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ENVIRONMENTAL ASPECTS OF SAFE MANAGEMENT OF LITHIUM-ION BATTERY WASTE: A LITERATURE REVIEW

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ABSTRACT: The growing use of lithium-ion batteries – particularly in e-mobility and consumer electronics – calls for the development of effective methods for their collection, transport, storage, and processing. These batteries contain valuable raw materials – lithium, cobalt, nickel, and manganese – that are essential to modern technologies. Improper handling of spent batteries poses serious environmental and health hazards, including the risk of overheating, fires, and explosions. A specific concern is the water used to extinguish battery fires, which can carry toxic substances into surface water and groundwater. As the number of batteries in circulation increases, it becomes crucial to implement regulations and technologies that ensure safe storage, such as temperature and gas detection systems. At the same time, recycling aligned with circular economy principles helps reduce dependence on primary raw materials and lessen environmental pressure. Examples include systems for recovering critical metals and initiatives aimed at simplifying disassembly, using biodegradable materials, and standardising cell design. A comprehensive approach to end-of-life battery management enhances safety, resource efficiency, and environmental protection. This article provides a concise synthesis of safety issues and the sustainable management of end-of-life lithium-ion batteries. It presents the mechanisms by which hazards arise, including the initiation and propagation of thermal runaway, and discusses risk-mitigation measures such as optimising separator design, early fault detection through battery management systems (BMS), and engineering solutions for battery thermal management. The European regulatory framework for batteries is reviewed and summarised. The main recycling pathways are compared, and the binding European Union targets relevant to the circular economy are listed.

KEYWORDS: environmental hazard, lithium-ion batteries, waste management

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List of Abbreviations:

ADR – European Agreement concerning the International Carriage of Dangerous Goods by Road
BMS – Battery Management System
CCS – Carbon Capture and Storage
CFD – Computational Fluid Dynamics
EPR – Extended Producer Responsibility
IATA – International Air Transport Association (Dangerous Goods Regulations)
ICAO – International Civil Aviation Organisation
IMDG – International Maritime Dangerous Goods Code
LCA – Life – Cycle Assessment
LFP – Lithium Iron Phosphate (cathode chemistry)
LIB / LIBs – Lithium-Ion Battery / Batteries
NMC – Nickel – Manganese – Cobalt (cathode chemistry)
PCM – Phase-Change Material
RID – Regulations concerning the International Carriage of Dangerous Goods by Rail
SOC – State of Charge

Introduction

Climate change necessitates a global eco-transformation, encompassing both emission reduction and the implementation of innovative energy technologies. Carbon dioxide emissions serve as a key indicator of progress in this transformation, as they reflect the extent to which fossil fuels are being replaced by cleaner energy sources (Shahbazi & Nasab, 2016). Understanding these trends is essential for planning the further decarbonization of the economy and the development of sustainable technologies. Eco-transformation requires systematic monitoring of emissions to effectively mitigate human impact on the climate and build a secure future. One of the crucial solutions in this process is carbon capture and storage (CCS) technology, which can significantly reduce industrial emissions (Shahbazi & Nasab, 2016). At the same time, the advancement of renewable energy sources and efficient energy storage systems – such as lithium-ion batteries – forms the foundation for constructing a low-emission economy, as illustrated in Figure 1.

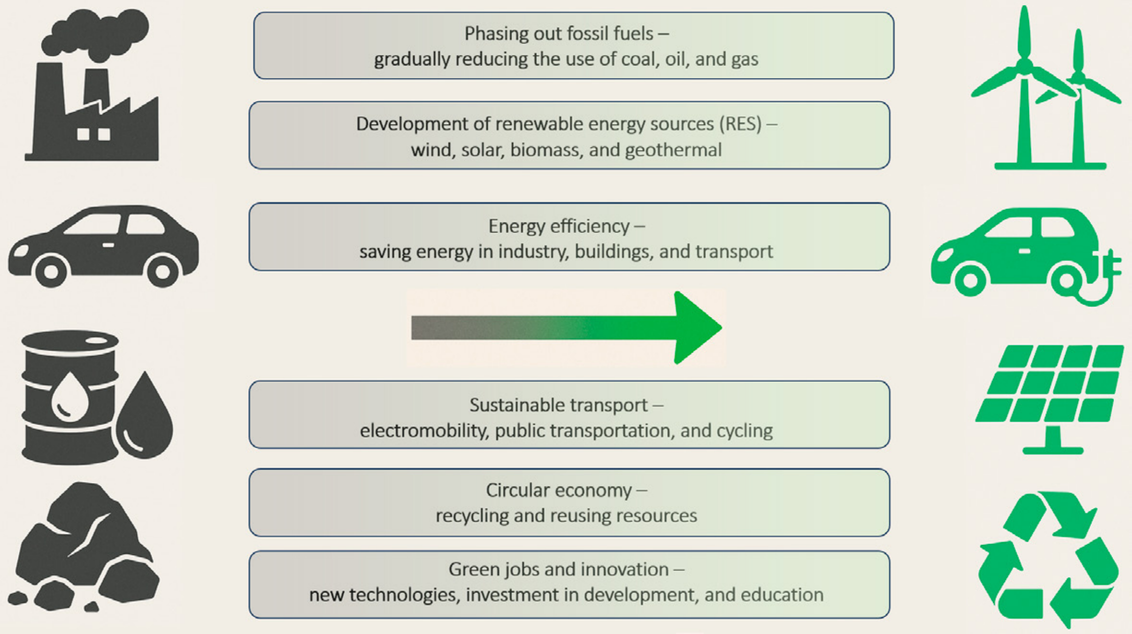

Figure 1. The process of achieving climate goals and developing a low-emission economy

Source: authors' work based on Shahbazi, Nasab, 2016.

