



Review

Scaling lithium-ion battery recycling: Systemic failures, innovation pathways, and policy imperatives

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ABSTRACT

The global lithium-ion battery market is projected to exceed by 2030, highlighting the need for scalable and sustainable solutions to address the anticipated rise in end-of-life batteries. Traditional recycling techniques exhibit systemic inefficiencies marked by high energy requirements, considerable greenhouse gas emissions, and restricted economic feasibility, especially for low-value materials such as lithium iron phosphate. This review analyzes the limitations and presents direct regeneration as a feasible solution, providing enhanced economic and environmental results. Direct regeneration consumes only 16% of the energy and generates merely 1.34% of greenhouse gas emissions compared to Hydrometallurgy, while achieving nearly double the profit of conventional methods. To realize its full potential, the sector must tackle the “black mass bottleneck” by establishing a quality-based routing framework, exemplified by the Black Mass Quality Index, which channels high-purity feedstocks towards value-maximizing Direct regeneration pathways. The EU Batteries Regulation promotes this transition through the establishment of mandatory targets for recycled content and carbon footprint thresholds. Achieving true circularity requires an integrated smart recycling ecosystem that includes the Digital Battery Passport, AI-assisted disassembly, and advanced Direct regeneration technologies. The implementation of enhanced circularity metrics, such as EVDP and CTI-LCIA, is advocated to assess and promote the resource efficiency of cathode-to-cathode recycling.

1. Introduction

The rapid expansion of lithium-ion batteries (LIBs) has positioned them at the core of global electrification, underpinning the transition toward low-carbon energy systems (Qiu et al., 2026). Initially developed for portable electronics, LIB deployment is now dominated by electric vehicles (EVs) and stationary energy storage systems (ESS), leading to a sharp increase in global production capacity (Zhang et al., 2025). Projections indicate that annual demand could rise from hundreds of GWh in the early 2020s to several TWh by 2030 (Fig. 1a), reflecting an unprecedented scale-up of battery manufacturing (Li et al., 2025). However, this growth trajectory is intrinsically coupled with a delayed but inevitable surge in end-of-life (EoL) batteries, as systems deployed over the past decade approach retirement (Fang et al., 2025). As a result, global volumes of spent LIBs are expected to exceed 11 million tons in the coming decades (Fig. 1b), transforming batteries from a strategic energy asset into a rapidly emerging waste stream (Li et al., 2025).

This challenge is further intensified by a structural shift in battery chemistries. While early LIB markets were dominated by cobalt-rich

systems such as lithium cobalt oxide (LCO), recent developments have driven a transition toward nickel-rich layered oxides (e.g., NMC and NCA) to enhance energy density and reduce cobalt dependency (Windisch-Kern et al., 2022). Simultaneously, lithium iron phosphate (LFP) has re-emerged as a dominant chemistry due to its cost advantages, safety profile, and long cycle life, particularly in large-scale EV deployment (Azimi and Mohammad Zadeh, 2026). This diversification of chemistries complicates recycling, as different material systems require distinct processing strategies and exhibit varying economic values (Rehman et al., 2025a). Consequently, the convergence of rapid market growth, increasing waste generation, and evolving material compositions presents a critical challenge for the development of scalable and efficient recycling systems (Qureshi et al., 2026).

From a technological perspective, LIB recycling is commonly classified into three pathways: pyrometallurgy (PMR), hydrometallurgy (HMR), and direct regeneration (DR), each with distinct trade-offs. PMR is industrially mature and can process heterogeneous feedstocks, but is energy-intensive, emission-heavy, and inefficient for lithium recovery due to slag losses (Qureshi et al., 2026). HMR enables selective metal

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extraction with higher recovery efficiency, though it requires well-controlled feedstock composition and generates secondary waste streams (Soldan Cattani et al., 2025). DR has recently emerged as a promising alternative, aiming to restore cathode materials in situ while preserving their structure (Qureshi et al., 2026). Despite its advantages in energy efficiency and value retention, its applicability remains strongly dependent on feedstock purity and is largely limited to laboratory and pilot-scale studies.

A substantial body of literatures have focused on improving these individual recycling processes, particularly through advances in leaching chemistry, thermal treatment optimization, and cathode regeneration strategies (Gao et al., 2025a; Qureshi et al., 2026; Su et al., 2025). However, despite these advances, existing studies predominantly adopt a process-centric perspective, treating recycling pathways as isolated unit operations. Recent review articles have examined LIBs recycling from both technological and systemic perspectives (Azimi and Mohammad Zadeh, 2026; Rehman et al., 2025). Process-oriented

reviews primarily focus on material recovery pathways with strong emphasis on reaction mechanisms, lithium replenishment, and structural reconstruction of cathode materials. These studies clearly demonstrate the growing potential of DR as a low-energy, closed-loop approach that preserves cathode integrity and improves sustainability (Natarajan and Noda, 2025; Qureshi et al., 2026). In parallel, system-level analyses have addressed broader challenges related to regulatory frameworks, supply chain constraints, and global policy heterogeneity, emphasizing the role of circular economy strategies and governance mechanisms in shaping sustainable recycling systems (Yang et al., 2025).

However, these two research directions remain largely disconnected. Process-focused studies assume uniform feedstocks, while policy-oriented works overlook material-level constraints, leaving feedstock heterogeneity and its impact on process selection insufficiently addressed. Therefore, the key gap is not the lack of technologies, but the absence of an integrated framework linking feedstock quality, process

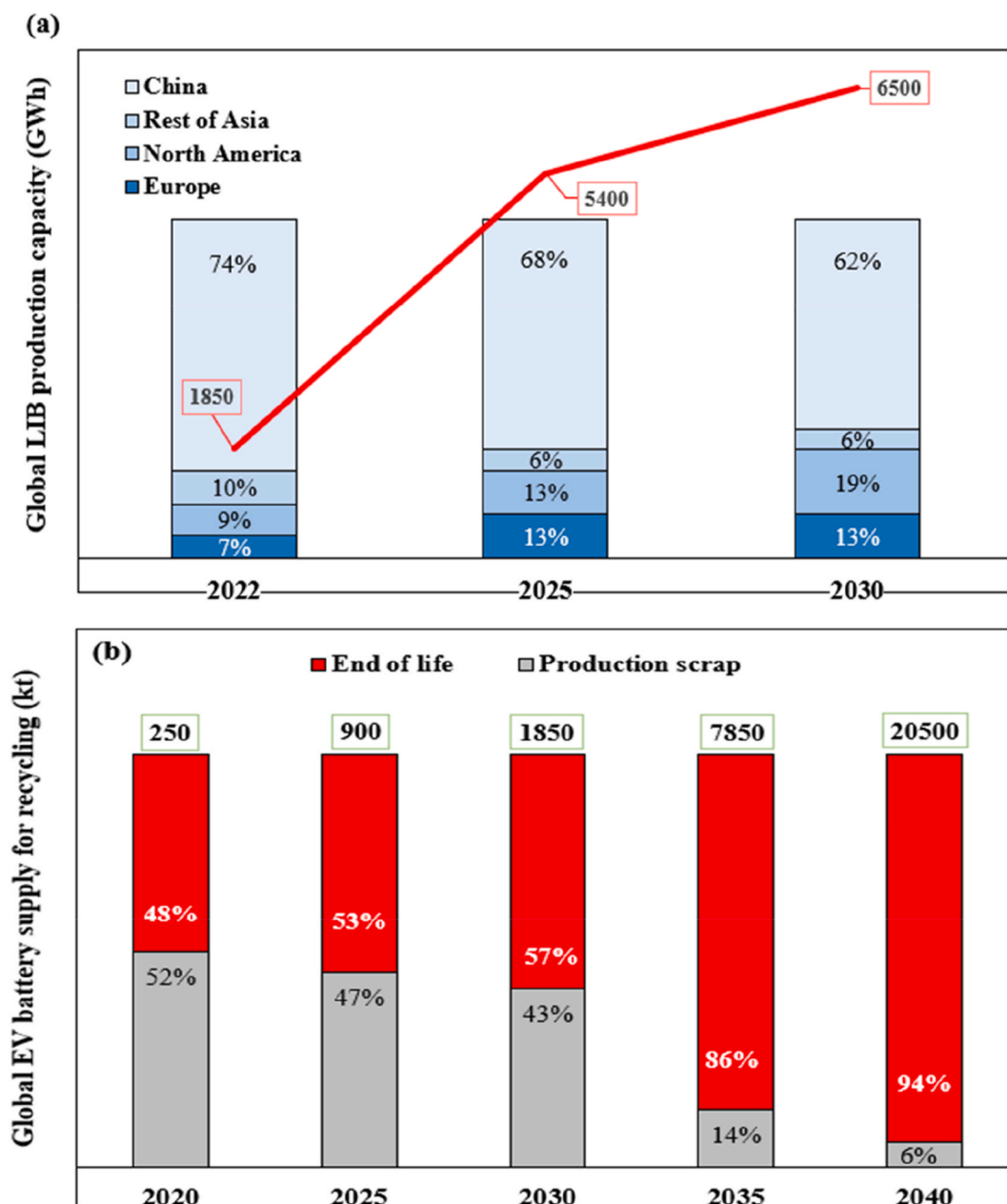


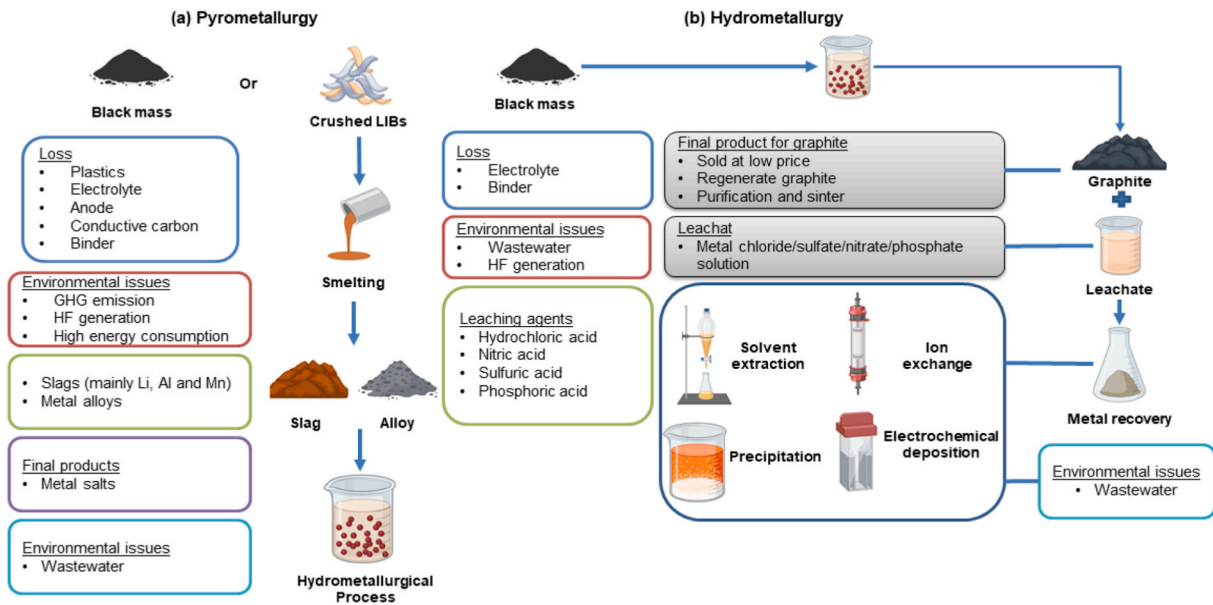
Fig. 1. (a) LIB demand from 2022 to 2030; (b) available battery materials from 2020 to 2040.

selection, and system-level decision-making.

A key gap in the literature lies in the lack of system-level integration and in the poor handling of feedstock heterogeneity. This is most evident in the so-called “black mass bottleneck,” where mechanical pre-treatment generates highly heterogeneous mixtures of cathode and anode materials, binder residues, and metallic impurities. Such variability limits the applicability of advanced recycling routes, particularly DR, which depends on controlled material purity. Despite this, industrial practice still follows a largely uniform processing approach, without clear criteria for feedstock classification or routing. As a result, materials that could be directly regenerated are often processed together with

degraded fractions, leading to unnecessary energy use and loss of material value.

This review addresses this limitation by adopting a system-level perspective that links material characteristics, process selection, and policy considerations. It frames the black mass bottleneck as a central barrier to scalable recycling and introduces the Black Mass Quality Index (BMQI) as a practical tool for feedstock classification and routing. By connecting material quality to appropriate recycling pathways, BMQI enables high-purity fractions to be directed toward value-preserving routes such as DR, while lower-quality streams are treated through conventional recovery processes. In addition, this work outlines an



(c)

Recycling method	PMR	HMR
Technology readiness	Blue	Light Blue
Complexity	Blue	Light Blue
Presorting	Blue	Light Blue
Quality of recovered material	Red	Blue
Waste generation	Red	Light Blue
Energy usage	Red	Light Blue
Sustainability	Red	Light Blue

Legend: Ideal (Blue), Light Blue, Purple, Red, Inferior (Red)

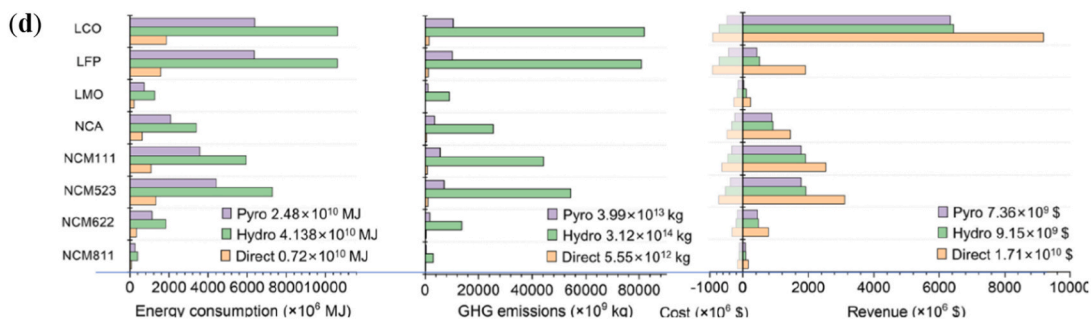


Fig. 2. Comparison of pyro, hydro, and direct recycling methods in terms of energy consumption, GHG emissions, revenue, and cost. Adapted and redraw with permission from ref. (G. Wei et al., 2023).

integrated recycling framework that combines Digital Battery Passports (DBP), AI-assisted disassembly, and advanced regeneration strategies within a single operational structure. In contrast to existing reviews that treat processes, economics, or policy in isolation, this study brings these elements together and shows how they interact in practice. By aligning process design with emerging regulatory requirements, such as the EU Batteries Regulation, it provides a realistic pathway from laboratory developments to industrial implementation.

