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Lithium-Ion Battery Waste Management: A Scoping Review Of Recycling Technologies, Environmental Impacts, And Policy Frameworks

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Abstract

The rapid growth of electric vehicles and renewable energy systems has driven unprecedented demand for lithium-ion batteries (LIBs), generating substantial volumes of hazardous end-of-life battery waste with serious environmental and public health implications. This scoping review aims to map the current state of evidence on LIB waste management, encompassing recycling technologies, environmental and health impacts, and governing policy frameworks. A systematic literature search was conducted across Scopus, ScienceDirect, SpringerLink, and Google Scholar, restricted to peer-reviewed articles published between 2020 and 2025. Results indicate that pyrometallurgy, hydrometallurgy, and direct physical recycling each present distinct trade-offs in recovery efficiency, energy demand, and secondary waste generation, with no single approach universally superior. Life cycle assessments demonstrate that environmental outcomes are strongly influenced by energy source, reagent use, and geographic context. Improper LIB disposal poses documented risks including heavy metal leaching, toxic gas release, and fire hazards. Policy frameworks remain inconsistent across jurisdictions, and collection infrastructure is particularly inadequate in developing countries, including Indonesia. This review concludes that sustainable LIB waste management requires an integrated approach combining technological development, comprehensive impact assessment, and robust regulatory governance adapted to local conditions.

Keywords: lithium-ion battery; waste management; recycling technology; life cycle assessment; circular economy

INTRODUCTION

The global transition toward electric vehicles and renewable energy infrastructure has firmly established lithiumion batteries (LIBs) as the backbone of modern energy systems, with a

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market value projected at around USD 44 billion in 2020 and EV sales estimated to reach approximately 245 million units by 2030 (Miao et al., 2022; IEA, 2023). This surge in demand for LIBs has simultaneously intensified pressure on critical raw materials such as lithium, cobalt, nickel, manganese, and graphite, exposing structural vulnerabilities in their global supply chains. Over the period 2018–2019 alone, lithium consumption increased by about 18%, while projected demand by 2050 is expected to surpass recoverable reserves by some 40 million tonnes, prompting the European Union to expand its list of critical raw materials from 14 to 30 substances (Miao et al., 2022; Rajaeifar et al., 2022). This confluence of resource scarcity, geopolitical concentration, and environmental stress has elevated LIB waste management from a mere technical concern to a strategic priority for sustainable industrial development (Miao et al., 2022; Chen et al., 2022).

Regionally, the implications are particularly acute in developing economies, where rapid urbanization and electrification are accelerating both the deployment of EVs and the proliferation of consumer electronics reliant on LIBs. Indonesia, for example, is witnessing a growing stock of electric twowheelers, mobility services, and household energy storage systems, yet formal frameworks for collecting and processing end-of-life batteries remain underdeveloped (Vongdala et al., 2022; Chowdhury et al., 2023). In such contexts, LIBs often enter the general waste stream or are informally disposed of, exposing informal workers and surrounding communities to toxic substances and fire hazards (Chen et al., 2022; Mrozik et al., 2021). Empirical surveys in Southeast Asia and the Global South further highlight that public awareness of proper battery disposal is limited, and collection infrastructure is fragmented, underscoring the urgency of integrating technical, environmental, and policy considerations into cohesive national strategies (Islam et al., 2022; Agarwal et al., 2023).

A substantial body of literature now attests to the environmental and public health risks of mismanaged LIB waste. Global LIB waste is estimated at about 250,000 tonnes in 2020, with projections indicating a five to sixfold increase in the European Union alone by 2030 (Miao et al., 2022; Mrozik et al., 2021). Under landfill conditions, spent LIBs can leach substantial fractions of lithium and manganese into leachate, alongside cobalt, nickel, copper, and lead, thereby contaminating soil and groundwater (Mrozik et al., 2021; Bolan et al., 2021). In addition, toxic electrolyte components such as $LiPF_6$ and organic carbonate solvents, as well as thermal degradation products like hydrogen fluoride from PVDF binders, contribute to air and water pollution and pose significant occupational risks during uncontrolled disposal or crude recycling (Chen et al., 2022; Mrozik et al., 2021). Ecotoxicological studies further demonstrate adverse effects of lithium battery residues on soil organisms and aquatic systems, reinforcing the view

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that lithium should be treated as an emerging environmental contaminant with implications for broader food chain exposure (Bolan et al., 2021; Chow et al., 2022).