At the public policy level, setting ambitious targets has become a catalyst for change. In February 2024, the European Union proposed a 90% reduction in net emissions by 2040, obligating member states to accelerate investments in clean technologies and infrastructure (European Commission, 2024). Despite a growing number of declarations, the pace of carbon capture and storage (CCS) deployment remains below what is needed. At the same time, the declining cost of lithium-ion batteries facilitates the integration of variable renewable energy sources and accelerates the electrification of transportation. This strategic direction was confirmed by the COP28 summit decision, which, for the first time, called on countries to phase out fossil fuels in a fair and orderly manner, thereby increasing pressure to decarbonise the energy and industrial sectors.

Integrating ambitious political targets with the rapid development of CCS and the falling costs of energy storage remains crucial to ensuring that the global eco-transformation progresses at a pace aligned with the goals of the Paris Agreement. Renewable energy sources such as photovoltaics and wind farms require flexible power buffering systems, and mounting evidence suggests that lithium-based technologies best meet these requirements due to their high energy density and relatively long lifespan (Armand & Tarascon, 2001). At the same time, the increasing number of electric vehicles, mobile devices, and stationary energy storage systems exacerbates the challenge of managing the growing volume of battery cells, which eventually become hazardous waste after their operational life ends (Kamińska & Pawlak, 2020).

In terms of risks, a key challenge remains the management of fire and explosion hazards, which may be caused by internal short circuits, overheating, or mechanical damage (Spotnitz & Franklin, 2003). Environmental concerns are also receiving growing attention, as the accidental release of electrolytes or toxic substances can lead to soil and groundwater contamination (Zheng et al., 2018). The first step in an integrated approach to lithium-ion battery management is therefore the identification of key issues: from safety and operational requirements, through logistical challenges and the necessity of selective collection, to the recycling and recovery of critical metals (Bąkowski et al., 2024). In the context of the European Union, there is an observed need to tighten regulations related to extended producer responsibility, as well as to improve the availability of battery collection points (European Commission, 2022). Legislative and educational initiatives are emerging with the aim of raising public awareness of safe battery use and the importance of selective collection and proper processing (European Commission, 2020). These elements form the foundation for further considerations regarding technical, environmental, and legal conditions.

The dynamics of the lithium-ion battery (LIB) market are reflected in a number of forecasting analyses indicating a sharp increase in their use in both e -mobility and stationary energy storage. This trend will inevitably translate into ever larger volumes of spent cells and modules, which in the coming years will generate significant waste streams requiring appropriate management (Zheng et al., 2018; Pigłowska et al., 2024). In response to these challenges, European Union legislation – particularly Regulation (EU) 2023/1542 – sets ambitious quantitative targets for collection and recovery. It provides that collection rates for portable batteries should reach 63% in 2027 and 73% in 2030, while minimum recovery levels for metals from waste should be at least 95% for cobalt, nickel, and copper, and 80% for lithium by 2031. It is worth emphasising that, in parallel with rising volumes, shifts in cell chemistries are being observed. The increasing share of NMC and LFP technologies justifies the need to segment streams already at the collection and pre – processing stage, which is important both for resource – recovery efficiency and for minimising environmental impacts (Zheng et al., 2018).

Objective

This paper provides a comprehensive review of the environmental and safety aspects of handling lithium-ion battery (LIB) waste across the entire life cycle – from operation through collection, transport, and storage. Its contribution lies in integrating a technical perspective (failure mechanisms, risk – mitigation tools) with current standards and regulatory requirements, and in formulating practical recommendations.

Methodology

This narrative literature review compiles and systematises current knowledge on the environmental, technical, and legal aspects of collecting spent lithium-ion batteries (LIBs). Source selection drew on peer-reviewed publications, reports from international organisations, and binding legal acts, enabling consideration of the issue from both engineering and environmental perspectives. Particular emphasis was placed on works published between 2000 and 2025, which document the rapid development of lithium-ion technologies and the concurrent evolution of the regulatory and environmental context. Earlier works of foundational importance to the field – such as classic studies from the early 2000s – were also included. Sources were selected for their currency, scholarly merit, and relevance to the article's scope, while popular-science publications and works that did not add value to the problem under discussion were excluded.

The analysis of the collected literature was qualitative. It focused on identifying key phenomena and engineering challenges – such as cell-failure mechanisms and thermal runaway – as well as on assessing environmental risks arising from improper storage or transport of spent batteries. In parallel, the current state of legal regulation was reviewed, noting both applicable standards and legislative initiatives that set directions for further development in battery – waste management. The resulting synthesis integrates technological and regulatory perspectives, maintains a balanced treatment of engineering and environmental viewpoints, and presents the topic comprehensively by linking academic scholarship with engineering and regulatory practice.