2. Systemic failures in current recycling practices

2.1. Limitations of conventional recycling methods

Despite growing interest and research in LIB recycling, current industrial practices remain largely reliant on two conventional approaches PMR and HMR, both of which face deep-rooted limitations that hinder their environmental performance, and economic viability (Naseri et al., 2022a, b). Fig. 2a and b illustrates the schematic of PMR and HMR process.

PMR, the more mature and widely implemented of the two, operates at extremely high temperatures, often exceeding 1000 °C, to extract valuable metals from spent LIBs. This method provides the benefit of accommodating various battery chemistries and contaminated feedstocks; however, it also presents significant disadvantages. The energy requirements are substantial, rendering this process one of the most carbon-intensive alternatives in the recycling framework. PMR not only contributes to substantial CO₂ emissions but also emits hazardous gases, including hydrofluoric acid (HF), which results from the decomposition of electrolytes and binders (Biswal et al., 2024; Naseri et al., 2019). These emissions necessitate additional treatment systems, increasing both operational complexity and cost. It was found that a total of $\sim 2.48 \times 10^{10}$ MJ of energy would be consumed for PMR, leading to the generation of $\sim 3.99 \times 10^{13}$ kg of GHG emissions (Fig. 2d) (Nguyen-Tien et al., 2022). More critically, this method fails to recover many essential battery components: graphite anodes, electrolytes, separators, and plastics are typically incinerated, while valuable lithium often ends up trapped in slag, from which it is rarely recovered unless additional, expensive post-treatment is applied (Fig. 2a) (J. Wang et al., 2024). As a result, PMR is only economically viable when processing high-cobalt cathodes like LCO or NCM111; it offers little return when applied to lower-value chemistries such as LFP, which are gaining market dominance (Jenis et al., 2024). It is worth mentioning that, PMR industrial application remains significant as a robust pretreatment method for large-scale operations (Zanoletti et al., 2024). In many centralized scenarios, PMR is utilized not only for metal extraction but as a critical means of hazardous waste volume reduction and stabilization, as the high furnace temperatures effectively break down flammable electrolytes and toxic organic binders without requiring laborious individual cell disassembly (Fig. 2c). Furthermore, the economic model of PMR facilities often relies on mechanisms beyond simple metal recovery value, such as “gate fees” disposal charges paid by the battery generator or direct government subsidies and grants designed to incentivize the diversion of hazardous electronic waste from landfills (Vinayak et al., 2024). Sensitivity analyses indicate that for recycling operations to remain profitable and avoid net losses, particularly when processing low-value feedstock like LFP, a disposal fee of at least 40 EUR/kWh (acting as a negative purchase cost) may be necessary to offset substantial initial investments and ongoing operational expenses. Thus, while energy-intensive, PMR serves as a necessary component of the current global recycling infrastructure, especially for treating highly heterogeneous waste streams where fine sorting is technically difficult or prohibitively expensive (Jenis et al., 2024; Lai et al., 2025).

HMR, by contrast, operates at lower temperatures and uses aqueous solutions of acids or organic chelating agents to leach out metals. This process generally achieves higher recovery rates for specific metals such as cobalt, nickel, and manganese, and consumes less energy compared to

PMR methods. The HMR was estimated to consume $\sim 4.14 \times 10^{10}$ MJ of energy and produce $\sim 4.12 \times 10^{14}$ kg of GHGs, which are slightly higher compared to PMR (Fig. 2d) (Nguyen-Tien et al., 2022). However, it is not without its own serious limitations. The leaching, co-precipitation, and washing steps generate large volumes of acidic or alkaline wastewater, requiring complex and expensive purification systems (Fig. 2c) (Pražanová et al., 2024). Moreover, the separation of metals with similar chemical properties remains technically challenging, often leading to co-extraction and lower-purity end products (Fig. 2b). The reagents themselves, especially strong inorganic acids, pose risks of equipment corrosion, secondary pollution, and worker safety concerns (Jia et al., 2024). Even when greener alternatives like organic acids are used, their high-cost limits widespread industrial adoption (G. Shi et al., 2023; D. Song et al., 2023). Even among recycling routes, HMR tends to show lower costs across cathode types, except for LFP in China, where its low recovery value results in near-zero or negative revenue (X. Wu et al., 2024). On the other hand, DR approaches, which aim to preserve the structure of cathode materials rather than reduce them to elemental metals, are beginning to demonstrate higher revenue potential, particularly for low-value chemistries like LFP and LMO (Naseri and Mousavi, 2024). In comparison to HMR and PMR, DR was found to be a more energy-efficient and environmentally friendly option, which would consume $\sim 0.72 \times 10^{10}$ MJ of energy and generate $\sim 5.55 \times 10^{12}$ kg of GHGs, corresponding to only 16% and 1.34% of the energy consumption and GHG emissions of HMR, respectively (Fig. 2d) (Nguyen-Tien et al., 2022). Importantly, due to the low recycling cost and high value of cathode production, DR could create a profit of 1.71 billion dollars, nearly double that of metallurgy-based recycling (Jia et al., 2024). These findings highlight the necessity of industrial application of DR, considering its favorable environmental impact, energy efficiency, and economic benefits. However, several challenges need to be addressed for the industrialization of direct recycling, which will be discussed in detail in the following content.

2.2. Macro-level economic and design barriers

Beyond the limitations of each method, broader systemic issues further complicate the LIB recycling landscape. Chief among them is the **economic viability** of current approaches. As battery chemistries evolve toward high-nickel and low-cobalt formulations, the market value of recovered metals is declining. This trend undermines the profitability of conventional methods that rely heavily on cobalt recovery to break even (H. Gao et al., 2022). For LFP batteries, projected to dominate the EV and stationary storage sectors, recycling is often economically unfeasible without subsidies or policy intervention (Zhao et al., 2024). Collection and transportation also present challenges, particularly for distributed, small-format batteries like LCO cells used in consumer electronics (Vinayak et al., 2024). These batteries are difficult to track and consolidate, and their low individual value doesn't justify the high logistical costs required for centralized recycling (J. Wang et al., 2024).

The **lack of standardization** in battery design and chemistry adds another layer of complexity. Each manufacturer's configuration, differing in cell formats, pack structures, and material compositions results in a highly heterogeneous waste stream. This variability increases the difficulty of dismantling, sorting, and pre-treatment, thereby requiring tailored recycling processes for each batch (Bai et al., 2024; Mayyas et al., 2023). Mechanical pre-processing techniques such as shredding and crushing, while scalable, often result in cross-contaminated material streams (G. Shi et al., 2023; Xu et al., 2023). These processes can damage sensitive active materials, reducing their purity and electrochemical performance, and making them unsuitable for direct reuse or upcycling. This contamination not only lowers the commercial value of the recovered materials but also creates technical barriers for reintroducing them into battery manufacturing (Lai et al., 2025; X. Wu et al., 2024).

Compounding these technical and economic challenges are the practical failures observed in real-world recycling operations (Vinayak et al., 2024). Numerous pilots and commercial-scale facilities have struggled to achieve profitability or operational stability. High energy costs, fluctuating commodity prices, dependence on skilled labor, and regulatory compliance burdens make it difficult for recycling companies to scale up sustainably (Biswal et al., 2024; Vinayak et al., 2024). Recycling facilities located in countries with high labors and infrastructure costs like the U.S, often struggle to compete with counterparts in countries such as China and South Korea. In those regions, vertically integrated supply chains and economies of scale help keep operational expenses much lower (Biswal et al., 2024; X. Wu et al., 2024). Recent studies and cost assessments confirm this disparity: the expenses involved in recycling LIBs through methods like PMR and HMR are consistently higher in the U.S., largely because of higher wages and the greater capital required to build and maintain processing infrastructure.

The current LIBs recycling system is held back by old infrastructure, outdated processes, and a mismatch between how fast battery technology is evolving and how slowly recycling methods are adapting. As battery production rapidly increases to support the global shift to EVs and renewable energy, traditional recycling won't be enough. If the industry doesn't shift to more efficient, cost-effective, and flexible recycling technologies, it risks becoming a major obstacle instead of helping build a truly circular battery economy (Biswal et al., 2024).

3. Innovation pathway I: the rise of direct recycling

3.1. Direct regeneration: principles and technologies

Direct regeneration is an emerging technology that stands out as a promising alternative to traditional LIB recycling methods. This non-destructive repair technology aims to rejuvenate spent electrode materials by restoring their functionality in situ, largely preserving their crystal structure and morphology, and healing structural defects without complete chemical decomposition (Xu et al., 2023). It is worth to mention that, in this study, DR is not introduced as a new recycling technology, but is reframed as a selective pathway within an integrated system, where its applicability depends on feedstock quality, process routing, and system-level constraints. As shown in Fig. 3, typical DR technologies for spent cathode materials include chemical relithiation (CR), hydrothermal relithiation (HR), solid-state sintering (SS), electrochemical relithiation (ER), molten salt relithiation (MSR), and ionothermal relithiation (IR). In these methods, spent cathode materials are exposed to an excess lithium source and lithium ions are driven back into the crystal by physical and chemical means. The transition metal elements in spent cathode materials have a higher valence due to a lack of lithium ions. Transition metal elements are also reduced back to their lower valence during the regeneration process of spent cathode materials (Naseri and Mousavi, 2024b). With the aid of a reductant, both

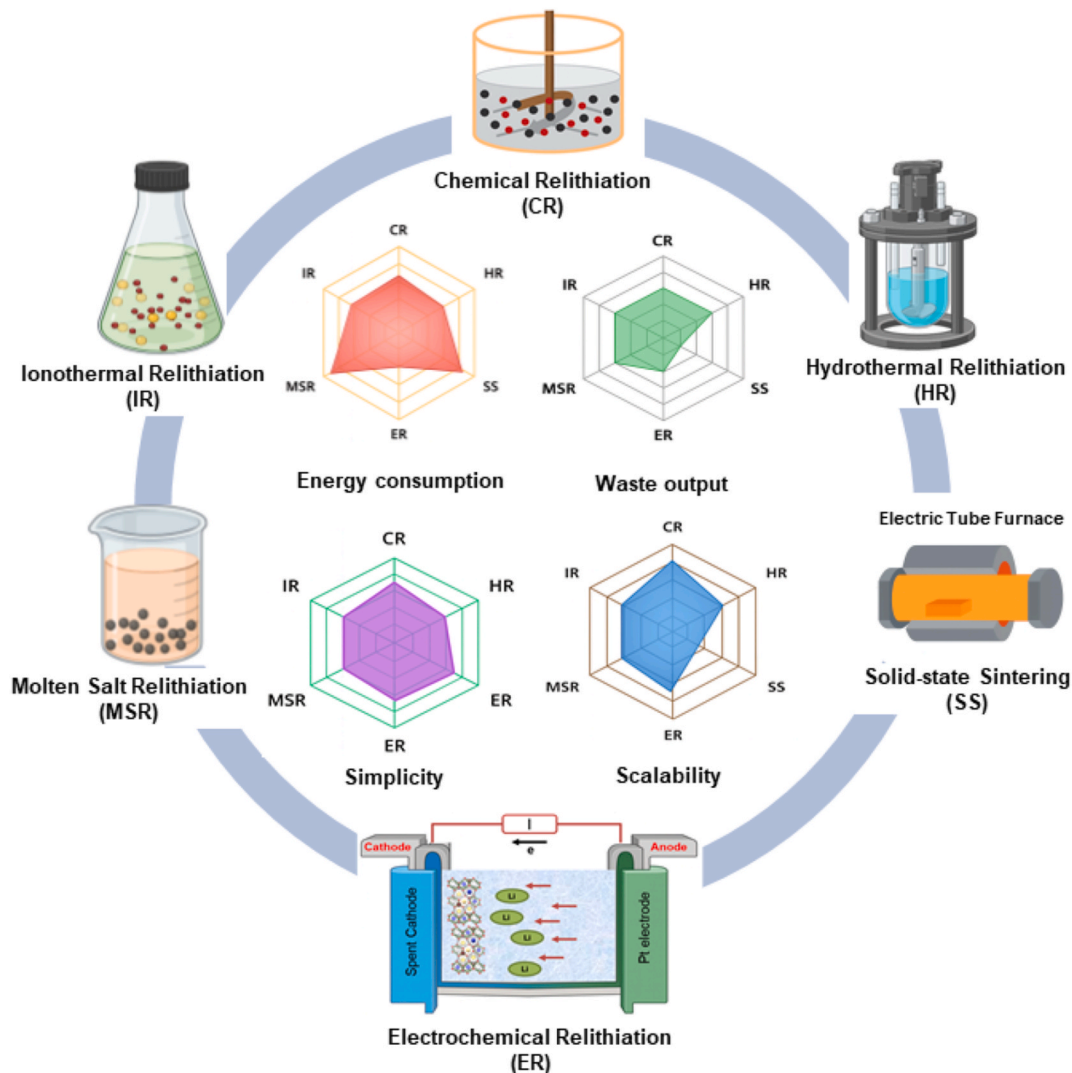


Fig. 3. Energy consumption, waste output, simplicity, and scalability of typical direct regeneration technologies. Redraw from ref (B. Zhang et al., 2024).

chemical relithiation and hydrothermal relithiation can be used to restore spent cathode materials at lower temperatures in Li-rich solutions (C. Wu et al., 2021). As with cathode material production, solid-state sintering involves embedding lithium ions into the crystal structure of spent cathode materials under high temperature conditions,

achieving high crystallinity and regenerating the structure (Ji et al., 2023). Electrochemical regeneration, in which lithium ions are electrochemically driven back to spent cathode materials, has been recognized as a sustainable and eco-friendly technology (Z. Liu et al., 2022). In mild conditions, ionic liquids can also be used as flux media for the

Table 1
Direct regeneration research for LFP and NMC cathode materials.

