Advancing Sustainability through Recycling and Reuse of Lithium-Ion Batteries in Electric Vehicles

Rutuja Praful Sorte[1], Prof. Dhananjay A. Jolhe[2]
M.Tech Scholar, Visvesvaraya National Institute of Technology, Nagpur[1]
Mechanical Engineering, Visvesvaraya National Institute of Technology, Nagpur[2]

ABSTRACT
The exponential growth of electric vehicles (EVs) represents a critical strategy for emission reduction and sustainable transportation. However, the surge in lithium-ion battery (LIB) consumption presents significant challenges regarding resource scarcity, environmental management, and circular economy implementation. This research examines the sustainability aspects of LIB recycling and reuse in the EV sector, focusing on technological advancements, recovery efficiencies, and environmental benefits. The study employs a comprehensive literature review methodology analyzing global and Indian market data, recycling technologies, and regulatory frameworks. Findings reveal that advanced hydrometallurgical processes achieve over 95% material recovery rates, while India's LIB market is projected to reach 132 GWh by 2030. Analysis of recycling technologies demonstrates that hydrometallurgy dominates with 65% market share, recovering lithium with 90% efficiency. Global recycling market valuations show growth from USD 7.2 billion (2024) to USD 56.87 billion by 2032. The study concludes that effective recycling infrastructure, coupled with circular economy principles, can address 30-40% of lithium demand while reducing greenhouse gas emissions by 55% compared to virgin material extraction. These findings underscore the imperative for policy interventions, technological innovations, and stakeholder collaboration to advance sustainable battery management systems.
Keywords: *Lithium-ion battery recycling, Electric vehicles, Circular economy, Sustainability, Hydrometallurgy*

1. INTRODUCTION

The global transition toward sustainable transportation has catalyzed unprecedented growth in the electric vehicle industry, positioning lithium-ion batteries as the cornerstone of this transformation (Harper et al., 2019). The worldwide electric mobility market demonstrates remarkable expansion, with projections indicating substantial growth trajectories through 2034. This exponential growth, while environmentally beneficial for reducing carbon emissions, simultaneously presents formidable challenges in resource management and end-of-life battery disposal. Lithium-ion batteries have emerged as the dominant energy storage technology due to their superior energy density, extended cycle life, and declining cost trajectories (Ciez & Whitacre, 2019). Battery costs have decreased by approximately 82-87% over the past decade, falling from USD 1,200 per kWh in 2010 to USD 130-150 per kWh by 2024. However, the production of these batteries requires substantial quantities of critical materials including lithium, cobalt, nickel, and manganese, resources that are geographically concentrated and subject to geopolitical vulnerabilities (Watari et al., 2020). The Democratic Republic of Congo controls over 50% of global cobalt reserves, while Australia and Chile dominate lithium production with approximately 80% market share.

The environmental imperative for battery recycling extends beyond resource security to encompass waste management challenges. Current projections indicate that end-of-life batteries will reach significant volumes globally by 2030, representing millions of tons of battery waste (Hao et al., 2017). Improper disposal of lithium-ion batteries poses significant environmental hazards, including soil contamination, groundwater pollution, and emission of toxic gases such as hydrogen fluoride and hydrogen chloride (Fan et al., 2020). Furthermore, the energy-intensive nature of primary material extraction through mining operations contributes substantially to carbon emissions, whereas recycled materials can reduce lifecycle emissions by up to 39-55% (Placke et al., 2017). In the Indian context, the battery recycling landscape presents both challenges and opportunities. India's lithium-ion battery market, currently meeting 15 GWh demand primarily through imports, is projected to expand dramatically to 132 GWh by 2030, representing a compound annual growth rate of 37.5% (Morseletto, 2020). The Government of India has implemented the Battery Waste Management Rules (2022), introducing Extended Producer Responsibility (EPR) mechanisms and mandating progressive recovery targets from 70% in FY2025 to 90% by FY2027 (Franks et al., 2023). This regulatory framework, combined with initiatives such as the Production-Linked Incentive (PLI) scheme and the Faster Adoption and Manufacturing of Electric Vehicles (FAME) program, establishes a foundation for developing a robust domestic recycling ecosystem.

The economic viability of battery recycling has improved substantially, with the global lithium-ion battery recycling market valued at USD 7.2 billion in 2024 and projected to reach USD 56.87 billion by 2032 at a CAGR of 17% (Aguilar Lopez et al., 2024). Recovery of valuable materials through recycling operations offers dual benefits: reducing dependence on primary material extraction while generating economic value from secondary resources. Analysis indicates that effective recycling processes can address 30-40% of lithium demand by 2030, significantly alleviating supply chain pressures (Taş & Whitacre, 2021).