Construction and Operating Principle of Lithium-Ion Batteries

A lithium-ion battery operates based on the phenomenon of intercalation-the reversible insertion of lithium ions into the crystal structure of the electrode material. This mechanism, first described over two decades ago, enables the combination of high energy density with a long cycle life, often reaching thousands of charge-discharge cycles (Armand & Tarascon, 2001). In a typical configuration, the cathode consists of layered metal oxides-most commonly nickel-manganese-cobalt (NMC) compounds or lithium iron phosphate (LFP)-while the anode is composed of porous graphite capable of storing Li^+ ions during charging. Positioned between the electrodes is a liquid electrolyte, typically a solution of lithium hexafluorophosphate ($LiPF_6$) in carbonate solvents, along with a microporous separator that prevents electron flow while allowing lithium ions to pass through (Feng et al., 2018). During charging, Li^+ ions migrate from the cathode to the anode. During discharge, this process is reversed, and the movement of ions generates an electric current that powers the external load. The reversibility of this process is a key advantage of lithium-ion technology, but it requires the chemical stability of all battery components. The structure and operating principle of a lithium-ion battery are illustrated in Figure 2.

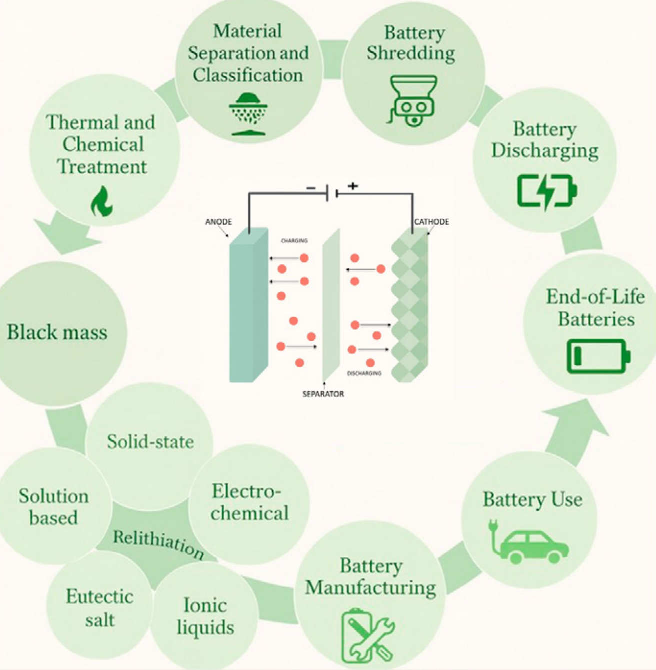

Figure 2.
Operating principle of a lithium-ion battery

Source: authors' work based on Feng et al., 2018.

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When a cell is overheated or crushed, rapid exothermic reactions occur within the electrolyte, which can lead to thermal runaway. In cylindrical 18650 cells, even slight deformation of the casing can shorten the time to thermal runaway initiation by approximately 50% (Bąkowski et al., 2024). Manufacturers are responding by reinforcing separators with ceramic coatings and developing less flammable polymer-ceramic electrolytes, which reduce the release of toxic fluorine compounds (Pigłowska et al., 2021). A second line of defence is modern electronics: Battery Management Systems (BMS) monitor the temperature, voltage, and impedance of each cell, while predictive algorithms can disconnect a compromised module several seconds before a rapid temperature increase occurs (Han et al., 2025). In transport, according to IATA regulations, standalone batteries must be shipped with a state of charge (SOC) of ≤ 30% and only if the specific battery type has passed the UN 38.3 test (UN, 2023; IATA, 2025). Once the cell capacity drops to 70–80%, batteries can be repurposed for "second-life" applications in stationary energy storage systems, where they operate under lower current loads (Pigłowska et al., 2024). When they are no longer viable even in such systems, the recycling process begins. Direct recycling techniques allow for the restoration of the cathode structure with approximately 30% less energy consumption compared to traditional hydrometallurgy, while retaining up to 95% of the original capacity after recrystallisation (Li et al., 2023). As a result, lithium, cobalt, and nickel are returned to the supply chain, supporting the European circular economy strategy (Zheng et al., 2018).

Key Environmental, Technical and Legal Considerations

In the process of ensuring the safety and sustainability of energy storage systems based on lithium-ion batteries, the analysis of environmental and technical conditions plays a fundamental role. Although lithium-ion cells are exceptionally efficient, they contain flammable and toxic substances such as heavy metals and highly reactive organic electrolytes (Pigłowska et al., 2021). Improper handling may lead to leaks or emissions of hazardous substances, contributing to soil and water contamination, particularly in cases of mechanical damage or degradation processes caused by inappropriate storage conditions (Pigłowska et al., 2021).