DR Method	Cathod	Parameters/Process	Discharge Capacity	Capacity Retention/Cycling Stability	Ref.
Solid-State Sintering/ Calcination (SS)	LFP	Solid-phase method incorporating Li_2CO_3 , crystal structure repair, and Cu doping. Treated at 650 °C for 12 h in argon.	160.15 mAh/g (0.05C). Also showed 130.94 mAh/g at 2C.	81.19% retention after 1000 cycles at 1C.	Yao et al. (2024)
	LFP	Oxidation-Reduction process by high-energy sand milling and spray drying.	Initial capacity 144.9 mAh/g at 1C. 135.4 mAh/g at 2C.	98% capacity retention after 400 cycles at 1C. 97% capacity retention after 400 cycles at 2C.	Qu et al. (2025a)
	LCO	Sintering with Li_2CO_3 at 900 °C for 12 h (Li/Co molar ratio: 1.05).	152.4 mA h/g at 30 mA/g (approx. 0.1C).	98.36% capacity retention after 80 cycles.	H. Nie et al. (2015)
	LMO/ NMC	Low-temperature sintering process (300 °C for 4 h) using LiNO_3 as Li source.	144.0 mAh/g (Initial capacity). 83 mAh/g (2C).	95.1% retention after 250 cycles at 0.5C.	Wang et al. (2025b)
	NCM111	D-NCM111 + Li_2CO_3 , sintering at 800 °C for 10h (with mechanochemical activation).	165 mAh/g at 0.2C.	Over 80% capacity retention after 100 cycles.	Chi et al. (2021)
	NCM523	Sintering with Li_2CO_3 (Li/Co ratio: 1.05) at 850 °C for 12 h in air.	162 mAh/g at 0.1C. 139.9 mAh/g at 1C.	91.9% capacity retention after 100 cycles at 1C.	Yue et al. (2020)
	NCM523	Sintering with LiOH at 800 °C for 8 h.	149.8 mAh/g at 0.5C.	94.5% capacity retention after 100 cycles.	Fan et al. (2021)
	NCM622	Preoxidation with $\text{Na}_2\text{S}_2\text{O}_8$ and NaOH, sintering with LiOH at 850 °C for 5 h in O ₂ .	153.82 mAh/g at 1C.	97.74% capacity retention after 200 cycles at 1C (also 94.74% after 100 cycles at 1C).	X. Yang et al. (2021)
	NCM811	Sintering with LiPO_3 (reacting with surface residual lithium) at 600 °C for 6 h.	198.3 mAh/g at 0.1C.	85.5% capacity retention after 50 cycles.	Feng et al. (2022)
Hydrothermal/ Solution-based (HT)	LFP	One-step hydrothermal method using DL-malic acid. Optimal conditions: 1.2 mol/L Li, 100 °C for 6 h.	Initial discharge capacity of 138.4 mAh/g (1C).	98.7% retention after 200 cycles.	J. J. Yang et al. (2023)
	LFP	Direct liquid-phase regeneration under low temperature (80 °C) and ambient pressure using ascorbic acid and LiOH.	High initial discharge capacity of 164.2 mAh/g (0.1C). 132.0 mAh/g at 5C.	93.1% capacity retention after 800 cycles at 5C.	S. Nie et al. (2025)
	LFP	Hydrothermal treatment using N, S-CQDs as multifunctional reductants.	Initial discharge capacity of 145.6 mAh/g (1C).	83.7% capacity retention after 1000 cycles.	Wang et al. (2025a)
	LFP	Hydrothermal treatment using L-threonine (multifunctional reductant) and CH_3COOLi .	155.1 mAh/g at 0.1C. 147.9 mAh/g at 1C.	82% capacity retention after 500 cycles at 1C. 86% capacity retention after 500 cycles at 5C.	Tang et al. (2024)
	NCM111	D-NCM111 in 4 M LiOH solution, HT at 220 °C for 2 h, followed by sintering at 850 °C for 4 h with 5 mol% Li_2CO_3 .	158.4 mAh/g at 0.1C.	158.4 mAh/g capacity maintained after 100 cycles at 0.1C.	Y. Shi et al. (2018)
	LFP	Molten salt regeneration using $\text{LiNO}_3\cdot\text{FeC}_2\text{O}_4$. Heating at 300 °C for 2 h, sintering at 650 °C for 6 h in Ar.	145 mAh/g at 0.5C.	over 90% capacity retention after 100 cycles.	Fan et al. (2023)
	LFP	Deep Eutectic Solvent (DES) using ethylene glycol and LiCl. Max reaction temperature of 80 °C. No annealing required.	Initial capacity of 155.6 mAh/g (0.1C).	93% capacity retention after 300 cycles at 1C.	Lin et al. (2025)
	LCO	Eutectic molten salt (LiNO_3/KCl) assisted by CaO.	128.1 mAh/g (2.0C)	95.6% capacity retention after 150 cycles at 0.5C	G. Gao et al. (2024)
	NCM622	LiOH/ Li_2SO_4 molten salt (6:1 M ratio), sintered at 900 °C for 20 h. Single-crystal product.	174 mAh/g (Discharge).	99.4% capacity retention after 250 cycles at 1C.	Qin et al. (2022)
Molten Salt/Deep Eutectic Solvent (MS/ DES)	NCM811	LiOH/NaCl molten salt (5:1 M ratio) at 850 °C for 15 h.	Higher capacity than commercial NCM.	86.5% capacity retention after 200 cycles at 1C.	Qin et al. (2024)
	NCA	LiOH/ Na_2SO_4 (5:1 M ratio) at 750 °C for 15 h. Single-crystal product.	204.8 mAh/g at 0.1C.	85.1% capacity retention after 250 cycles at 1C.	Qin et al. (2023)
	LFP	Low-Temperature Plasma (LTP) assisted Nitrogen Doping. Regeneration time over 5 times shorter than traditional methods.	160.2 mAh/g (0.1C). 153.1 mAh/g (1C).	Maintains 148 mAh/g after 100 cycles at 1C.	Hou et al. (2024)
	LFP	Liacac on black mass. Followed by heat treatment for carbon coating.	140 mAh/g (1C retained capacity).	88.5% capacity retention after 400 cycles at 1C.	Qin et al. (2024)
	LFP	Vapor deposition (Molecular Fencing) using Li stearate and creatine. Lithiation at 300 °C, coating at 560 °C.	146 mAh/g (0.5C); 149.52 mAh/g (1C).	95.83% retention after 200 cycles at 1C.	Qin et al. (2024)
	NCM622	Redox mediator-assisted chemical relithiation (DTBQ), 3 h immersion (Full cell test).	Initial charge capacity 178.2 mA h/g	76.7% capacity retention after 100 cycles.	Kim et al. (2025)
	NCM83	Advanced Oxidation-assisted Regeneration. Uses H_2O_2 to generate free radicals, followed by solid-state regeneration.	206 mAh/g at 0.1C.	80% capacity retention after 150 cycles at 0.5C.	R. Shi et al. (2024)
	NCM	Channel-Assisted Regeneration (CAR) using spent spinel LiMn_2O_4 for surface reconstruction.	151.6 mAh/g (Discharge capacity).	87.9% capacity retention after 500 cycles at 10C.	H. Zhang et al. (2025)
	LMO	Laser-assisted regeneration (PLAL) with simultaneous Ni doping (r-LMO-Ni).	150.51 mA h/g (1C) at 25 °C.	82.4% capacity retention after 100 cycles at 1C. 95.1% retention after 200 cycles at 1C.	Ye et al. (2025)

regeneration of spent cathode materials (T. Wang et al., 2020). Lithium can also be provided by eutectic salt mixtures with melting points below those of the constituent salts under atmospheric pressure. When molten salt reaches a sufficiently high temperature, lithium ions diffuse more easily, facilitating cathode regeneration (L. Liu et al., 2022). In order for regeneration processes to be sustainable, energy consumption, waste output, simplicity, and scalability need to be considered. Fig. 3 compared different DR technologies from various aspects. Since solid-state sintering usually consumes more energy and produces less waste. The heterogeneity of lithium deficiencies across different batches of spent cathodes makes large-scale sintering challenging. Chemical relithiation consumes relatively little energy due to mild reaction conditions. With simple adjustment of relevant process parameters, chemical relithiation is capable of directly regenerating diverse spent cathode materials with universal applicability. Moreover, relithiation occurs in liquid phase under ambient pressure, reducing complexity and facilitating scalability (J. Wang et al., 2023; C. Wu et al., 2021). Therefore, the development of green and low-cost reagents for chemical relithiation is crucial to drive the practical application.

Table 1 is shown the summary different method of DR for regeneration for two dominant chemistries (LFP and NMC) in EVs and ESSs.

Despite the promise of DR, several challenges remain in its widespread implementation, these challenges include the need for efficient and scalable separation processes to isolate cathode materials from other battery components while maintaining their functional integrity (Vinayak et al., 2024). Additionally, the optimization of relithiation, reconditioning, and thermal healing processes requires precise control over reaction conditions, such as temperature, pressure, and chemical composition, to avoid over- or under-processing of the cathode material (Z. Gao et al., 2025). The development of robust quality control measures is crucial to ensure that regenerated cathode materials meet the stringent performance requirements for use in new batteries (P. Li et al., 2024). Current research and development efforts are focused on addressing these challenges through the development of advanced characterization techniques, process optimization strategies, and closed-loop recycling systems that integrate material separation, regeneration, and quality control steps (J. Wang et al., 2024). Spontaneous lithium migration and electrically driven lithiation have also been demonstrated, exhibiting favorable reaction times, current utilization efficiency, and recyclability of lithium salts. The design of the battery is also very crucial in ensuring the cost, effort, and time in direct recycling of cathode and anode materials (Qiu et al., 2024).

Table 2
Comparative economic and environmental metrics of recycling methods.

Cathode Material	Recycling Method	Primary Mechanism	Profit/(kg or Cell)	GHG Emissions/(kg or Cell)	Energy Consumption/(MJ or Cell)	Citation
LFP	DER	CR (Room Temp)	\$6.24 per cell	0.56 kg/kg	0.85 MJ/kg	(Cai et al., 2025; C. Li et al., 2023)
LFP	DMR	Thermal/Lithium Rep.	\$4.69 per cell	1.15 kg/kg	4.25 MJ/kg	(C. Li et al., 2023; Qiu et al., 2025)
LFP	PMR	High Temp. Melting	\$0.46 per cell	1.95 kg/kg	2.59 MJ/kg	Qiu et al. (2025)
LFP	RA-LFP (Hydrothermal)	Solution Relithiation	\$2.93 per kg cells	N/A	N/A	Liao et al. (2025)
LFP	Cl-Doping Reg.	Oxidation-Reduction	\$2.93 per kg cathode	N/A	N/A	Qu et al. (2025b)
LFP	HMR	Acid Leaching	-\$1.05 per kg cathode	N/A	N/A	Qu et al. (2025a)
LFP	PMR	High Temp.	-\$3.50 per kg cathode	N/A	N/A	Qu et al. (2025b)
NCM 622	MSR	Eutectic Molten Salt	\$6.23 per kg feedstock	980 g/kg	24.391 MJ/kg	Z. Liu et al. (2025)
NCM 622	HMR	Acid Leaching	\$3.74 per kg feedstock	2512 g/kg	33.579 MJ/kg	Z. Liu et al. (2025)
NCM 622	PMR	High Temp.	\$2.39 per kg feedstock	1774 g/kg	4.534 MJ/kg	Z. Liu et al. (2025)

3.2. Economic and environmental superiority of direct regeneration

A comparative analysis of economic and environmental metrics for various battery recycling methods is presented in Table 2. The data unequivocally shows that DR methods, particularly Direct Electrode Reuse (DER- avoids high-temperature annealing and electrode reparation) and Direct Material Regeneration (DMR- avoid the complex leaching and resynthesis), offer a superior balance of profitability and sustainability.

For LFP cells, DER achieves the highest profit margin (\$6.24 per cell) while simultaneously cutting energy consumption by 80% compared to DMR and reducing GHG emissions to a fraction of those from HMR and PMR routes. The economic challenge of recycling LFP via traditional methods is further highlighted by the significant financial losses incurred by HMR and PMR at the cathode material level (C. Li et al., 2023).

This advantage extends to high-value chemistries like NMC 622, where the direct MS method delivers the highest profit (\$6.23 per kg) and the lowest GHG emissions. Although PMR shows lower direct energy usage for NMC, its higher emissions and lower profit make it a less attractive option overall (Z. Liu et al., 2025). The consistent trend across chemistries confirms that DR is the most viable strategy for aligning economic incentives with environmental goals.

However, the economic superiority of DR is intrinsically linked to the high volatility of critical metal prices. Between 2020 and 2023, the market witnessed extreme fluctuations: cobalt peaked at over \$82,000/t in early 2022 before stabilizing near \$36,000/t by late 2023 (J. Wang et al., 2024). Similarly, lithium carbonate spiked from \$5000/t to over \$70,000/t within a two-year window (T. Yang et al., 2023; J. Yang et al., 2023). These fluctuations profoundly impact conventional metallurgy-based routes (PMR and HMR), which rely heavily on high-value cobalt and nickel recovery to offset intensive operational costs; as chemistries shift toward high-nickel and low-cobalt (e.g., NCM 811) or zero-cobalt (LFP), the elemental recovery value declines, often rendering traditional methods unprofitable without disposal gate fees.

3.3. Engineering constraints and industrial throughput in direct regeneration

While DR offers compelling environmental advantages, its transition from laboratory-scale success to industrial production is hindered by significant engineering bottlenecks related to reaction kinetics and throughput capacity (Wu et al., 2025).

3.3.1. Solid-state sintering residence times

Despite its high technological maturity and potential for high throughput, this method is limited by solid-solid reaction kinetics that necessitate prolonged calcination periods, typically ranging from 10 to 36 h at high temperatures (600–950 °C) (Nekahi et al., 2024). These extended durations drive up energy costs and complicate the synchronization of recycling lines with high-volume manufacturing (Wu et al., 2025).

3.3.2. Hydrothermal method throughput limits

The hydrothermal approach faces severe scalability hurdles due to its reliance on high-pressure reactors (autoclaves) to withstand temperatures exceeding 180 °C and pressures often above 10 MPa (11 atm) (Shi et al., 2023). These requirements typically necessitate batch-based processing rather than continuous production, which inherently limits industrial throughput and introduces safety risks related to potential explosions (Wu et al., 2025).

3.3.3. Electrochemical and molten salt constraints

Electrochemical regeneration is characterized by slow processing speeds and intricate equipment requirements (e.g., three-electrode stations or H-type electrolytic cells), which significantly limit its processability for large-scale applications (Huang et al., 2024). While eutectic molten salt methods can operate at atmospheric pressure and offer faster mass transport than solid-state diffusion, they still require significant post-treatment washing to remove solidified salts, which can lead to Li loss on the particle surface and increase the complexity of the recycling loop (Wu et al., 2025).