Parallel to these environmental concerns, the economic rationale for systematic LIB recycling is well documented. Spent LIBs contain cobalt at 5–20%, nickel at 5–10%, and lithium at 5–7% by weight—concentrations that are roughly 10 times higher than those in primary lithium ore and 30 times higher than lithium brine, yielding an estimated intrinsic material value of approximately USD 7,708 per tonne (Miao et al., 2022; Zhang, 2024). The market price of lithium carbonate exceeded USD 17,000 per metric tonne in 2018, and the material content of a single EV battery pack is comparable to that of around 1,000 smartphones, underscoring the scale of embedded value (Bae & Kim, 2021; Miao et al., 2022). Nevertheless, global lithium recycling rates remain below 1%, cobalt recovery from portable LIBs in Europe reaches only about 22%, and LIB collection rates in the EU, the United States, and Australia hover between 2% and 5% (Miao et al., 2022; Takacova et al., 2023). These discrepancies highlight that the barrier to realizing this economic potential lies not primarily in chemical limitations but in systemic failures—insufficient collection infrastructure, inconsistent regulatory frameworks, weak economic incentives, and battery designs that do not anticipate end-of-life management (Melin et al., 2021; Thompson et al., 2020; Bird et al., 2022).

Within the domain of recycling technologies, scholars have mapped a diverse spectrum of options, including pyrometallurgy, hydrometallurgy, biohydrometallurgy, electrochemical recovery, and more recently direct physical recycling (DPR), each displaying distinct tradeoffs in recovery efficiency, energy intensity, and secondary waste generation (Bae & Kim, 2021; Duan et al., 2022; Yu et al., 2024). Life cycle assessments further indicate that the environmental performance of these pathways is highly context dependent, shaped by factors such as energy mix, reagent consumption, and pretreatment quality, and that no single technology is universally superior (Mohr et al., 2020; Petzold & Flamme, 2024). In parallel, policy analyzes emphasize that the integration of extended producer responsibility (EPR), battery passports, secondlife cascades, reverse logistics, and consumer engagement is essential for closing the gap between theoretical recovery potential and actual material flows (Islam & IyerRaniga, 2022; Melin et al., 2021; Bird et al., 2022). Despite these advances, critical syntheses that regularly connect environmental, technical, economic, and governance dimensions of LIB waste management remain scarce, especially in developing country contexts (Chowdhury et al., 2023; Mohr et al., 2020).

Against this backdrop, the present scoping review aims to map the current state of evidence on LIB waste management, with a particular focus on the interplay between recycling

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technologies, environmental and health impacts, and policy frameworks. The study addresses three interconnected questions: (1) how different recycling pathways shape material recovery and environmental outcomes; (2) what environmental and public health risks are associated with improper LIB disposal; and (3) how existing policy frameworks mediate the feasibility and effectiveness of LIB recycling, particularly in developing economies such as Indonesia. By adopting a systematic scoping review methodology and synthesizing recent literature published between 2020 and 2025, this review intends to clarify the research gaps and inconsistencies in the field, by contributing both theoretically—by advancing an integrated framework for LIB waste management—and practically—by informing policy design, infrastructure development, and safer technology deployment in resource-constrained settings (Miao et al., 2022; Mohr et al., 2020; Chowdhury et al. al., 2023).

METHOD

This study was conducted using a qualitative approach with a scoping review methodology. This methodology was deliberately chosen to ensure that the processes of literature collection, selection, and analysis could be carried out in a transparent, structured, and reproducible manner — criteria that are especially important when synthesizing evidence across diverse disciplines including environmental science, materials technology, and waste governance.