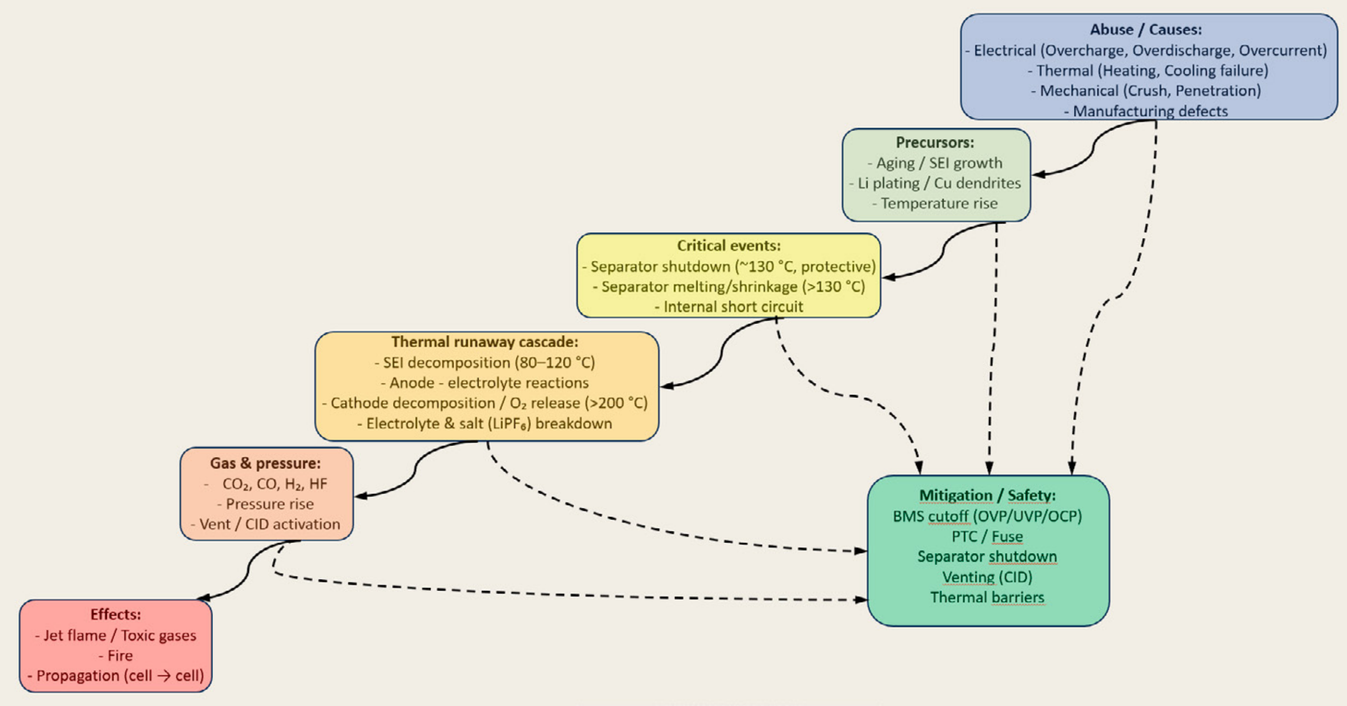

Figure 3. Mechanisms of Initiation and Propagation of Thermal Runaway in Lithium-Ion Batteries and Safety Measures

Source: authors' work based on Feng et al., 2018, Ouyang et al., 2019.

At the industrial scale, the main threats stem from the potential for exothermic reactions and rapid fires. The literature identifies multiple phenomena leading to so-called thermal runaway, including internal short circuits, overheating due to high charging currents, or separator damage (Feng et al., 2018). The mechanism of fire propagation within battery cell packs can develop very dynamically. The cause-and-effect relationships that lead to lithium-ion cell failure are illustrated in Figure 3.

In Poland and across EU member states, regulations classify lithium-ion battery cells as hazardous waste, which implies the need for specialised storage procedures (Aleksandrowicz et al., 2002). A critical aspect is also the prevention of the spread of corrosive or toxic substances that may escape into the environment in the event of a casing breach or leak (Zheng et al., 2018). For this reason, facility operators responsible for storing lithium-ion battery waste implement multiple protective measures, including real-time monitoring of temperature, humidity, and the state of charge (SOC) of individual modules, as well as the use of smoke and gas detection sensors (Ouyang et al., 2019). In large-scale storage facilities, it is also recommended to carry out Computational Fluid Dynamics (CFD) simulations to predict heat flow conditions and analyse gas behaviour in the event of a fire. When storing large quantities of cells, it becomes essential to separate them into smaller units or to secure them using flame-retardant materials to prevent rapid fire spread to other areas of the storage site (Bąkowski et al., 2024; PN-EN135011, 2019-02). Technical construction regulations currently in force in Poland do not define specific or stricter requirements for storing such waste compared to other flammable materials (Regulation of the Minister of Infrastructure, 2002). When designing new buildings, the only structural parameter affecting load-bearing capacity, sealing, and thermal insulation of the construction elements used for battery storage is fire load density (PN-B-02852, 2001). This value, defined in the Polish Standard, refers to the thermal energy (expressed in megajoules) that may be released during the combustion of flammable materials stored in a given fire zone or facility, normalised per square meter of floor area (PN-B-02852, 2001). Designers typically calculate fire load density for lithium-ion batteries based on the heat of combustion of polymers, although this approach does not accurately reflect the real hazard posed by the latent chemical energy stored in lithium-ion battery waste. An effective safety strategy to address these risks must combine material and structural solutions with thermal management systems and intelligent monitoring adapted to the specific characteristics of lithium-ion cells (Ouyang, 2019). To prevent overheating, air, liquid, or phase-change material (PCM) cooling methods are used to more efficiently dissipate heat generated during charging and discharging processes. However, the issue of end-of-life cells remains problematic. One key factor is the state of charge during storage. Sources indicate that storing batteries at full charge for extended periods increases the risk of degradation processes (Wang et al., 2024). Therefore, for the interim storage of lithium-ion battery waste, it is recommended to maintain cells at a reduced state of charge-typically around 20–30%-to reduce the likelihood of internal damage. The UN Manual of Tests and Criteria (2023) serves as a reference document outlining the qualification procedures for lithium-ion cells and batteries classified for transport as UN 3480 (standalone) or UN 3481 (contained in or packed with equipment). The manual mandates eight tests simulating transport conditions: pressure, extreme temperatures, vibration, shock, external short circuit, impact/crush resistance, overcharge, and forced discharge (UN Manual of Tests and Criteria, 2018). Successful completion of all tests is required for a production series to be approved for international distribution. Based on these test results, regulatory bodies (e.g., ICAO-IATA for air transport, IMO/IMDG for maritime, and ADR/RID for road and rail) have established additional operational requirements: lithium-ion cells and batteries must be shipped at a charge level not exceeding 30% of their rated capacity. This threshold minimises the amount of chemical energy that could be released rapidly during a short circuit or charging incident, while remaining high enough to avoid impairing the chemical stability of the cell during storage and transit. In practice, manufacturers and energy storage operators adopt a working SOC range of 20–30% both for new products in transit and for temporarily stored cells awaiting recycling. This direct alignment between qualification testing (UN 38.3) and operational charge limits (≤ 30% SOC) has resulted in a consistent global standard that mitigates the risk of thermal runaway during transport and storage. However, one unresolved issue is the interim storage of lithium-ion battery waste at the point of origin, particularly within industrial, warehousing, or public utility facilities, prior to recycling.