3.3.4. Comparative scalability and techno-economic ranking of DR technologies

Although DR is often discussed as a single recycling pathway, its industrial feasibility varies substantially across process configurations (Islam et al., 2025). From a scalability perspective, solid-state delithiation currently appears to have the strongest industrial potential because it can be integrated with established cathode manufacturing infrastructure, including calcination furnaces, rotary kilns, and milling systems (Beletskii et al., 2026). Its main advantages are high throughput potential and relatively low capital barriers compared with more specialized liquid-phase systems (Beletskii et al., 2026; Cai et al., 2025). However, its performance remains highly sensitive to feedstock purity, lithium dosing, and contamination by residual binders or current collector fragments (Islam et al., 2025).

Molten salt regeneration occupies an intermediate position. Its accelerated diffusion kinetics and strong performance for Ni-rich cathodes make it attractive from a materials standpoint, but scale-up is constrained by corrosion, salt recovery, and by-product management. These requirements increase capital intensity and complicate continuous operation (Beletskii et al., 2026; Li et al., 2026). Hydrothermal regeneration faces similar scale-up limitations, although for different reasons. Its reliance on high-pressure autoclaves restricts throughput, favors batch processing, and introduces additional safety and certification requirements that raise capital cost (Song et al., 2023).

By contrast, electrochemical and chemical delithiation routes remain closer to laboratory scale (Kurz et al., 2025). While both benefit from mild operating conditions, their industrial deployment is limited by low throughput (Beletskii et al., 2026), sensitivity to feedstock condition, and dependence on specialty reagents or electrochemical hardware (Beletskii et al., 2026; Li et al., 2023). In these cases, operating cost rather than fixed capital may become the dominant constraint, particularly when process efficiency depends on consumable electrolytes, redox mediators, or carefully controlled reaction environments (Beletskii et al., 2026).

Taken together, these comparisons suggest that DR technologies should not be treated as equally scalable. Solid-state delithiation presently offers the clearest route toward industrial implementation, while

molten salt and hydrothermal systems remain promising but more capital intensive (Beletskii et al., 2026). Electrochemical and solution-based methods may be valuable for niche applications or highly controlled feedstocks, but they still face a significant scalability gap (Beletskii et al., 2026; Song et al., 2023). Across all DR routes, the decisive constraint is not only regeneration chemistry itself, but the ability to secure sufficiently pure, well-characterized feedstock through upstream disassembly and pre-treatment (Islam et al., 2025).

4. Innovation pathway II: resolving the black mass bottleneck

4.1. The Black Mass Quality Index (BMQI) framework

The efficiency and economic viability of LIB recycling hinge critically on the quality and purity of the precursor material known as “black mass”, the finely crushed powder generated during the mechanical pre-treatment of spent batteries (Qiu et al., 2024). Current industrial practices often yield heterogeneous black mass containing a mixture of cathode/anode materials, binder residues, and metallic impurities, reducing the feasibility of advanced recovery techniques (Pražanová et al., 2024). To address this challenge, the systematic Black Mass Quality Index (BMQI), or Feedstock Readiness Level (FRL) framework are proposed, which classifies black mass based on its chemical uniformity and purity. This index provides a practical tool for recyclers, policymakers, and researchers to assess feedstock quality and select the most appropriate and economically optimal recycling pathway.

The foundational principle of this framework is that the quality of pre-treatment directly dictates the complexity and efficiency of subsequent recycling processes. By classifying the black mass into three distinct grades (A, B, and C), the industry can strategically invest in upstream processes to “upgrade” the material quality, moving toward lower-cost, high-value recovery methods. To improve the operational relevance of this framework, Table S3 now includes indicative quantitative ranges for key parameters, including metallic impurities (e.g., Cu, Al, Fe), residual carbon/binder content, and chemical uniformity. These ranges provide a clearer distinction between Grade A, B, and C feedstocks, addressing the limitations of purely qualitative descriptors. This approach ensures that the BMQI remains both practically applicable and adaptable across different battery chemistries, pre-treatment routes, and recycling systems.

The BMQI framework's economic value is realized when high-purity feedstock enables structural restoration that defines battery-grade materials. For NMC cathodes, achieving Grade A purity allows methods like the LiBr-LiOH molten salt strategy to reduce the critical Li/Ni anti-site ratio from 9.5% to 3.2% in NCM622, this structural repair justifies the \$6.23/kg profit premium over conventional metal recovery (J. Wang et al., 2024). Similarly, for LFP, successful DR converts degraded FePO₄ phases back to electroactive LiFePO₄, restoring the Li/Fe molar ratio to approximately 1.05. This structural preservation, rather than mere metal recovery, constitutes the core value proposition of DR and directly enables compliance with the EU Regulation's quality-focused mandates (Guan et al., 2021; Qiu et al., 2024).

4.2. Operationalizing the BMQI framework

For the BMQI to be useful in practice, it needs to be based on measurable parameters rather than general descriptions. In real systems, black mass is rarely uniform. It typically contains a mixture of cathode chemistries, partially attached electrode particles, binder residues, and metallic contamination introduced during shredding. Because of this variability, classification cannot rely on nominal battery type alone (Bjerre-Christensen et al., 2025). A practical grading approach should consider several key aspects. The first is chemical purity, meaning how dominant a single cathode chemistry is within the mixture. The second is the level of metallic impurities, particularly Cu, Al, and Fe, which are known to interfere with downstream processing. The third is the

second-life operators. The DBP is the indispensable policy enabler for the intelligent, data-driven system proposed in Section 5.

- 5.1.2.2. Design for Recyclability (DfR) and Reuse:** The regulation mandates design requirements specifically targeting EoL management and improved durability. This requires that the physical design of batteries supports disassembly and repair, and that cells be readily removable and replaceable (starting 2027 for LMT batteries). These DfR strategies are a direct policy lever, forcing manufacturers toward design choices (e.g., simplified architecture, use of soluble binders) that are compatible with the advanced, automated recycling systems needed to overcome the disassembly bottleneck (Picatoste et al., 2022).

5.1.3. Ensuring accountability: collection, extended producer responsibility, and material recovery

To close the physical loop, the regulation solidifies accountability through Extended Producer Responsibility (EPR) and sets ambitious targets for collection and material recovery.

5.1.3.1. EPR. The core mechanism is the EPR system, which makes the producer responsible for the financial and operational aspects of waste battery management (J. Yang et al., 2025). This principle ensures accountability throughout the battery's life cycle and creates a direct incentive for manufacturers to design batteries that are cheaper to collect, disassemble, and recycle (Rufino Júnior et al., 2024).

5.1.3.2. Collection targets. These targets focus on the physical accumulation of waste batteries. The regulation sets stringent collection targets for waste batteries, ensuring sufficient feedstock for the recycling industry: (i) Portable Batteries: 73% collection rate by the end of 2030, (ii) LMT Batteries: 61% collection rate by the end of 2031 (Rizos and Urban, 2024; Rufino Júnior et al., 2024).

5.1.3.3. Material recovery targets (process efficiency mandates). Distinct from the Recycled Content Targets (which mandate input), these targets set minimum thresholds for the output efficiency of the recycling process itself. The regulation mandates specific percentages of key materials that must be recovered from the mass of processed waste batteries by a recycling facility (Table 3). This policy directly forces recycling companies to invest in more efficient technologies to maximize extraction rates, especially for lithium (Rizos and Urban, 2024; J. Yang et al., 2025).

5.2. Critical assessment and remaining policy-industry gaps

While the EU Batteries Regulation is a global benchmark, its ambitious goals expose several critical implementation challenges, creating the fundamental policy-industry gaps that must be addressed by technological innovation:

a. Scaling and Industrialization Deficit: The binding deadlines for recycled content place immense pressure on the recycling industry. DR

Table 3
Battery regulation material requirements.

Material	Minimum Recycled Content Target (from 2031)	Material Recovery Targets (by 2027)
Lithium	6% (increasing to 12% from 2036)	50% (increasing to 80% by 2031)
Nickel	6% (increasing to 15% from 2036)	90% (increasing to 95% by 2031)
Cobalt	16% (increasing to 26% from 2036)	90% (increasing to 95% by 2031)
Lead	85%	90% (increasing to 95% by 2031)
Copper	-	90% (increasing to 95% by 2031)

technologies, in particular, remain largely at the laboratory stage and struggle with scaling up to industrial volumes. The current infrastructure may lag in building the highly specialized capacity required to process the sheer volume of retired batteries expected by 2030 (Rizos and Urban, 2024; Rufino Júnior et al., 2024). **b. Data Transparency and Interoperability:** The efficacy of the DBP hinges on reliable data sharing, yet critical challenges remain, including defining interoperability standards and addressing concerns about sharing proprietary cell chemistry data (Rizos and Urban, 2024). **c. Ambiguity in EPR and Responsibility Transfer:** Practical ambiguities exist in transferring DBP duties when a battery is reused or repurposed, and in handling data at the final recycling stage. Clearer guidance is needed to ensure seamless accountability across the battery's lifecycle (Bassi et al., n.d.). **d. Lagging Technical Standards:** Policy ambition has outpaced technical guidance. A critical gap is the absence of a standardized metric for defining the "material quality" of recycled outputs—a policy corollary to the BMQI framework (Husmann et al., 2024). **e. Global Harmonization:** Harmonizing these global standards is critical to reduce trade barriers and ensure that DfR principles are incentivized globally (Rufino Júnior et al., 2024).

5.3. Global regulatory comparison: EU, China, and the U.S

The EU Batteries Regulation is one of the most comprehensive and binding frameworks currently in place. However, its structure and priorities differ in important ways from approaches adopted in China and the U.S. These differences shape how quickly new technologies are adopted, how investments are made, and how recycling systems evolve.

5.3.1. China: centralized EPR and industrial policy alignment

China has implemented an EPR system for power batteries since 2018, requiring manufacturers to establish traceability systems and take responsibility for EoL management (Ali et al., 2025). The regulatory approach is strongly aligned with industrial policy, emphasizing domestic material security and vertical integration between battery manufacturers and recyclers.

Unlike the EU framework, China does not currently mandate binding recycled content targets in new batteries. Instead, policy instruments focus on traceability platforms, white lists of approved recycling enterprises, and technical guidelines for dismantling and cascade utilization (Yang et al., 2025). Enforcement is supported by centralized administrative oversight, but transparency and standardized quality definitions for recycled materials remain less developed compared to the EU's emerging carbon footprint and recycled content mechanisms. As a result, China's framework prioritizes industrial scaling and supply chain security, while the EU places stronger emphasis on environmental metrics and market-based quality incentives (Chacon et al., 2026).

5.3.2. U.S: fragmented federal-state structure

In contrast to both the EU and China, the U.S lacks a unified federal battery recycling regulation comparable to the EU Batteries Regulation (Natarajan and Noda, 2025). Policy development remains fragmented across federal initiatives, state-level legislation, and voluntary industry programs (Meegoda et al., 2025).

Federal efforts, such as funding through the Infrastructure Investment and Jobs Act (IIJA) and the Inflation Reduction Act (IRA), primarily focus on strengthening domestic supply chains and incentivizing critical mineral recovery (Natarajan and Noda, 2025). However, there are no nationwide binding recycled content mandates, carbon footprint thresholds, or standardized digital passport requirements. At the state level, regulations vary significantly. California has begun developing extended producer responsibility models for batteries, but harmonization across states remains limited (Natarajan and Noda, 2025). This regulatory fragmentation creates uncertainty for recyclers and manufacturers and may slow the coordinated deployment of DR.

5.3.3. Key regulatory gaps and implications

Three major gaps emerge from this comparison:

Binding Recycled Content Mandates: The EU is currently the only jurisdiction with legally binding recycled content targets tied to battery manufacturing. Neither China nor the U.S. has implemented comparable minimum thresholds (Dong et al., 2026).

Carbon Footprint Integration: The EU uniquely integrates lifecycle carbon footprint declarations and future thresholds into battery regulation. In China and the U.S., environmental performance is addressed more indirectly through broader environmental law or voluntary

reporting schemes (M. Liu et al., 2025).

Digital Traceability and Standardization: While China operates national traceability platforms and the U.S. invests in data infrastructure, the EU's DBP introduces a harmonized, legally mandated data framework linking product design, use-phase monitoring, and EoL management (Mayyas et al., 2023). These differences have strategic implications. The EU model creates strong regulatory pull for high-quality cathode-to-cathode recycling pathways, including DR and BMQI-driven routing. China's model facilitates rapid industrial scaling but places less emphasis on standardized quality-based metrics (Su et al.,

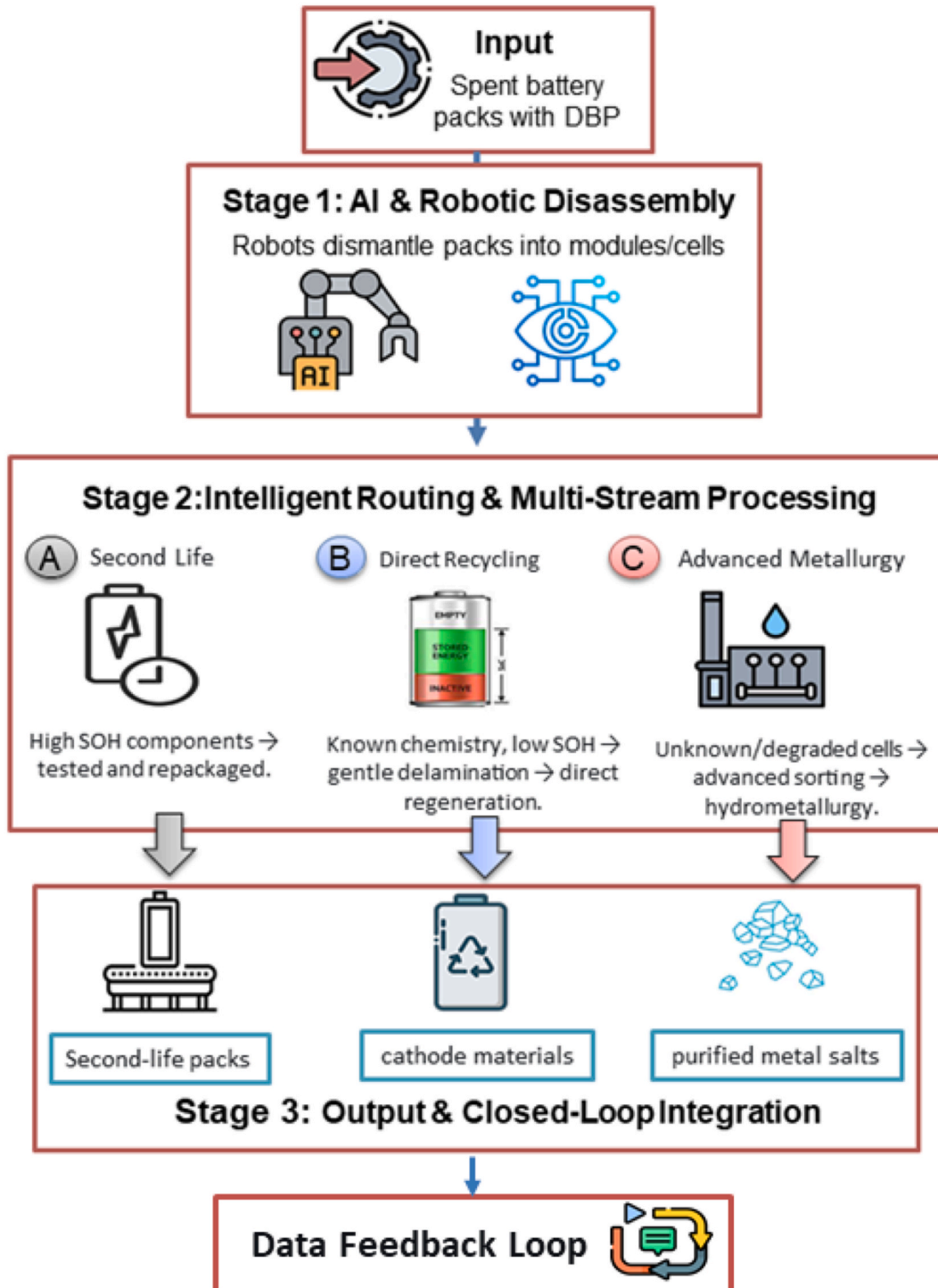


Fig. 4. Conceptual workflow of the Integrated Smart Recycling Plant.