Literature searches were conducted across four major scientific databases: Scopus, ScienceDirect, SpringerLink, and Google Scholar. These databases were selected on the basis of their broad and complementary coverage of peer-reviewed publications in the fields of environmental health, energy systems, and materials sciences. Searches were performed using Boolean operator combinations to maximize both the relevance and breadth of retrieved results:*("lithium battery" OR "lithium-ion" OR "Li-ion" OR "battery waste") AND ("waste management" OR "recycling" OR "disposal" OR "treatment") AND ("environmental impact" OR "sustainability" OR "pollution" OR "hazardous waste") AND ("collection" OR "processing" OR "storage" OR "regulation") AND ("circular economy" OR "resource recovery" OR "reuse" OR "life cycle")*

Searches were restricted to publications from 2020 to 2025 to capture the most current evidence reflecting recent developments in lithium battery waste management practice and policy. Articles were included if they addressed the management of lithium-ion battery waste, were published between 2020 and 2025, were written in English or Indonesian, were peer-reviewed scientific articles, and focused on environmental, recycling, or waste management

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policy dimensions. Articles were excluded if they did not specifically address lithium batteries, focused solely on electrochemical performance without waste management relevance, were identified as duplicates, or were unavailable in full text.

Data were extracted from each included article, covering author(s), year of publication, study location, waste management methods examined, relevant policy frameworks discussed, and identified environmental and health impacts. The scoping review approach enabled analysis to be conducted both descriptively and comparatively, with the aim of mapping the breadth of available evidence, identifying global trends, and highlighting research gaps.

RESULTS AND DISCUSSION

The studies reviewed encompass analyzes of recycling technologies, collection systems and policy frameworks, and assessments of the environmental and health impacts associated with improper lithium battery disposal. The reviewed literature can be broadly grouped into three thematic areas: (1) recycling and waste management technologies, (2) policy frameworks and collection systems, and (3) environmental and health impacts. The following table presents a structured summary of the reviewed studies, including their methods and key findings.

Table 1 Summary of the literature review on the technology and environmental impacts of lithium-ion battery waste management

No	Source (link/DOI)	Title	Methods	Main Results
1	10.3390/batteries10100337	"Recycling of Lithium-Ion Batteries via Electrochemical Recovery: A Mini-Review"	Short literature review on techniques used in lithium-ion battery recycling processes	Electrochemical recovery methods, particularly leaching and electrodeposition, offer a more cost-effective and environmentally friendly recycling solution compared to conventional approaches [21]
2	10.3390/ma16124264	*"Current Trends in Spent Portable Lithium Battery Recycling"*	Review of recycling techniques for spent portable lithium batteries, covering pre-treatment, hydrometallurgy, and pyrometallurgy stages	Hydrometallurgy is more effective than pyrometallurgy for lithium recycling, yielding higher metal recovery rates and lower energy consumption [17]
3	10.1021/acssuschemeng.1c04938	*"Environmental Impacts of Graphite*	Life cycle assessment (LCA) to evaluate the environmental	The combination of hydrometallurgical and pyrometallurgical processes in graphite recycling from spent LIBs yields

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		Recycling from Spent Lithium-Ion Batteries Based on Life Cycle Assessment"	impacts of graphite recycling from spent lithium batteries	more environmentally favorable outcomes [16]
4	10.1515/ntrev-2020-0119	*"High-efficiency method for recycling lithium from spent LiFePO4 cathode"*	Wet process involving lithium extraction from LiFePO4 using HCl and NaClO interaction to dissolve Li^+ ions	An efficient lithium extraction method from LiFePO4 achieving an average total recovery rate of 97% through purification and solvent extraction [20]
5	10.3390/recycling7030033	*"Lithium-Ion Battery Recycling in the Circular Economy: A Review"*	Literature review on the integration of lithium-ion battery recycling into the circular economy	Transitioning toward a circular economy for lithium batteries requires the integration of recycling technology advancements with holistic lifecycle management strategies [9]
6	10.3390/en15051611	*"Recycling of Lithium Batteries—A Review"*	Literature review of lithium battery recycling technologies including pyrometallurgy, acid leaching, solvent extraction, electrochemical methods, chlorination, and ammoniation	Each recycling technology presents distinct advantages and limitations; future research directions are proposed to achieve more efficient, economically viable, and environmentally sound recycling processes [7]
7	10.1039/D0GC02745F	*"The importance of design in lithium ion battery recycling–a critical review"*	Literature review examining lithium battery recycling challenges from design, economic, and environmental sustainability perspectives	Emphasizes the importance of battery design — such as module-free packs and reversible adhesives — as an integral recycling strategy rather than merely an end-of-pipe solution [18]
8	10.1039/D1MA00216C	"Technologies of lithium recycling from waste lithium ion batteries: a	Literature review covering pre-treatment and extraction stages of spent lithium-ion	A comprehensive review of lithium battery recycling technologies comparing efficiency, cost, and environmental impact to support the transition toward a sustainable circular economy [1]