System-Level Safety Standards in Battery Waste Management

As lithium-ion batteries increasingly become the “connective tissue” of electromobility, industrial energy storage, and renewable energy buffering systems, unifying the entire recovery chain – from end-of-life phase to metal recycling – is no longer optional. It is becoming an engineering imperative for safety and resource efficiency. On the regulatory side, this was codified by Regulation (EU) 2023/1542 (Regulation, 2023; Shqairat et al., 2024). This regulation not only replaced the previous Directive 2006/66/EC, but for the first time treated the battery as a “cradle-to-grave” product. It imposes on manufacturers the obligation to collect material data, carbon footprint, cycle count, and all service interventions through a digital product passport, which, starting from February 2027, will be a prerequisite for the commercialisation of traction and stationary systems above 2 kWh (Gianvincenzi et al., 2024). In parallel, the regulation raises the collection targets for portable batteries from the current 45% to 63% by 2027 and 73% by 2030, while also setting mandatory minimum recovery rates for metals: ≥ 95% for cobalt, nickel, and copper, and ≥ 80% for lithium by 2031 (Shqairat et al., 2024). As a result, it compels investment in selective logistics channels, such as those described in circular models analysed by Kamińska and Pawlak in the context of Retriev Technologies (Kamińska & Pawlak, 2020). In the field of recovery technologies, hydrometallurgical processes and direct recycling currently take the lead. The synergy of three pillars – rigid regulatory thresholds, the digital passport as a carrier of LCA and safety data, and global UN 38.3 testing synchronised with SOC limits – has produced the world’s first coherent end-of-life management ecosystem for lithium-ion batteries (Li et al., 2023). This framework enables both fire risk reduction and efficient recovery of strategic metals that might otherwise end up in landfills or the illegal market.

For large industrial players operating in the recycling sector, safety standards frequently include cooperation with research institutions to further modernise processes. Emerging automated disassembly lines and metal separation systems at early stages of processing represent model approaches to improving safety (Kaarlela et al., 2024). These efforts have also attracted interest from international stakeholders, increasing the likelihood of harmonising practices across the common market. In such a system, recycling efficiency improves, and environmental risks are reduced, which is particularly important in light of growing public pressure for operations to align with sustainability principles. A systemic approach also includes using inspection results to refine existing procedures. This means periodically evaluating to what extent operators comply with regulations and identifying areas where preventive actions can be improved – for example, by implementing stricter thermal management protocols or deploying more advanced sensor arrays (Han et al., 2025). Industry organisations are also gradually emerging, developing safety certification schemes for recycling plants and cell manufacturers, which helps drive up service quality in the market (Kaarlela et al., 2024). All these elements are key to developing global standards that enhance consistency and transparency in battery waste management and form the foundation for modern implementation strategies.

Advanced Directions of Development

Research on lithium-ion batteries is increasingly focused on ensuring that operational safety and resource recovery efficiency improve simultaneously rather than at each other’s expense (Wang et al., 2024). The first area of innovation is cell architecture: engineers are modifying electrode layouts and designing separators with enhanced thermal resistance, which significantly reduces the risk of internal short circuits. In parallel, safer electrolytes are being developed – from low-flammability liquids to polymer-ceramic systems that limit the emission of toxic compounds during failures (Pigłowska et al., 2021). Before such formulations reach mass production, they undergo multi-stage research campaigns – from thermal stability testing of individual cells (Ouyang et al., 2019) to full-scale module propagation trials described in recent reviews (Dai & Panahi, 2025).

The second development vector involves thermal monitoring systems. Conventional liquid and air cooling is now being supplemented with phase change materials (PCMs) and artificial intelligence algorithms that analyse BMS signals in real time and can halt charging a few seconds before the critical temperature is reached (Han et al., 2025). Such solutions reduce the probability of thermal runaway to statistically negligible levels. Automation of disassembly is also advancing rapidly. Robotic stations disassemble spent battery packs layer by layer, eliminating human contact with potentially charged electrodes and reducing the risk of sparking (Kaarlela et al., 2024). The materials are subsequently directed to integrated recycling lines where hydrometallurgy and direct recycling – i.e., restoring the cathode without fully breaking down its structure – ensure high recovery rates of lithium, cobalt, nickel, and manganese while minimising secondary waste (Zheng et al., 2018; Li et al., 2023). Life cycle assessments indicate that such technologies can reduce the overall carbon footprint of recycling by several dozen percent compared to non-selective recovery chains.