2025). The U.S. approach prioritizes supply chain resilience and domestic capacity building but lacks regulatory coherence at present (Penttinen and Burlinghaus, 2025). Greater international alignment on quality standards, traceability, and recycled content definitions will be essential to avoid trade distortions and ensure interoperability across global battery value chains.

6. The smart industrial ecosystem for battery recycling

The preceding analysis has deconstructed the LIB recycling value chain, revealing both profound challenges (Section 2) and an ambitious, yet difficult, policy framework (Section 4). The ambitious mandates of the EU Regulation have established **what** must be done; this section presents the system required to execute **how** it can be achieved. Overcoming the Policy-Industry Gaps detailed in 4.2 requires a paradigm shift from incremental improvements to a holistic, systems-level approach. This section presents a vision for an integrated smart recycling ecosystem, where digital intelligence, robotic automation, and advanced recycling processes converge to create a responsive, value-maximizing, and truly circular system.

6.1. Integrated Smart Recycling Plant: a vision for maximizing material value

The individual technologies of DR, AI-driven disassembly, and advanced mechanical separation, while promising, are often discussed in isolation. However, their true potential is unlocked not through standalone application, but through deep integration. To overcome the fundamental mismatch between heterogeneous battery waste and high-purity recycling requirements, we propose a visionary framework: the Integrated Smart Recycling Plant. This model moves beyond sequential, destructive processing to create an intelligent, adaptive system that maximizes material value and recycling efficiency by synergizing digital, physical, and chemical technologies. The core philosophy is a shift from destructive, one-size-fits-all shredding to a non-destructive strategy that preserves the inherent value of battery materials. The conceptual workflow of this plant, which enables intelligent multi-stream processing, is illustrated in Fig. 4.

6.2. The integrated workflow: maximizing value through intelligent multi-stream processing

The smart plant's operation relies on three interconnected, data-driven stages designed to route material to its highest possible value stream, ensuring compliance with policy mandates (G. Wei et al., 2023).

Stage 1: The Intelligent Gateway (DBP-Guided Disassembly and Routing): The initial disassembly of EoL battery packs is a critical bottleneck. The smart plant addresses this through a fusion of AI, robotics, and data. The process is guided by the DBP data (mandated in 4.1.2.1), supplemented by non-destructive diagnostics that assess the State of Health (SOH). This combined data creates a “digital twin” for each battery, enabling the intelligent routing central to the plant's operation. This is how the system determines whether a component is destined for high-value second-life application (Pathway A) or material recovery (Pathways B or C). AI and robotic systems, guided by this routing plan, perform intricate disassembly tasks safely and precisely, leveraging the cost efficiencies created by DfR principles (Chigbu, 2024; G. Wei et al., 2023; Wolf et al., 2024). However, the practical implementation of such AI-driven disassembly systems must account for the significant variability in battery design across manufacturers (e.g., Tesla, BYD, Volkswagen) (Choux et al., 2024). Many packs utilize non-detachable connections such as structural adhesives, potting resins, and laser-welded joints to ensure mechanical stability (Liao et al., 2025). These joining methods are difficult to separate using conventional techniques and often require

semi-destructive approaches, such as using milling tools to break snap-fit connections or destroy welds (Rehman et al., 2025b). While standard robots excel at repetitive tasks in structured environments, they cannot process the complex uncertainties of damaged or rusted battery components (Liao et al., 2025). To address structural uncertainty, systems must integrate computer vision, sensor fusion, and reinforcement learning to adaptively respond to the specific state and geometry of each incoming pack in real time (Rehman et al., 2025b).

Stage 2: High-Purity Pre-Processing (Advanced Mechanical Separation): To achieve the high-purity feedstock required for DR, this stage functions as a high-fidelity purification module that replaces crude shredding. Instead of destruction, techniques like mechanical delamination (e.g., solvent-based separation) are used to selectively detach the active materials from their current collectors, which preserves the cathode crystal structure. For other or mixed feedstocks, advanced sensor-based sorting (e.g., hyperspectral imaging) is used to homogenize the “black mass,” yielding a consistent, high-purity powder. The successful execution of this stage is essential for translating the theoretical value defined by the BMQI into a practical, high-value commodity stream (Scott et al., 2023; G. Wei et al., 2023; B. Zhang et al., 2024). While this stage is designed to enable high-purity feedstock for DR, it must also operate under conditions of significant feedstock heterogeneity. In practice, recycling facilities frequently encounter mixed battery chemistries, partially degraded materials, and residual fractions that cannot be directly classified as black mass (Chernyaev et al., 2024). In this context, Stage 2 functions not only as a purification step, but as a classification and routing stage. High-quality fractions are directed toward DR pathways, whereas mixed or contaminated materials are redirected to alternative recovery routes, such as HMR or PMR processing, where elemental extraction is more robust (Zeng et al., 2025). In parallel, non-powder residues including metallic components, current collectors, and polymeric materials are separated and managed as secondary streams to ensure comprehensive material recovery (Lefherz et al., 2025). In addition, the system must accommodate damaged or structurally unstable cells, which represent a critical safety and operational challenge (Hayagan et al., 2024). Such inputs are identified upstream and diverted from standard disassembly and purification routes toward safer processing pathways that prioritize stabilization and controlled material recovery (Pagnanelli et al., 2024). From a system perspective, this highlights that the future of battery recycling lies not in a single optimized process, but in intelligent routing across multiple pathways, where feedstock quality determines the most appropriate treatment route (Zeng et al., 2025). This flexible approach ensures that the system remains robust under realistic conditions, where variability and contamination are the norm rather than the exception.

Stage 3: Closed-Loop Material Regeneration and Integration: The final stage transforms the purified components back into battery-grade materials, closing the physical loop. For high-purity cathode materials routed via Pathway B, a suite of DR methods is employed. The success of the entire system is ultimately measured by its ability to return high-quality materials to battery manufacturers, thus fulfilling the Recycled Content Targets (4.1.1.2). The DBP ensures traceability, providing manufacturers with the verified data needed to incorporate recycled content with confidence. A continuous data feedback loop, where performance data from new batteries made with recycled materials refines recycling parameters, creates a self-optimizing, learning system (R. Shi et al., 2024).

6.3. Broader ecosystem innovations

Beyond the centralized smart plant, other innovations are emerging that complement this model and enhance circularity across the value

chain.

- **Decentralized Microrecycling:** The concept of micro-factories offers a distributed approach, processing low waste volumes locally to reduce transport costs and act as a feeder system for larger hubs (Hu et al., 2022; Rezaei et al., 2025).
- **b. Green Process Chemistry:** Advancements in using organic acids (green lixivants) and energy-efficient methods are making hydrometallurgical routes (Pathway C) more sustainable (Rezaei et al., 2025).
- **c. Design for Recycling (DfR):** Crucially, the efficiency of the entire smart ecosystem is fundamentally predicated on batteries being designed for it. As introduced in Section 4, principles like using water-soluble binders, modular pack architectures, and standardized components are essential to make automated disassembly and high-purity separation economically viable, serving as the necessary design input for the Stage 1 Intelligent Gateway (Gonçalves et al., 2025; Scott et al., 2023).

7. Future outlook and strategic pathways

The preceding analysis has deconstructed the LIB recycling value chain, revealing both profound challenges and promising solutions. The central question is no longer *if* a circular economy is needed, but *how* to orchestrate the necessary technological, industrial, and regulatory components into a coherent, functioning system. The pathway forward hinges on executing three synergistic strategies: orchestrating material flows, accelerating technological convergence, and hardening the enabling infrastructure (Fig. 5).

7.1. Strategic integration 1: orchestrating the material flow from collection to cathode

The theoretical value of black mass must be translated into a practical, high-value commodity stream.

- **Operationalizing the BMQI:** The BMQI must evolve from a conceptual framework into an industry-wide standard for pricing and process selection. This requires developing rapid, inline analytical techniques to assign BMQI grades in real-time, enabling automated routing of feedstock within the Integrated Smart Recycling Plant.
- **b. Designing for the Grade A Pipeline:** The highest-value DR pathways require BMQI Grade A feedstock. Future efforts must focus on making the sophisticated pre-processing needed to achieve this grade (e.g., solvent-based delamination, advanced sorting) more cost-effective and robust, turning it from a technical possibility into an economic driver. At first glance, these approaches may appear disadvantageous from an energy perspective, as they introduce additional steps, particularly in solvent recovery and process control (Gao et al., 2025). However, their impact cannot be judged in isolation (Tang et al., 2024). While conventional mechanical shredding is often associated with a relatively low direct carbon intensity (approximately 0.30-0.36 kg CO₂ per kg of battery), it typically produces lower-grade black mass that requires further energy-intensive downstream refining, such as HMR or PMR processing (Liu et al., 2026). In contrast, solvent-based approaches can improve material selectivity, but introduce additional energy demand, particularly during solvent recovery. For instance, commonly used solvents such as N-methyl-2-pyrrolidone (NMP) are effective for binder removal, yet their distillation is energy-intensive (11.2 MJ per kWh) and can significantly contribute to the global warming potential of the pre-treatment stage (Narimani-Qurtlar et al., 2024). However, recent developments indicate that this impact can be mitigated. The use of alternative “green” solvents, along with solvent recovery and reuse strategies, can substantially reduce both energy demand and environmental burden (Deng et al., 2026). In particular, recycling NMP through optimized distillation processes has been shown to lower processing costs and reduce associated emissions compared to the use of virgin solvents (Maske et al., 2023). These findings further reinforce the importance of evaluating pre-processing strategies within a system-level context, where local energy inputs must be balanced against downstream efficiency gains.

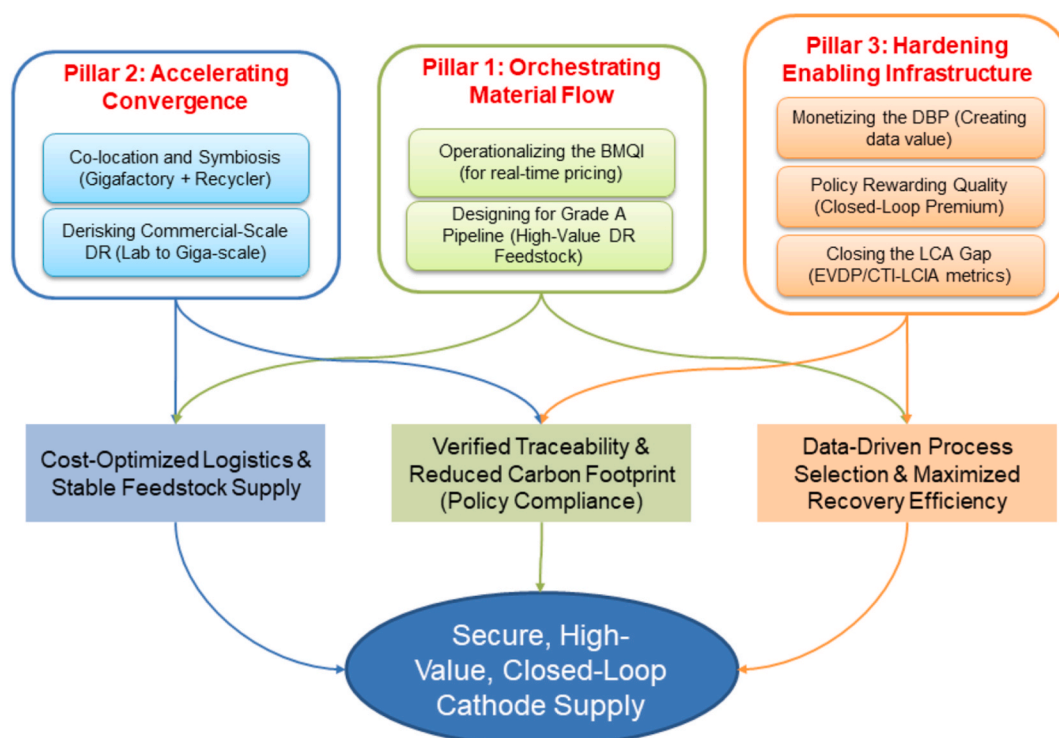


Fig. 5. The strategic convergence model for a circular battery economy.

Similarly, automated, AI-assisted sorting systems introduce additional electricity demand to operate robotic platforms and sensor arrays. However, this energy input is relatively modest when compared to the efficiency gains achieved through improved material selectivity. By enabling the targeted separation and batching of specific chemistries, such systems enhance the recovery of critical elements, while ensuring that the resulting feedstock meets the purity requirements necessary for high-value recycling pathways, including DR (Peixoto et al., 2026).

7.2. Strategic integration 2: accelerating the convergence of manufacturing and recycling

The current disconnect between battery producers and recyclers is a major barrier to scale.

