiFePO_4$ cathode materials for retired lithium-ion battery. Ningbo: Ningbo Institute of Material Technology, Chinese Academy of Sciences, 2021.

[28] Makuma B, Tian Q H, Guo X Y, et al. Pyrometallurgical options for recycling spent lithium-ion batteries: a comprehensive review. Journal of Power Sources, 2021, 491: 229622.

[29] Yu J D, Liu Y J, Li J H. Galvanic leaching recycling of spent lithium-ion batteries via low entropy-increasing strategy. Nature Communications, 2025, 16: 2440.

[30] Xu Jinmei, Gao Yanfeng. Research progress on green recovery technologies of valuable metals from waste lithium batteries. Scientia Sinica (Technologica), 2025, 55(4): 630–661.

[31] Long Guangwu. Recovery and restoration of valuable metals from waste lithium ion batteries. Ganzhou: Jiangxi University of Science and Technology, 2024.

[32] Zheng Rujuan. The resynthesis and reuse from materials of spent lithium ion batteries of phosphate and mixture. Harbin: Harbin Institute of Technology, 2017.

[33] Liu Jiangshan. Research on low-temperature crushing, grinding and flotation of spent lithium-ion battery electrode materials. Xuzhou: China University of Mining and Technology, 2020.

[34] Gan Tao. Study on magnetic separation mechanism and technology of electrode materials for waste lithium ion batteries. Guangzhou: Guangdong University of Technology, 2021.

[35] Chen Lingyu, Ye Lingxiao, Wang Xiangjin, et al. Research progress on the recycling process of cathode materials of decommissioned lithium-ion batteries. Chemical Engineer, 2025, 39(1): 70–74.

[36] Roy J J, Cao B, Madhavi S. A review on the recycling of spent Lithium-Ion Batteries (LIBs) by the bioleaching approach. Chemosphere, 2021, 282: 130944.