Efforts are also underway to optimise cathode chemistry. Studies show that the addition of high-melting-point elements improves the thermal stability of critical metals by up to 40°C, providing a larger safety margin during emergency events. In mobile applications, recent findings indicate that mechanical damage to cylindrical 18650 cells can shorten the time to thermal runaway by nearly 50%, which explains the growing interest in reinforced module casings (Bąkowski et al., 2024). In terms of recovery, Li et al. (2023) confirm that direct recycling allows for the regeneration of NMC cathodes with 30% lower energy consumption than conventional hydrometallurgy, while preserving up to 95% of the original capacity after recrystallisation. Pigłowska et al. (2024) further indicate that early separation of NMC and LFP streams in automated lines – as described by Kaarlela et al. (2024) – reduces acid reagent use by approximately 33%.

As lithium-ion technology evolves, pilot projects and experimental installations are playing an increasingly important role in testing full post-use battery handling chains under near-real conditions. A key research area is the performance of energy storage systems under variable load scenarios, especially those caused by cyclical increases and drops in power from renewable sources. From the operator's perspective, maintaining stability during deep discharge or fast charging – common in photovoltaic and wind systems – is critical. Experiments in test environments highlight the growing importance of dynamic current distribution between modules to prevent overheating and differences in the state of charge (Han et al., 2025). By applying machine learning algorithms, BMSs can predict critical events and respond before permanent cell damage occurs (Han et al., 2025). Pilot programmes also increasingly address safety, including the development of early warning systems, local containment of battery fire effects, and rapid isolation of faulty modules (Dai & Panahi, 2025). Equally important is the development of cooperation networks between battery manufacturers and recycling plants. Some projects demonstrate practical second-life mechanisms, where modules retired from electric vehicles are reused in stationary storage systems (Pigłowska et al., 2024). This requires precise measurements of internal resistance and remaining capacity, as well as strict rejection criteria for defective units (Kaarlela et al., 2024). Such pilot initiatives provide real-world data on service life and failure risk, which, when combined with life cycle analysis, enable a sound assessment of the economic viability of redeployment (Pigłowska et al., 2024).

These standards have the potential to be implemented more broadly across the European Union, particularly in the context of international agreements and regulations obliging member states to ensure the safe handling of hazardous waste (Regulation, 2023). Complementing laboratory-based efforts are logistical trials: several research centres are transporting pilot battery packs in accordance with the ≤ 30% SOC limit and packaging procedures outlined in official guidelines (IATA, 2025). The results help verify the actual level of transport safety and refine practical instructions for supply chain operators.

Pilot installations thus serve as testing grounds that confirm the effectiveness of methods developed under laboratory conditions and facilitate their transition into tools that are practically applicable at the industrial level (Li et al., 2023; Zheng et al., 2018). The compiled observations form the foundation for further refinement of both technologies and regulatory policies, which, in the long term, contribute to greater flexibility and stability in energy systems based on lithium-ion batteries.

A review of the available literature indicates that current innovations in lithium-ion battery energy storage go beyond standard modernisation efforts. They encompass holistic projects that integrate material development, automated recycling processes, and intelligent control systems (Sheng et al., 2024). One key focus remains the improvement of electrolyte composition and electrode materials to eliminate highly flammable and toxic substances to the greatest extent possible (Pigłowska et al., 2021). These efforts aim to reduce the risk of violent reactions, including thermal runaway during high-load charging or internal short circuits.

In large-scale energy storage systems, there is a clear trend towards testing modular battery packs that can be quickly separated in the event of a single cell failure. The introduction of exchangeable block concepts enables containment of high temperatures within localised areas, directly enhancing operational safety (Kamińska & Pawlak, 2020). Beyond structural considerations, it is also crucial to implement complex charge–discharge scenarios developed using artificial intelligence algorithms, which help balance the load across individual modules in real time (Nayak et al., 2018).

Significant progress is also being made in the methods of sorting and selecting used batteries, which form the foundation for recycling operations and second-life applications (Bąkowski et al., 2024). Some companies have begun to implement systems that identify internal resistance and the remaining functional capacity, allowing for initial classification of batteries into those suitable for further stationary use and those intended directly for materials processing (Spotnitz & Franklin, 2003). Another emerging challenge addressed in pilot initiatives is the implementation of more integrated hydrometallurgical and pyrometallurgical models, aimed at more efficient recovery of strategic metals (Zheng et al., 2018). In fire risk scenarios, tests are also being conducted with alternative extinguishing agents – alongside water cooling, a vermiculite-based insulating granulate is being trialled, which limits oxygen access from the surrounding atmosphere (Armand & Tarascon, 2001). Automotive industry studies indicate that the rapid detection of short circuits or increasing overheating, combined with intelligent disconnection control for individual cells, can significantly reduce the scale of damage. This also translates into improved safety regulations and training programmes for personnel responsible for managing large lithium-ion battery storage facilities (Sheng et al., 2024).