- **Co-location and Symbiosis:** The ultimate expression of a circular economy is the physical integration of recycling facilities with gigafactories. This eliminates transportation costs, ensures a consistent feedstock, and allows for the direct reintegration of regenerated materials into the production line. Pilot projects demonstrating this symbiosis are a critical next step.
- **b. From Lab to Giga-scale: The Derisking Imperative:** While lab-scale results for DR are compelling, the leap to industrial volumes remains a high-risk endeavor. A concerted effort involving public-private partnerships is needed to fund and derisk first-of-their-kind commercial-scale DR facilities, focusing on the most promising and profitable routes like DER.

7.3. Strategic integration 3: hardening the enabling infrastructure: data, policy, and standards

The soft infrastructure of data and standards is as important as the physical infrastructure of recycling plants.

- **a. Monetizing the DBP:** The DBP must become more than a compliance tool; it must become a source of value. This will require solving core challenges of data ownership and interoperability to create trusted, liquid data markets. Recyclers should be able to pay a premium for batteries with a rich, verifiable DBP, creating a market-based incentive for data quality.
- **b. Policy that Rewards Quality, Not Just Quantity:** Future regulation should advance beyond basic mass-based targets for recycled content. Establishing a premium for closed-loop, cathode-to-cathode recycling as opposed to downcycling, thus directly promoting the most sustainable technologies, represents the next advancement in recycling policy.
- **c. Closing the LCA Gap for Circularity Metrics:** Current LCA methodologies fundamentally undervalue direct regeneration due to the absence of metrics that account for material quality retention. Existing frameworks rely on conventional indicators such as Abiotic Depletion Potential (ADP) and assume full equivalence between primary and secondary materials, thereby neglecting the structural and functional value preserved in cathode-to-cathode recycling (Zanoletti et al., 2024).

To address this limitation, advanced circularity-oriented metrics such as Contribution to Inaccessibility (CTI-LCIA) and Economic Value Dissipation Potential (EVDP) should be incorporated into future assessment frameworks (Islam and Iyer-Raniga, 2022). CTI-LCIA extends conventional life cycle impact assessment by quantifying the extent to which materials become physically or economically inaccessible to further use within the technosphere after processing (Dewulf et al., 2024). In contrast to ADP, which assumes complete resource consumption upon extraction, CTI evaluates accessibility losses along the value chain. Its calculation is based on process-level inventory data

and considers how processing routes alter the recoverability of materials, for example through dilution, dispersion, or thermodynamic trapping (Cappelli et al., 2025). In this context, DR results in near-zero inaccessibility, as the cathode structure remains intact and directly reusable, whereas PMR routes exhibit high CTI values due to the loss of lithium into slag phases and the need for additional recovery steps.

Complementarily, EVDP captures the dissipation of economic and functional value during recycling by comparing the theoretical maximum value of a material if preserved at battery-grade cathode level with the actual value recovered through a given process route. The metric therefore reflects the extent of downcycling, with higher EVDP values indicating greater loss of structural and functional integrity (Santillán-Saldivar et al., 2023). In practical terms, processes that reduce cathode materials to elemental or low-grade compounds exhibit high value dissipation, while DR retains both material structure and performance, resulting in significantly lower EVDP. Together, CTI-LCIA and EVDP shift the assessment framework from mass-based recovery toward quality-aware circularity metrics, enabling differentiation between recycling pathways based on both environmental performance and functional material preservation. Their implementation would provide a quantitative basis for policy instruments that incentivize high-value recovery routes. To ensure consistency and interoperability across the value chain, their deployment should be supported by standardized data infrastructures such as the DBP and coordinated industry-wide data-sharing mechanisms.

A further limitation in current LCA-based evaluations of DR lies in the incomplete treatment of upstream reagent production within system boundaries. While DR is often characterized by lower energy demand and structural preservation advantages (Shen et al., 2023), recent studies consistently identify rethiation and reactivation steps as dominant environmental hotspots. Lithium sources such as LiOH and related salts can contribute on the order of 40-43% of total global warming potential, and in some cases dominate resource depletion indicators (Chen et al., 2023; Kurz et al., 2025). Similarly, solvents and auxiliary reagents frequently simplified or excluded in gate-to-gate assessments, introduce additional upstream burdens that are not consistently captured across studies (Mousavinezhad et al., 2023). These discrepancies are further compounded by methodological inconsistencies, including variations in system boundaries, assumptions on solvent losses, and reliance on ex-ante laboratory-scale data (S. Wang et al., 2025). Compared to DR, HMR routes explicitly account for acid and reagent consumption (e.g., H₂SO₄, HCl, NaOH), where chemical inputs often dominate environmental impacts (Mousavinezhad et al., 2023), while PMR assessments may underestimate chemical burdens by separating high-temperature processing from downstream refining stages (Hanna et al., 2025). Consequently, LCA studies that exclude upstream reagent production risk systematically biasing conclusions in favor of DR by masking one of its primary environmental burdens (Kurz et al., 2025). A robust evaluation therefore requires cradle-to-cradle system boundaries that explicitly incorporate reagent production, solvent management, and material substitution effects (Chen et al., 2023; Plachý et al., 2026).

While Fig. 5 presents the strategic convergence model at a system level, Table S4 translates this framework into a stepwise technology roadmap, linking specific tools and processes to their circular objectives and regulatory drivers.

7.4. Implementation priorities for future innovation pathways

To move from concept to practice, future innovation should focus on a few key steps instead of trying to scale everything at once. The first priority is better feedstock control. DR only works when the input material is clean and well-defined. In reality, battery waste is highly variable and often contaminated, which makes process performance unstable. Recent studies show that impurities such as Al, Cu, and fluorine strongly affect regeneration efficiency and product quality. To

address this, rapid sorting and characterization methods need to be implemented before any processing step. A quality-based routing approach, such as a BMQI, can help decide whether a stream is suitable for DR or should be treated by HMR routes.

The second priority is scaling DR through integrated pilot systems. Most regeneration approaches still operate at laboratory scale and under controlled conditions. However, industrial waste streams are more complex and inconsistent. This creates a gap between reported performance and real-world feasibility. Instead of focusing only on new chemistries, more effort should go into process stability, impurity tolerance, and reproducibility. This includes developing pre-treatment steps to remove contaminants, optimizing relithiation conditions, and validating regenerated materials using standardized electrochemical testing. For example, magnetic-assisted flotation (MAGFLO) can improve the separation of cathodic active material from graphite (Efendi et al., 2026), which can be a scalable solution for pretreatment of black mass before DR.

The third priority is the practical use of digital tools. The DBP should not be treated only as a regulatory requirement. It can also support sorting, safety assessment, and process selection if the data are accessible and reliable. In combination with AI-based disassembly and sensor-based sorting, it can reduce uncertainty at the early stages of recycling. At the same time, policy frameworks need to shift from quantity-based targets to quality-based incentives. Recovering material mass is not enough if material functionality is lost. Supporting closed-loop recycling, especially cathode-to-cathode recovery, will be critical for long-term sustainability. Overall, implementation will depend on combining better sorting, more robust processing, and improved data use. These elements are already discussed in the literature, but they are often treated separately. Bringing them together in one system is the main challenge for future industrial deployment.

8. Conclusion

This review critically examined the systemic barriers limiting the scalability and economic viability of current LIB recycling practices. We first analyzed the structural weaknesses of conventional PMR and HMR routes, highlighting their energy intensity, environmental burden, and declining profitability under evolving cathode chemistries. DR was then evaluated as a promising alternative, with particular attention to its environmental advantages, economic potential, and engineering constraints that currently hinder industrial implementation. A central contribution of this work is the identification of the “black mass bottleneck” as a key limiting factor in advanced recycling pathways. To address this issue, we proposed the BMQI framework as a structured approach to classify feedstock quality and guide process selection. By linking feedstock grading to recycling route suitability, the BMQI provides a practical decision-support tool for improving material routing and enabling higher-value cathode-to-cathode recovery. In addition, the study analyzed the role of the EU Batteries Regulation as a policy driver for technological transition and introduced the concept of an integrated smart recycling ecosystem combining DBP implementation, AI-assisted disassembly, high-purity pre-processing, and DR technologies. Achieving a truly circular LIB system requires a shift from isolated process improvements toward integrated, quality-driven recycling systems. The future of the industry will not be defined by a single technology, but by the coordinated use of DBP, BMQI, and smart recycling infrastructures. Through improved alignment of material flows and quality-based regulatory mechanisms, a resilient and sustainable circular battery system can be realized.

CRedit authorship contribution statement

Tannaz Naseri: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Kerstin Kuchta:** Supervision,

Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2026.129934>.

Data availability

Data will be made available on request.

References

- Azimi, G., Mohammad Zadeh, A.H., 2026. Recycling of spent lithium iron phosphate batteries—a review of processes, economics, and carbon footprint. *Waste Manag* 209, 115203. <https://doi.org/10.1016/j.wasman.2025.115203>.
- Bai, X., Sun, Y., Li, X., He, R., Liu, Z., Pan, J., Zhang, J., 2024. A deep dive into spent lithium-ion batteries: from degradation diagnostics to sustainable material recovery. *Electrochem. Energy Rev.* 7 (1), 33. <https://doi.org/10.1007/s41918-024-00231-y>.
- Barbosa de Mattos, D.F., Duda, S., Petranikova, M., 2025. Recycling of Lithium iron phosphate (LiFePO₄) batteries from the end product quality perspective. *Batteries* 11 (1), 33. <https://doi.org/10.3390/batteries11010033>.
- Bassi, A., Candelaresi, J. F., Ferrara, A., & Ardenne, F. (n.d.). Rules for the calculation of the carbon footprint of electric vehicle batteries (CFB-EV) final draft. <https://joint-research-centre.ec.europa.eu>.
- Biswal, B.K., Zhang, B., Thi Minh Tran, P., Zhang, J., Balasubramanian, R., 2024. Recycling of spent lithium-ion batteries for a sustainable future: recent advancements. *Chem. Soc. Rev.* 53 (11), 5552–5592. <https://doi.org/10.1039/D3CS00898C>.
- Bjerre-Christensen, N., Eriksen, C.B., Sylvester-Hvid, K.O., Ravnsbæk, D.B., 2025. Characterization of industrial black mass from end-of-life LiFePO₄-graphite batteries. *Batteries* 11. <https://doi.org/10.3390/batteries11060210>.
- Cai, J., Li, Y., Xu, S., Li, Y., Wang, Z., Liu, J., Yang, S., Yan, X., 2025. A review on the insights into redox-based regeneration strategies for LiFePO₄ batteries. *Nanoscale* 17 (19), 12048–12064. <https://doi.org/10.1039/D4NR04671D>.
- Cappelli, A., Barbini, F., Paoli, R., Marzeddu, S., Romagnoli, F., 2025. Critical raw materials in life cycle assessment: innovative approach for abiotic resource depletion and supply risk in the energy transition. *Energies (Basel)* 18, 6103. <https://doi.org/10.3390/en18236103>.
- Chen, Q., Lai, X., Hou, Y., Gu, H., Lu, L., Liu, X., Ren, D., Guo, Y., Zheng, Y., 2023. Investigating the environmental impacts of different direct material recycling and battery remanufacturing technologies on two types of retired lithium-ion batteries from electric vehicles in China. *Sep. Purif. Technol.* 308. <https://doi.org/10.1016/j.seppur.2022.122966>.
- Chernyaev, A., Kobets, A., Liivand, K., Tesfaye, F., Hannula, P.M., Kallio, T., Hupa, L., Lundström, M., 2024. Graphite recovery from waste Li-ion battery black mass for direct re-use. *Miner. Eng.* 208. <https://doi.org/10.1016/j.mineng.2024.108587>.
- Chi, Z., Li, J., Wang, L., Li, T., Wang, Y., Zhang, Y., Tao, S., Zhang, M., Xiao, Y., Chen, Y., 2021. Direct regeneration method of spent LiNi 1/3 Co 1/3 Mn 1/3 O 2 cathode materials via surface lithium residues. *Green Chem.* 23 (22), 9099–9108. <https://doi.org/10.1039/D1GC03526F>.
- Chigbu, B.I., 2024. Advancing sustainable development through circular economy and skill development in EV lithium-ion battery recycling: a comprehensive review. *Front. Sustain.* 5. <https://doi.org/10.3389/frsus.2024.1409498>.
- Dong, Z., Hao, H., Sun, X., Liu, B., Dou, H., Zhao, F., Liu, Z., 2026. The EU's recycled content targets for batteries cannot effectively drive domestic recycling without sufficient cathode production capacity. *Sustain. Prod. Consum.* 63, 75–85. <https://doi.org/10.1016/j.spc.2026.01.003>.
- Efendi, R., Parian, M., Chehreh Chelgani, S., 2026. Magnetic-flotation: a sustainable solution for the flotation recycling of batteries' blackmass. *Clean. Eng. Technol.* 30. <https://doi.org/10.1016/j.clet.2026.101146>.
- Fan, M., Chang, X., Guo, Y.-J., Chen, W.-P., Yin, Y.-X., Yang, X., Meng, Q., Wan, L.-J., Guo, Y.-G., 2021. Increased residual lithium compounds guided design for green recycling of spent lithium-ion cathodes. *Energy Environ. Sci.* 14 (3), 1461–1468. <https://doi.org/10.1039/D0EE03914D>.
- Fan, M., Chang, X., Meng, X.-H., Gu, C.-F., Zhang, C.-H., Meng, Q., Wan, L.-J., Guo, Y.-G., 2023. Structural restoration of degraded LiFePO₄ cathode with enhanced kinetics