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		review"	battery recycling processes	
9	10.1007/s11356-022-19681-2	"Waste battery disposal and recycling behavior: a study on the Australian perspective"	Literature review on consumer perspectives and behavior in waste battery recycling in Australia	Consumer behavioral factors — grounded in knowledge, socioeconomic status, and convenience — are key considerations in designing effective battery collection and recycling schemes [8]
10	10.1371/journal.pone.0303933	"Economic benefit analysis of lithium battery recycling based on machine learning algorithm"	Development of an economic benefit analysis model for lithium battery recycling termed SR-BPNN (Stepwise Regression Backpropagation Neural Network)	The SR-BPNN model demonstrates a high success rate of 98% and proves financially advantageous for recycling operations [22]
11	10.3390/met14020151	"Recycling Strategies for Spent Consumer Lithium-Ion Batteries"	Literature review analyzing the lithium battery market, spent battery return volumes, and sorting technologies	Automated sorting based on cathode material type using X-ray and optical sensor technologies significantly improves economic efficiency and supports the achievement of recycling targets [15]

Based on the reviewed literature, lithium-ion battery (LIB) waste management technologies generally consist of three main stages: pre-treatment, material recovery, and final purification. The pre-treatment stage includes discharging, dismantling, and mechanical and/or thermal separation to reduce safety hazards and improve the efficiency of downstream processes. This stage is considered critical given that spent lithium batteries carry significant reactivity and fire risk if not handled correctly.2,3

Material recovery is broadly approached through three pathways: pyrometallurgy, hydrometallurgy, and hybrid combinations of the two. Pyrometallurgy utilizes high temperatures to recover valuable metals and is relatively tolerant of variability in feed composition; however, it carries well-documented disadvantages including high energy consumption and emission generation.[5],[6] Hydrometallurgy, by contrast, has been more extensively studied in recent years owing to its capacity to operate under milder conditions and its greater selectivity in recovering metals such as lithium, cobalt, nickel, and manganese.[3],[10] Several studies confirm that hydrometallurgical routes consistently outperform pyrometallurgical approaches in terms of metal recovery yield and energy efficiency, particularly for portable and consumer-grade cells.[10]

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A number of studies have highlighted the recovery of specific materials — notably lithium from $LiFePO_4$ cathodes — underscoring the importance of leaching process selectivity in maximizing recovery efficiency while minimizing secondary waste generation. One wet-process approach employing HCl and NaClO interaction achieved a mean total lithium recovery rate of 97%, demonstrating that high-purity recovery is technically achievable with appropriate process design. Beyond cathode materials, more recent literature has begun directing attention toward anode graphite recycling, a component that has historically been overlooked despite constituting a substantial fraction of battery mass and carrying significant environmental implications. Life cycle assessments across multiple graphite recycling methods report global warming potentials ranging from 0.53 to 9.76 kg CO_2 equivalent per kilogram recovered, with the chemical purification stage consistently identified as the primary environmental hotspot due to large reagent volumes involved.

From an environmental impact perspective, several LCA studies make clear that LIB recycling does not automatically produce better environmental outcomes than primary extraction. The environmental profile of any given recycling process is heavily determined by technology type, energy source, acid consumption, and residue management practices. This finding carries important implications for how recycling is evaluated — recovery rate alone is an insufficient metric, and the broader environmental burden of the process must be assessed holistically.

Beyond environmental impacts, the reviewed literature also raises concerns regarding health and ecotoxicological risks associated with lithium battery waste. Toxicological studies on soil organisms — including earthworms and gastropods — have documented adverse effects of lithium battery residue exposure on survival rates and biological function. These findings reinforce the position that uncontrolled disposal of spent lithium batteries generates genuine ecological and long-term public health risks, not merely a materials management problem.

DISCUSSION

The reviewed evidence makes clear that no single recycling technology is superior across all dimensions. Pyrometallurgy offers process robustness and the ability to handle heterogeneous battery chemistries without extensive pre-treatment, but it is comparatively inefficient in terms of energy and environmental performance. Hydrometallurgy delivers higher recovery efficiency and greater process flexibility, yet generates liquid waste streams and demands rigorous chemical management. This trade-off is why the bulk of current literature

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converges on recommending hybrid process approaches as the most practical compromise between technical efficiency and environmental sustainability.