In the long term, advanced technologies such as digital twins of energy storage systems and expanded big data analysis tools will enable precise modelling of all fluctuations in charge levels, temperatures, and internal pressures within specific blocks (Ouyang et al., 2019). This will not only support faster responses to faults, but also help optimise unit loads, extending the lifespan of the entire system. Literature also points to the commercial potential of grid-stabilising services, which encourages further investment in research initiatives. Innovation in the lithium-ion battery sector is therefore not limited to individual aspects such as materials or recycling but represents a complex challenge that integrates monitoring strategies, legal frameworks, numerical modelling, and engineering practices (Pigłowska et al., 2021). The research and pilot efforts described above suggest that the implementation of novel solutions will further enhance safety, efficiency, and coherence across the entire lithium-ion value chain. On the horizon, there is also a growing need to tighten EU-level regulations to prevent divergent national interpretations regarding cell storage and emergency procedures (Shqairat et al., 2024). The absence of harmonised guidelines risks shifting waste to regions with less stringent standards, disrupting the market and undermining the viability of processing facilities (Rizos & Urban, 2024). On the other hand, overly strict procedures – if not accompanied by adequate support instruments – may hinder innovation. Therefore, it is essential to develop a regulatory balance in which safety and environmental responsibility are aligned with business development potential. An integrated engineering – environmental perspective, combining fire and contamination prevention with maximum metal recovery, defines strategic directions for the lithium-ion industry. More and more actors are viewing battery waste not as a burden, but as a valuable resource and an opportunity to implement circular economy models (Zheng et al., 2018). In this context, concurrent efforts in design optimisation, predictive operation methods, alternative electrolyte research, and recycling process improvements are becoming the foundation for the sector's future evolution and the achievement of eco-transformation goals.

Economic Aspects and Regulatory Framework

The EU regulatory framework sets the direction for the economics of LIB waste management. Regulation (EU) 2023/1542 raises collection targets for portable batteries to 63% (2027) and 73% (2030) and introduces minimum metal -recovery levels: at least 95% for cobalt, nickel, and copper and 80% for lithium by 2031. The regulation also establishes a digital battery passport (for traction and stationary systems > 2 kWh from February 2027) to increase value – chain transparency and improve the quality of environmental and operational data. Together, these measures create a strong investment signal for selective logistics, materials traceability, and high – efficiency recovery technologies.

Complementing the EU framework are transport and storage standards. Under UN 38.3, type testing of cells and batteries is a prerequisite for transport, while operational rules (including the IATA Dangerous Goods Regulations) limit the state of charge (SOC) to ≤ 30% for air transport. In industry practice, a 20 – 30% SOC range is adopted for interim storage and transit, which reduces the risk of thermal runaway and material losses – with clear economic benefits (fewer incidents, lower insurance costs, and reduced downtime).

At the national level (example: Poland), technical and building regulations do not impose specific, more stringent requirements for LIB – waste storage beyond the general rules for combustible materials; the principal design parameter remains fire – load density under PN-B-02852. This gap between actual risk and technical standards favours risk-based approaches (zoning, low – flammability materials, CFD simulations) and intelligent monitoring systems – both increasing safety and reducing the costs of incidents and repairs.

From a process-economics perspective, solutions that increase recovery efficiency and reduce energy demand are gaining importance: hydrometallurgy remains the mainstay of critical – metal recovery, while direct recycling enables regeneration of cathode materials with approximately 30% lower energy use than conventional hydrometallurgy and retention of up to ~ 95% of electrochemical properties after reconditioning. Early segmentation of NMC/LFP streams further reduces reagent consumption (about 33%) and operating costs. Ongoing automation of disassembly and early – stage sorting improves workplace safety and shortens the time needed to prepare feedstock for recycling. These technical trends align with EU thresholds and the battery passport, creating a coherent end – of – life ecosystem that supports both environmental objectives and economic performance.

More broadly, extended producer responsibility and digital flow-tracking systems reduce the risk of streams leaking into the informal sector, support the development of a secondary raw-materials market, and lower transaction costs. The combination of regulatory requirements (collection, recovery and passport) with operational practices (SOC control, UN 38.3 compliance, data standardisation) strengthens the profitability of recycling and the resilience of cathode-metal supply chains – positioning LIB recycling as a pillar of the circular economy.

Summary

The growing importance of lithium-ion batteries across diverse sectors – from electromobility and industrial applications to energy storage in the renewable economy – necessitates a multidimensional perspective that integrates knowledge from materials science, process engineering, ecology, and logistics. Ensuring the safe and efficient use of lithium cells begins at the design stage, where the application of eco-design principles and the standardisation of modules can significantly facilitate future disassembly, recycling, and the prevention of potential hazards. At the same time, the development of modern electrode materials and low-flammability electrolytes represents a solid step towards reducing the occurrence and scale of fires and exothermic events.

Another key pillar is the implementation of digital solutions: cloud-based tools, BMS systems with predictive algorithms, and methods for tracking battery usage history improve the ability to detect anomalies early and respond quickly in case of damage. This contributes to the stable operation of energy storage systems while minimising maintenance costs and potential losses. At the same time, the importance of recycling processes continues to grow. Hydrometallurgical and pyrometallurgical innovations, supported by partial or full automation, increase the efficiency of recovering critical elements such as lithium, cobalt, and nickel. The development of specialised disassembly and sorting lines at an early stage allows for further minimisation of secondary waste.

Ultimately, national and EU regulations play a fundamental role in promoting circular economy practices. Extended producer responsibility enhances transparency in the flow of used batteries and supports the integration of smaller facilities into broader processing networks. Meanwhile, advanced record-keeping systems supported by digital tools help mitigate the risk of illegal disposal and facilitate the development of a unified secondary raw materials market. In this context, safety considerations – including storage standards and procedures for extinguishing long-duration battery fires – are closely linked to environmental impact mitigation. Altogether, these efforts contribute to building public trust in lithium-ion solutions, while reinforcing their role as a pillar of both energy and industrial transformation – where safety, efficiency, and sustainable resource management form a coherent vision for the future.