- using residual lithium in spent graphite anodes. *CCS Chem.* 5 (5), 1189–1201. <https://doi.org/10.31635/ccschem.022.202201996>.
- Fang, J., Wan, G., Zheng, M., Liu, T., Lu, J., 2025. Recycling of spent lithium-ion batteries in view of lithium. *Adv. Energy Mater.* (15). <https://doi.org/10.1002/aenm.202501318>.
- Feng, Z., Zhang, S., Huang, X., Ren, Y., Sun, D., Tang, Y., Yan, Q., Wang, H., 2022. Interfacial reviving of the degraded LiNi 0.8 Co 0.1 Mn 0.1 O 2 cathode by LiPO 3 repair strategy. *Small* 18 (16). <https://doi.org/10.1002/sml.202107346>.
- Gao, G., Zhu, Y., Di, S., Zhao, J., Liu, C., Wang, S., Li, L., 2024. Direct regeneration of spent LiCoO₂ cathodes with Ca²⁺-assisted molten salt strategy. *Acta Mater.* 273, 119969. <https://doi.org/10.1016/j.actamat.2024.119969>.
- Gao, H., Tran, D., Chen, Z., 2022. Seeking direct cathode regeneration for more efficient lithium-ion battery recycling. *Curr. Opin. Electrochem.* 31, 100875. <https://doi.org/10.1016/j.coelec.2021.100875>.
- Gao, Z., Liu, Y., El-Bahy, Z.M., Chen, G., Helal, M.H., Lu, B., Han, J., Zhou, J., 2025. Closed-loop recycling methods to treat spent cathode: efficient and direct regeneration. *Adv. Funct. Mater.* 35 (35). <https://doi.org/10.1002/adfm.202503674>.
- Gonçalves, R., Soares, M.I., Morshed Varzandeh, M.H., Chen, Q., Lourenço, E., 2025. Sustainable battery design: lean design for excellence as an enabler. *Proced. CIRP* 135, 685–690. <https://doi.org/10.1016/j.procir.2025.01.068>.
- Guan, L., Liu, M., Yu, F., Qiu, T., Zhou, T., Lin, X., 2021. A LiFePO₄ regeneration method based on PVAc alcoholysis reaction. *Renew. Energy* 175, 559–567. <https://doi.org/10.1016/j.renene.2021.04.129>.
- Hanna, F., Somers, C., Ancill, A., 2025. Life cycle assessment of lithium-ion battery recycling: evaluating the impact of recycling methods and location. *Environ. Sci. Technol.* 59, 14432–14443. <https://doi.org/10.1021/acs.est.4c13838>.
- Hartley, K., van Santen, R., Kirchherr, J., 2020. Policies for transitioning towards a circular economy: expectations from the European Union (EU). *Resour. Conserv. Recycl.* 155, 104634. <https://doi.org/10.1016/j.resconrec.2019.104634>.
- Hayagan, N., Gaalich, I., Loubet, P., Croguennec, L., Aymonier, C., Philippot, G., Olchowka, J., 2024. Challenges and perspectives for direct recycling of electrode scraps and end-of-life lithium-ion batteries. *Batter. Supercaps* 7. <https://doi.org/10.1002/batt.202400120>.
- Hou, D., Chen, J., Bai, F., Meng, F., Dong, P., Zhang, C., Zhang, Y., Hu, J., 2024. Efficient regeneration of waste LiFePO₄ cathode material by short process low temperature plasma assisted nitrogen doped technology. *J. Power Sources* 613, 234845. <https://doi.org/10.1016/j.jpowsour.2024.234845>.
- Hu, X., Yan, W., Zhang, X., Feng, Z., Wang, Y., Ying, B., Zhang, H., 2022. LRP-based design of sustainable recycling network for electric vehicle batteries. *Processes* 10 (2). <https://doi.org/10.3390/pr10020273>.
- Husmann, J., Beylot, A., Perdu, F., Pinochet, M., Cerdas, F., Herrmann, C., 2024. Towards consistent life cycle assessment modelling of circular economy strategies for electric vehicle batteries. *Sustain. Prod. Consum.* 50, 556–570. <https://doi.org/10.1016/j.spc.2024.09.001>.
- Jenis, P., Zhang, T., Ramasubramanian, B., Lin, S., Rayavarapu, P.R., Yu, J., Ramakrishna, S., 2024. Recent progress and hurdles in cathode recycling for Li-ion batteries. In: *Circular Economy*, vol. 3. Elsevier B.V. <https://doi.org/10.1016/j.ccc.2024.100087>. Issue 2.
- Ji, G., Wang, J., Liang, Z., Jia, K., Ma, J., Zhuang, Z., Zhou, G., Cheng, H.-M., 2023. Direct regeneration of degraded lithium-ion battery cathodes with a multi-functional organic lithium salt. *Nat. Commun.* 14 (1), 584. <https://doi.org/10.1038/s41467-023-36197-6>.
- Jia, K., Yang, G., He, Y., Cao, Z., Gao, J., Zhao, H., Piao, Z., Wang, J., Abdelkader, A.M., Liang, Z., Kumar, R.V., Zhou, G., Ding, S., Xi, K., 2024. Degradation mechanisms of electrodes promotes direct regeneration of spent li-ion batteries: a review. *Adv. Mater.* 36 (23). <https://doi.org/10.1002/adma.202313273>.
- Kim, S., Shin, U., Yoon, H.J., Yoon, S.A., Song, J., Ma, J., Woo, J.J., Nam, K.W., Seo, D.H., Ryu, W.H., 2025. Unraveling redox mediator-assisted chemical relithiation mechanism for direct recycling of spent Ni-Rich layered cathode materials. *Adv. Sci.* 12 (11). <https://doi.org/10.1002/advs.202417094>.
- Lai, Z., Long, J., Lu, Y., Luo, F., Zeng, L., Lai, W., Li, Y., Qian, Q., Chen, Q., Zhang, K., Yan, Z., Chen, J., 2025. Direct recycling of retired lithium-ion batteries: emerging methods for sustainable reuse. In: *Advanced Energy Materials*, vol. 15. John Wiley and Sons Inc. <https://doi.org/10.1002/aenm.202501009>. Issue 21.
- Li, C., Du, H., Kang, Y., Zhao, Y., Tian, Y., Wozny, J., Lu, J., Li, T., Tavajohi, N., Huang, M., Lan, B., Kang, F., Li, B., 2023. Room-temperature direct regeneration of spent LiFePO₄ cathode using the external short circuit strategy. *Sustainability* 1, 100008. <https://doi.org/10.1016/j.nxsust.2023.100008>.
- Li, P., Liu, Q., Møller, M., Wang, D., Jensen, L.R., Xia, X., 2024. Direct regeneration of spent lithium-ion batteries: a mini-review. *Mater. Lett.* 357. <https://doi.org/10.1016/j.matlet.2023.135724>.
- Li, S., Wu, Z., Zhang, M., Xu, J., Jin, Z., Gan, Y., Xu, Z., Wang, Q., Zhang, W., Xia, Y., He, X., Zhang, J., 2025. Direct recycling of cathode materials from spent lithium-ion batteries: principles, strategies, and perspectives. *Chem. Eur. J.* 31. <https://doi.org/10.1002/chem.202404461>.
- Liao, Y., Chai, Z., Zhang, S., Zhang, Y., Wang, L., Qiu, X., Han, Q., Xie, L., Zhu, L., Cao, X., 2025. Closed-loop regeneration of degraded lithium iron phosphate: low-energy and high-value recovery via reduction-lattice reconstruction strategy. *Mater. Today Chem.* 49, 103075. <https://doi.org/10.1016/j.mtchem.2025.103075>.
- Lin, Y., Wang, T., Gao, C., Zhang, X., Yu, W., Wang, M., Yang, C., Zhang, J., 2025. Direct and low-temperature regeneration of degraded LiFePO₄ cathodes at ambient conditions using green and sustainable deep eutectic solvent. *Adv. Sci.* 12 (28). <https://doi.org/10.1002/advs.202504683>.
- Liu, L., Zhang, Y., Zhao, Y., Jiang, G., Gong, R., Li, Y., Meng, Q., Dong, P., 2022a. Surface growth and intergranular separation of polycrystalline particles for regeneration of stable single-crystal cathode materials. *ACS Appl. Mater. Interfaces* 14 (26), 29886–29895. <https://doi.org/10.1021/acsami.2c06351>.
- Liu, Z., Bian, Z., Zhang, H., Wu, X., Fu, Z., Zhang, H., Wang, G., Zhang, Y., Zhao, H., 2025. Direct regeneration of highly degraded LiNi_{0.6}Co_{0.2}Mn_{0.2}O₂ to high-performance single-crystalline cathodes. *Energy Storage Mater.* 78, 104240. <https://doi.org/10.1016/j.ensm.2025.104240>.
- Liu, M., Sun, X., Shen, R., Zhou, X., Zhang, Y., Pan, X., Kim, H.C., Shen, W., De Castro Gomez, D., He, X., Wu, Y., Zhang, S., 2026. Real-world life-cycle assessment of industrial-scale lithium-ion-battery hydrometallurgical recycling. *Environ. Sci. Technol.* 60, 6203–6214. <https://doi.org/10.1021/acs.est.5c10922>.
- Liu, Z., Zhang, C., Ye, M., Li, H., Fu, Z., Zhang, H., Wang, G., Zhang, Y., 2022b. Closed-Loop regeneration of a spent LiFePO₄ cathode by integrating oxidative leaching and electrochemical relithiation. *ACS Appl. Energy Mater.* 5 (11), 14323–14334. <https://doi.org/10.1021/acsami.2c02883>.
- Ma, R., Tao, S., Sun, X., Ren, Y., Sun, C., Ji, G., Xu, J., Wang, X., Zhang, X., Wu, Q., Zhou, G., 2024. Pathway decisions for reuse and recycling of retired lithium-ion batteries considering economic and environmental functions. *Nat. Commun.* 15 (1), 7641. <https://doi.org/10.1038/s41467-024-52030-0>.
- Maske, T., Anwani, S., Methekar, R., 2023. Development of environmentally and economically sustainable delamination process for spent lithium-ion batteries. *Energy Sour. Part A: Recov. Util. Environ. Effects* 45, 2572–2586. <https://doi.org/10.1080/15567036.2023.2187899>.
- Mayyas, A., Moawad, K., Chadly, A., Alhseinat, E., 2023. Can circular economy and cathode chemistry evolution stabilize the supply chain of Li-ion batteries? *Extr. Ind. Soc.* 14, 101253. <https://doi.org/10.1016/j.exis.2023.101253>.
- Meegoda, J.N., Watts, D., Patil, U., 2025. Regulations and policies on the management of the end of the life of lithium-ion batteries in electrical vehicles. *Energies (Basel)* 18, 604. <https://doi.org/10.3390/en18030604>.
- Mousavinezhad, S., Kadivar, S., Vahidi, E., 2023. Comparative life cycle analysis of critical materials recovery from spent Li-ion batteries. *J. Environ. Manage.* 339. <https://doi.org/10.1016/j.jenvman.2023.117887>.
- Narimani-Qurtlar, A., Sayyah, A., Pakseresh, S., Mostafaei, J., Akbulut, H., Cetinkaya, T., Asghari, E., Niaei, A., 2024. Investigating the environmental impacts of lithium-oxygen battery cathode production: a comprehensive assessment of the effects associated with oxygen cathode manufacturing. *J. Clean. Prod.* 482. <https://doi.org/10.1016/j.jclepro.2024.144199>.
- Naseri, T., Bahaloo-Horeh, N., Mousavi, S.M., 2019. Bacterial leaching as a green approach for typical metals recovery from end-of-life coin cells batteries. *J. Clean. Prod.* 220, 483–492. <https://doi.org/10.1016/j.jclepro.2019.02.177>.
- Naseri, T., Beigi, V., Namdar, A., Keikavousi Behbahani, A., Mousavi, S.M., 2022a. Biohydrometallurgical recycling approaches for returning valuable metals to the battery production cycle. *Nano Technology for Battery Recycling, Remanufacturing, and Reusing* 217–246. <https://doi.org/10.1016/B978-0-323-91134-4.00005-4>.
- Naseri, T., Mousavi, S.M., 2024. Treatment of spent lithium iron phosphate (LFP) batteries. *Curr. Opin. Green Sustainable Chem.* 47, 100906. <https://doi.org/10.1016/j.cogsc.2024.100906>.
- Naseri, T., Pourhossein, F., Mousavi, S.M., Kaksonen, A.H., Kuchta, K., 2022b. Manganese bioleaching: an emerging approach for manganese recovery from spent batteries. *Rev. Environ. Sci. Biotechnol.* 21 (2), 447–468. <https://doi.org/10.1007/s11157-022-09620-5>.
- Nekahi, A., Kumar, M.R., Xia, A., Deng, S., Zaghbi, K., 2024. Sustainable LiFePO₄ and LiMn_xFe_{1-x}PO₄ (x=0–1) cathode materials for lithium-ion batteries: a systematic review from mine to chassis. *Mater. Sci. Eng. R Rep.* 159, 100797. <https://doi.org/10.1016/j.mser.2024.100797>.
- Nguyen-Tien, V., Dai, Q., Harper, G.D.J., Anderson, P.A., Elliott, R.J.R., 2022. Optimising the geospatial configuration of a future lithium ion battery recycling industry in the transition to electric vehicles and a circular economy. *Appl. Energy* 321, 119230. <https://doi.org/10.1016/j.apenergy.2022.119230>.
- Nie, H., Xu, L., Song, D., Song, J., Shi, X., Wang, X., Zhang, L., Yuan, Z., 2015. LiCoO₂: recycling from spent batteries and regeneration with solid state synthesis. *Green Chem.* 17 (2), 1276–1280. <https://doi.org/10.1039/C4GC01951B>.
- Nie, S., Xia, Y., Xiao, Y., Lin, W., Yang, G., Peng, W., Peng, S., Meng, F., Hu, R., Yuan, B., 2025. Direct liquid-phase regeneration of eluting spent LiFePO₄ upgrade for fast-charging cathodes under low temperature and ambient pressure. *ACS Appl. Mater. Interfaces* 17 (14), 21257–21268. <https://doi.org/10.1021/acsami.5c00736>.
- Pagnanelli, F., Altamari, P., Colasanti, M., Coletta, J., D'Annibale, L., Mancini, A., Russina, O., Schiavi, P.G. Recycling Li-Ion Batteries via the Re-Synthesis Route: Improving the Process Sustainability by Using Lithium Iron Phosphate (LFP) Scraps as Reducing Agents in the Leaching Operation. *Metals (Basel)*. 14. <https://doi.org/10.3390/met14111275>.
- Peixoto, T., Di Persio, F., Agostini, A., 2026. Lithium-ion battery recycling routes: an environmental assessment in the context of the European battery regulation. *Sustain. Chem. Environ.* 13. <https://doi.org/10.1016/j.scenv.2025.100306>.
- Penttinen, S.-L., Burlinghaus, E., 2025. The Battery Rush and Global Supply Chains: Regulatory Pathways Towards Resilient Supply Chains of Critical Minerals in the United States and the EU. <https://doi.org/10.3316/informit.T2026022300016800852672712>.
- Picatoste, A., Justel, D., Mendoza, J.M.F., 2022. Exploring the applicability of circular design criteria for electric vehicle batteries. *Proced. CIRP* 109, 107–112. <https://doi.org/10.1016/j.procir.2022.05.222>.
- Pražanová, A., Plachý, Z., Kocí, J., Fridrich, M., Knap, V., 2024. Direct recycling technology for spent lithium-ion batteries: limitations of current implementation. In: *Batteries*, vol. 10. Multidisciplinary Digital Publishing Institute (MDPI). <https://doi.org/10.3390/batteries10030081>. Issue 3.