The principle of design for recycling is receiving growing emphasis across the literature, and rightly so. Battery designs that facilitate easier dismantling, favor material compatibility, and minimize the use of hazardous adhesives have been shown to improve occupational safety and reduce end-of-life environmental burden considerably. As one critical review notes, battery design must be treated as an integral component of recycling strategy rather than as a separate engineering concern addressed only at the end-of-pipe stage. The persistence of PVDF binder systems — soluble only in the toxic solvent NMP — as a standard in electrode manufacturing exemplifies how upstream design decisions can structurally constrain downstream recycling options.

From an environmental and public health standpoint, the literature is unambiguous: lithium battery waste management cannot be oriented solely around the economic recovery of valuable materials. Toxicological risk, soil and groundwater contamination potential, and fire hazards during collection and transport collectively demand the application of rigorous safety standards and hazardous waste management protocols throughout the battery lifecycle. LCA findings further reinforce this point — optimizing recycling technology must account for energy consumption, emissions, and secondary waste generation, not merely material recovery rates.[4]

In the context of developing countries, including Indonesia, the principal challenges in LIB waste management lie in infrastructure limitations, technological readiness, and the absence of integrated collection systems. The available literature suggests that without adequate management systems in place, spent lithium batteries are likely to enter the general household waste stream, substantially elevating environmental and health risk. Technology adoption in such settings therefore needs to be calibrated to local conditions — industrial capacity, energy availability, and hazardous waste management capability — rather than defaulting to the most technically advanced approaches developed for high-income contexts. A phased approach emphasizing safety, environmental risk reduction, and incremental capacity building is more realistic and ultimately more sustainable than attempting to transplant complex industrial-scale technologies without the necessary supporting infrastructure.

Several research gaps emerge clearly from this review. First, there remains a striking shortage of studies that integrate recycling technology evaluation with direct health impact assessment, particularly in developing country contexts. Second, anode graphite recycling continues to receive disproportionately little attention relative to cathode metal recovery, despite its significant mass contribution and environmental implications. Third, LCA studies

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grounded in local conditions — accounting for regional energy mixes, waste management systems, and environmental characteristics — are largely absent from the literature, limiting the applicability of existing findings to non-European and non-North American settings. Fourth, the intersection of occupational safety and toxicology with recycling technology choices remains underexplored. These gaps point to a clear need for future research that integrates technical, environmental, and health dimensions comprehensively in support of sustainable lithium battery waste governance.

CONCLUSION

The results of this review indicate that the management of lithium-ion battery scrap requires an integrative approach, combining recycling technology options, environmental and health impact assessments, and a consistent policy framework. Technically, no single recycling pathway is inherently superior; pyrometallurgy, hydrometallurgy, and hybrid approaches each offer different trade-offs between material recovery efficiency, energy consumption, and secondary waste generation, so the strongest recommendation favors a combination of processes tailored to local infrastructure readiness and energy characteristics. Environmentally and health-wise, unsafely managed lithium-ion battery scrap can potentially lead to heavy metal releases to soil and water, contamination by electrolyte components and degradation products, and the risk of fire and occupational accidents. Therefore, waste management systems must prioritize safety and hazardous waste standards, not just the quantity of material recovered. Policy-wise, regulatory misalignment and weak collection infrastructure, particularly in developing countries like Indonesia, hinder closing the gap between theoretical recycling potential and actual material flows, necessitating the development of an expanded producer responsibility framework, battery passports, reverse logistics strategies, and consumer education.

The limitations of this study are primarily related to the focus on English-language literature and the publication period of 2020–2025, which may have overlooked some emergent and locally contextual studies that have not yet been formally published, as well as the limited availability of empirical data on worker and community health impacts in developing countries. Further research is recommended incorporating local context-specific life cycle assessments, studies of toxicology and direct health risks, and technological economic studies that consider industrial capacity and domestic waste systems. Practically, these results imply the need for integration of national policies in the fields of energy, environment, and health, strengthening

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inter-agency coordination, and gradual investment in technology and human resources to ensure a transition to a sustainable and safe lithium battery circular economy for society.

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