First, in storage and logistics, it is crucial to maintain a reduced state of charge (approx. 20–30% SOC) during interim storage and to consistently segregate streams by chemistry (e.g., NMC vs. LFP) and technical condition (intact vs. damaged). In practice, this goes hand in hand with continuous temperature and off-gas monitoring and the use of appropriate packaging and fire compartments, and -during transport – with compliance with type – testing requirements and modal regulations. The opportunity here is a clear reduction in incident probability and insurance costs, whereas the challenge lies in additional capital and organisational expenditure (infrastructure, procedures, flow tracking).

Second, fire prevention and response require a layered approach: early anomaly detection by the BMS and sensors (thermal, gas), rapid isolation of suspect modules, and operational readiness for long-duration firefighting. An integral part of the plan should be the retention and treatment of fire-water, as well as defined post – incident decontamination procedures. From an operational perspective, systems designed in this way shorten downtime and reduce the environmental footprint, but they require periodic staff training and competence maintenance.

Third, environmental controls and legal compliance include impermeable surfaces and secondary containment, emissions control (including fluorine compounds), proper classification and labelling of hazardous fractions, and safe electrolyte management throughout the chain. The advantage is reduced environmental liability and remediation costs; the barrier is the cost of continuous monitoring and the permitting requirements for installations.

Fourth comes design and manufacturing. Applying eco – design and design – for – disassembly principles, standardizing modules and interfaces, and selecting lower – flammability electrolytes and more robust separators reduce risk at the source and facilitate downstream processes. Requirements concerning data carriers and compliance with the digital battery passport strengthen value – chain transparency. This paves the way for higher yields and safer end – of – life treatment, but entails product redesign and qualification costs.

In recycling, it is essential to sort as early as possible by chemistry and condition to match the technological route appropriately: regeneration of cathode materials through direct recycling where warranted, and metal recovery via hydro-/pyrometallurgical methods for mixed streams. Automation of disassembly and early-stage sorting improves workplace safety and shortens feedstock preparation time, translating into lower material and energy intensity. The opportunity is higher yields and more stable secondary raw – material supply chains; the challenge is variability in feed quality and the requirements of scaling up installations.

Finally, data and governance. Extended producer responsibility and digital tracking systems – including the battery passport – enable end–to–end traceability, facilitate compliance audits, and curb the leakage of waste into the informal sector. Establishing metrics (incidents, recovery efficiency, compliance) and a reporting culture strengthens operational credibility. This, in turn, supports financing of safety and recycling investments, but requires data interoperability and a clear allocation of roles and responsibilities among supply – chain participants.

The contribution of the authors

Conceptualization, P.L. and I.M.-K.; literature review, P.L. and A.B.; methodology, P.L. and I.M.-K.; formal analysis, P.L., I.M.-K. and A.B.; writing, P.L., I.M.-K. and A.B.; conclusions and discussion, P.L. and I.M.-K.; supervision, I.M.-K.; visualisation, A.B.; validation, I.M.-K.

The authors have read and agreed to the published version of the manuscript.

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ŚRODOWISKOWE ASPEKTY BEZPIECZNEGO GROMADZENIA ODPADÓW NA PRZYKŁADZIE AKUMULATORÓW LITOWO-JONOWYCH: PRZEGLĄD LITERATURY

STRESZCZENIE: Rosnące wykorzystanie akumulatorów litowo-jonowych – szczególnie w elektromobilności i elektronice użytkowej – wymaga opracowania skutecznych metod ich zbierania, transportu, przechowywania i przetwarzania. Akumulatory te zawierają cenne surowce – lit, kobalt, nikiel i mangan – niezbędne dla nowoczesnych technologii. Niewłaściwe postępowanie z zużytymi akumulatorami stwarza poważne zagrożenia dla środowiska i zdrowia, w tym ryzyko przegrzewania się, pożarów i eksplozji. Szczególnym problemem jest woda używana do gaszenia pożarów akumulatorów, która może przenosić toksyczne substancje do wód powierzchniowych i gruntowych. Wraz ze wzrostem liczby akumulatorów w obiegu kluczowe staje się wdrażanie regulacji i technologii zapewniających bezpieczne przechowywanie, takich jak systemy detekcji temperatury i gazów. Jednocześnie recykling zgodny z zasadami gospodarki o obiegu zamkniętym pomaga ograniczyć zależność od surowców pierwotnych i zmniejszyć presję na środowisko. Przykłady obejmują systemy odzysku metali krytycznych oraz inicjatywy mające na celu uproszczenie demontażu, stosowanie materiałów biodegradowalnych i standaryzację konstrukcji ogniw. Kompleksowe podejście do zarządzania akumulatorami po zakończeniu ich cyklu życia zwiększa bezpieczeństwo, efektywność wykorzystania zasobów i ochronę środowiska. Niniejszy artykuł stanowi zwięzłą syntezę zagadnień bezpieczeństwa i zrównoważonego postępowania z zużytymi akumulatorami litowo-jonowymi. Przedstawiono mechanizmy powstawania zagrożeń, w tym inicjację i propagację ucieczki termicznej, oraz omówiono środki ograniczania ryzyka, takie jak optymalizacja konstrukcji separatorów, wczesne wykrywanie uszkodzeń przez systemy BMS i inżynierskie rozwiązania zarządzania termicznego baterii. Przegląd obejmuje i podsumowuje europejskie ramy regulacyjne dotyczące akumulatorów. Porównano główne ścieżki recyklingu oraz zestawiono wiążące cele Unii Europejskiej istotne dla gospodarki o obiegu zamkniętym.

SŁOWA KLUCZOWE: akumulatory litowo-jonowe, gospodarka odpadami, zagrożenie dla środowiska

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