- Qin, Z., Wen, Z., Xu, Y., Zheng, Z., Bai, M., Zhang, N., Jia, C., Wu, H. Bin, Chen, G., 2022. A ternary molten salt approach for direct regeneration of LiNi 0.5 Co 0.2 Mn 0.3 O 2 cathode. *Small* 18 (43). <https://doi.org/10.1002/sml.202106719>.
- Qin, Z., Zhang, T., Gao, X., Luo, W., Han, J., Lu, B., Zhou, J., Chen, G., 2024. Self-reconstruction of highly degraded LiNi 0.8 Co 0.1 Mn 0.1 O 2 toward stable single-crystalline cathode. *Adv. Mater.* 36 (5). <https://doi.org/10.1002/adma.202307091>.
- Qin, Z., Zhang, Y., Luo, W., Zhang, T., Wang, T., Ni, L., Wang, H., Zhang, N., Liu, X., Zhou, J., Chen, G., 2023. A universal molten salt method for direct upcycling of spent Ni-rich cathode towards single-crystalline li-rich cathode. *Angew. Chem. Int. Ed.* 62 (25). <https://doi.org/10.1002/anie.202218672>.
- Qiu, Y., Gao, Y., Liu, J.R., Cai, Y., Mei, Y., Xia, L., Ng, H.Y., Zhao, Y., Van der Bruggen, B., Tang, C., 2026. In-situ construction of ZIF-embedded hydrogel electro-driven membranes for lithium selectivity. *J. Memb. Sci.* 741, 125043. <https://doi.org/10.1016/j.memsci.2025.125043>.
- Qiu, Y., Wang, C., Liu, Y., Han, Q., Xie, L., Zhu, L., Cao, X., 2025. Ambient-pressure relithiation of spent LiFePO4 using alkaline solutions enables direct regeneration of lithium-ion battery cathodes. *J. Energy Storage* 105, 114721. <https://doi.org/10.1016/j.est.2024.114721>.
- Qiu, X., Wang, C., Xie, L., Zhu, L., Cao, X., Ji, X., 2024. Challenges and perspectives towards direct regeneration of spent LiFePO4 cathode. *J. Power Sources* 602, 234365. <https://doi.org/10.1016/j.jpowsour.2024.234365>.
- Qu, X., Li, J., Gao, Y., Zhu, K., Li, P., Cao, D., 2025a. Efficient regeneration of spent Lithium iron phosphate cathodes materials via oxidation-reduction for industrial-scale recycling. *Adv. Funct. Mater.* 35 (44). <https://doi.org/10.1002/adfm.202507117>.
- Qu, X., Li, J., Gao, Y., Zhu, K., Li, P., Wu, H., Cao, D., 2025b. Direct regeneration of spent LiFePO4 cathodes with Cl-doping assisted oxidative regeneration strategy. *Energy Storage Mater.* 82, 104658. <https://doi.org/10.1016/j.ensm.2025.104658>.
- Qureshi, K., Haider, R., Zhang, C., Li, L., Yu, X., Yuan, X., 2026. Sustainable recycling of Lithium-ion batteries: a perspective on emerging technologies toward entire cell regeneration. *Appl. Energy* 412, 127742. <https://doi.org/10.1016/j.apenergy.2026.127742>.
- Rezaei, M., Nekahi, A., Kumar, M.R.A., Nizami, A., Li, X., Deng, S., Nanda, J., Zaghbi, K., 2025. A review of lithium-ion battery recycling for enabling a circular economy. *J. Power Sources* 630, 236157. <https://doi.org/10.1016/j.jpowsour.2024.236157>.
- Rizos, V., Urban, P., 2024. IMPLEMENTING THE EU DIGITAL BATTERY PASSPORT CEPS IN-DEPTH ANALYSIS Opportunities and Challenges for Battery Circularity.
- Rufino Júnior, Riva Sanseverino, E., Gallo, P., Koch, D., Diel, S., Walter, G., Trilla, L., Ferreira, V.J., Pérez, G.B., Kotak, Y., Eichman, J., Schweiger, H.-G., Zanin, H., 2024. Towards to battery digital passport: reviewing regulations and standards for second-life batteries. *Batteries* 10 (4), 115. <https://doi.org/10.3390/batteries10040115>.
- Scott, S., Islam, Z., Allen, J., Yingnakorn, T., Alflakian, A., Hathaway, J., Rastegarpanah, A., Harper, G.D.J., Kendrick, E., Anderson, P.A., Edge, J., Lander, L., Abbott, A.P., 2023. Designing lithium-ion batteries for recycle: the role of adhesives. *Next Energy* 1 (2), 100023. <https://doi.org/10.1016/j.nxener.2023.100023>.
- Shi, G., Cheng, J., Wang, J., Zhang, S., Shao, X., Chen, X., Li, X., Xin, B., 2023. A comprehensive review of full recycling and utilization of cathode and anode as well as electrolyte from spent lithium-ion batteries. *J. Energy Storage* 72, 108486. <https://doi.org/10.1016/j.est.2023.108486>.
- Shi, R., Wang, B., Tang, D., Wei, X., Zhou, G., 2024a. Towards high value-added recycling of spent lithium-ion batteries for catalysis application. *Electrochem. Energy Rev.* 7 (1), 28. <https://doi.org/10.1007/s41918-024-00220-1>.
- Shi, R., Zheng, N., Ji, H., Zhang, M., Xiao, X., Ma, J., Chen, W., Wang, J., Cheng, H., Zhou, G., 2024b. Homogeneous repair of highly degraded Ni-Rich cathode material with spent lithium anode. *Adv. Mater.* 36 (13). <https://doi.org/10.1002/adma.202311553>.
- Shi, Y., Chen, G., Liu, F., Yue, X., Chen, Z., 2018. Resolving the compositional and structural defects of degraded LiNi x Co y Mn z O 2 particles to directly regenerate high-performance lithium-ion battery cathodes. *ACS Energy Lett.* 3 (7), 1683–1692. <https://doi.org/10.1021/acsenerylett.8b00833>.
- Song, D., Yu, J., Wang, M., Tan, Q., Liu, K., Li, J., 2023. Advancing recycling of spent lithium-ion batteries: from green chemistry to circular economy. In: *Energy Storage Materials*, vol. 61. Elsevier B.V. <https://doi.org/10.1016/j.ensm.2023.102870>.
- Tang, D., Ji, G., Wang, J., Liang, Z., Chen, W., Ji, H., Ma, J., Liu, S., Zhuang, Z., Zhou, G., 2024. A multifunctional amino acid enables direct recycling of spent LiFePO 4 cathode material. *Adv. Mater.* 36 (5). <https://doi.org/10.1002/adma.202309722>.
- The European Parliament and the Council of the European Union, 2023. Regulation (EU) 2023/1542 of the European Parliament and of the Council of 12 July 2023 Concerning Batteries and Waste Batteries, Amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and Repealing Directive 2006/66/EC.
- Vinayak, A.K., Li, M., Huang, X., Dong, P., Amine, K., Lu, J., Wang, X., 2024. Circular economies for lithium-ion batteries and challenges to their implementation. *Next Mater.* 5, 100231. <https://doi.org/10.1016/j.nxm.2024.100231>.
- Wang, J., Jia, K., Ma, J., Liang, Z., Zhuang, Z., Zhao, Y., Li, B., Zhou, G., Cheng, H.-M., 2023. Sustainable upcycling of spent LiCoO2 to an ultra-stable battery cathode at high voltage. *Nat. Sustain.* 6 (7), 797–805. <https://doi.org/10.1038/s41893-023-01094-9>.
- Wang, J., Ma, J., Zhuang, Z., Liang, Z., Jia, K., Ji, G., Zhou, G., Cheng, H.M., 2024. Toward direct regeneration of spent lithium-ion batteries: a next-generation recycling method. In: *Chemical Reviews*, 124. American Chemical Society, pp. 2839–2887. <https://doi.org/10.1021/acs.chemrev.3c00884>. Issue 5.
- Wang, J., Tan, B., Chen, D., Liu, X., Zhou, R., Hu, C., Liu, C., Zeng, G., Luo, X., 2025a. Multifunctional N, S-co-doped carbon quantum dots enable defect healing and conductive network construction in spent LiFePO4 cathodes. *Chem. Eng. J.* 522, 167249. <https://doi.org/10.1016/j.cej.2025.167249>.
- Wang, T., Luo, H., Bai, Y., Li, J., Belharouak, I., Dai, S., 2020. Direct recycling of spent NCM cathodes through ionothermal lithiation. *Adv. Energy Mater.* 10 (30). <https://doi.org/10.1002/aenm.202001204>.
- Wang, Y., Shen, K., Yuan, C., 2025b. A sustainable direct recycling method for <sc>LMO</sc>/<sc>NMC</sc> cathode mixture from retired lithium-ion batteries in <sc>EV</sc>. *Energy Environ. Mater.* 8 (4). <https://doi.org/10.1002/eeem.212863>.
- Wei, G., Liu, Y., Jiao, B., Chang, N., Wu, M., Liu, G., Lin, X., Weng, X.F., Chen, J., Zhang, L., Zhu, C., Wang, G., Xu, P., Di, J., Li, Q., 2023. Direct recycling of spent Li-ion batteries: challenges and opportunities toward practical applications. In: *iScience*, vol. 26. Elsevier Inc. <https://doi.org/10.1016/j.isci.2023.107676>. Issue 9.
- Wolf, A., Nagler, F., Daubinger, P., Neef, C., Mandel, K., Flegler, A., Giffin, G.A., 2024. Circular battery design: investing in sustainability and profitability. *Energy Environ. Sci.* 17 (22), 8529–8544. <https://doi.org/10.1039/D4EE03418J>.
- Wu, C., Hu, J., Ye, L., Su, Z., Fang, X., Zhu, X., Zhuang, L., Ai, X., Yang, H., Qian, J., 2021. Direct regeneration of spent Li-ion battery cathodes via chemical relithiation reaction. *ACS Sustain. Chem. Eng.* 9 (48), 16384–16393. <https://doi.org/10.1021/acssuschemeng.1c06278>.
- Wu, X., Liu, Y., Wang, J., Tan, Y., Liang, Z., Zhou, G., 2024. Toward circular energy: exploring direct regeneration for lithium-ion battery sustainability. *Adv. Mater.* 36 (32). <https://doi.org/10.1002/adma.202403818>.
- Wu, J., Xiao, L., Liu, P., Zhu, Y., Li, J., 2025. Direct regeneration and upcycling of cathode material from spent lithium ion batteries: Recent advances and perspectives. *Sep. Purif. Technol.* 355, 129574. <https://doi.org/10.1016/j.seppur.2024.129574>.
- Xu, P., Tan, D.H.S., Jiao, B., Gao, H., Yu, X., Chen, Z., 2023. A materials perspective on direct recycling of lithium-ion batteries: principles, challenges and opportunities. In: *Advanced Functional Materials*, vol. 33. John Wiley and Sons Inc. <https://doi.org/10.1002/adfm.202213168>. Issue 14.
- Yang, J., Jiang, Q., Zhang, J., 2025. Bridging the regulatory gap: a policy review of extended producer responsibility for power battery recycling in China. *Energy Sustain. Dev.* 86, 101697. <https://doi.org/10.1016/j.esd.2025.101697>.
- Yang, J., Zhou, K., Gong, R., Meng, Q., Zhang, Y., Dong, P., 2023. Direct regeneration of spent LiFePO4 materials via a green and economical one-step hydrothermal process. *J. Environ. Manag.* 348, 119384. <https://doi.org/10.1016/j.jenvman.2023.119384>.
- Yang, T., Luo, D., Yu, A., Chen, Z., 2023. Enabling future closed-loop recycling of spent lithium-ion batteries: direct cathode regeneration. *Adv. Mater.* 35 (36). <https://doi.org/10.1002/adma.202203218>.
- Yang, X., Zhang, Y., Xiao, J., Zhang, Y., Dong, P., Meng, Q., Zhang, M., 2021. Restoring surface defect crystal of Li-Lacking LiNi 0.6 Co 0.2 Mn 0.2 O 2 material particles toward more efficient recycling of lithium-ion batteries. *ACS Sustain. Chem. Eng.* 9 (50), 16997–17006. <https://doi.org/10.1021/acssuschemeng.1c05809>.
- Yao, T., Zhang, H., Qi, C., Ma, J., Zhou, Z., Sun, Q., Song, L., Jin, Y., Zhang, M., 2024. Effective regeneration of waste LiFePO4 cathode material by Cu doping modification. *Appl. Surf. Sci.* 659, 159920. <https://doi.org/10.1016/j.apsusc.2024.159920>.
- Ye, X., Fei, X., Liu, M., Gao, H., Qiu, B., Yin, H., Zhang, Z., Lee, L.Y.S., 2025. Laser-induced regeneration of spent LiMn 2 O 4 cathode into high-performance Ni-doped LiMn 2 O 4 cathode. *Adv. Mater.* 37 (5). <https://doi.org/10.1002/adma.202416537>.
- Yue, L.-P., Lou, P., Xu, G.-H., Xu, H., Jin, G., Li, L., Deng, H., Cheng, Q., Tang, S., Cao, Y.-C., 2020. Regeneration of degraded LiNi0.5Co0.2Mn0.3O2 from spent lithium ion batteries. *Ionics* 26 (6), 2757–2761. <https://doi.org/10.1007/s11581-020-03479-8>.
- Zhang, B., Xu, Y., Silvester, D.S., Banks, C.E., Deng, W., Zou, G., Hou, H., Ji, X., 2024. Direct regeneration of cathode materials in spent lithium-ion batteries toward closed-loop recycling and sustainability. *J. Power Sources* 589, 233728. <https://doi.org/10.1016/j.jpowsour.2023.233728>.
- Zhang, H., Ji, H., Qu, H., Ji, G., Zhuang, Z., Wang, J., Zhou, G., 2025. Multifunctional spinel structure for efficient direct recycling of spent layered cathodes into fast-charging materials. *Adv. Mater.* 37 (24). <https://doi.org/10.1002/adma.202420467>.
- Zhao, T., Choi, Y., Wu, C., Zhang, Z., Wang, C., Liu, D., Xu, W., Huang, H., Huo, X., Zhao, W., Zhao, Z., Li, W., 2024. A review on direct regeneration of spent lithium iron phosphate: from waste to wealth. *Sci. Total Environ.* 957, 177748. <https://doi.org/10.1016/j.scitotenv.2024.177748>.