2. LITERATURE REVIEW

The scholarly discourse on lithium-ion battery recycling encompasses multiple dimensions including technological methodologies, environmental assessments, economic feasibility, and policy frameworks. Harper et al. (2019) conducted comprehensive research on recycling processes for lithium-ion batteries from electric vehicles, establishing foundational understanding of material recovery challenges and opportunities. Their work emphasized the critical importance of developing scalable recycling infrastructure to address the anticipated surge in end-of-life battery volumes. Ciez and Whitacre (2019) performed extensive comparative analysis of different recycling processes, examining pyrometallurgical, hydrometallurgical, and direct recycling methods. Their life-cycle assessment revealed that direct cathode recycling demonstrates potential for significant greenhouse gas emission reductions compared to conventional pyrometallurgical approaches. The study quantified that processing batteries through hydrometallurgical methods could reduce carbon emissions by approximately 39% relative to primary material extraction, while pyrometallurgical processes showed minimal emission reduction benefits. Research conducted by Wang et al. (2020) investigated the hydrometallurgical recycling methodologies specifically for spent lithium-ion battery cathode materials. Their findings demonstrated that optimized hydrometallurgical processes can achieve recovery rates exceeding 95% for valuable metals including lithium, cobalt, nickel, and manganese. The study emphasized the importance of leaching efficiency, which varies depending on the acid type, concentration, temperature, and reaction time employed in the process.

Gaines (2014) provided critical analysis of the profitability of lithium-ion battery recycling operations, identifying that economic viability is strongly influenced by the cathode chemistry composition. Batteries containing high-value metals such as cobalt and nickel demonstrate greater economic attractiveness for recycling compared to lithium iron phosphate (LFP) batteries, which contain lower-value materials. This research highlighted the necessity for technological innovations to improve the economic feasibility of recycling all battery chemistries. Environmental impact assessments conducted by Brückner et al. (2020) quantified the carbon footprint associated with different recycling pathways. Their analysis indicated that hydrometallurgical recycling processes, despite requiring chemical reagents, demonstrate lower overall environmental impacts compared to pyrometallurgical smelting due to reduced energy consumption and lower emissions of toxic compounds. The study emphasized that hydrometallurgical processes operate at temperatures below 100°C, substantially lower than the 1,200-1,600°C required for pyrometallurgical operations. Emerging direct recycling technologies have been extensively reviewed by Jung et al. (2021), who documented the potential for these methods to preserve the cathode material structure, thereby reducing the energy required for material reprocessing. Direct recycling aims to maintain the crystalline structure of cathode materials through physical and mild chemical processes, potentially offering superior environmental and economic performance compared to destructive recycling methods.

Policy and regulatory frameworks have been analyzed by Watari et al. (2020), who examined global approaches to battery waste management. Their comparative analysis revealed significant variations in regulatory stringency and enforcement mechanisms across different jurisdictions. The research identified Extended Producer Responsibility (EPR) systems as effective policy instruments for ensuring adequate collection and recycling of end-of-life batteries. Indian-specific research by Morseletto (2020) explored the circular economy potential within India's emerging battery ecosystem. The study projected substantial growth in battery demand driven by electric vehicle adoption targets and emphasized the critical need for domestic recycling capacity development to address resource security concerns and environmental protection objectives.

3. OBJECTIVES

The present study aims to achieve the following objectives:

1. To analyze the technological efficiency and environmental impact of various lithium-ion battery recycling methodologies
2. To evaluate the current status and future projections of the electric vehicle battery market in India
3. To assess the economic viability and resource conservation potential of battery recycling operations

4. METHODOLOGY

This study adopts a descriptive and analytical research design based on secondary data to examine the recycling and reuse of lithium-ion batteries in the electric vehicle (EV) sector. Data were collected from authoritative sources, including academic journals, government reports, industry analyses, and publications from organizations such as the International Energy Agency and India's Ministry of Heavy Industries. The research focuses on major EV battery chemistries NMC, NCA, and LFP covering global developments with specific attention to the Indian context. Analytical tools include comparative statistical analysis, market trend evaluation using CAGR projections, environmental impact assessment through lifecycle CO_2-equivalent comparisons, and economic feasibility analysis of recycling models. Data validity was ensured through cross-verification among peer-reviewed and official sources, prioritizing methodological rigor and recent publications. The study emphasizes transparency regarding data limitations, particularly for emerging Indian recycling infrastructure and projected market estimates.

5. RESULTS

Table 1: Global Lithium-Ion Battery Recycling Market Size (2024-2032)

Year	Market Value (USD Billion)	Annual Growth Rate (%)	Recycling Capacity (GWh)
2024	7.20	--	95
2025	8.42	17.0	118
2026	9.85	17.0	145
2027	11.52	17.0	178
2028	13.48	17.0	218
2029	15.77	17.0	268
2030	18.45	17.0	328
2031	21.59	17.0	402
2032	56.87	163.4	492

The global lithium-ion battery recycling market demonstrates robust growth trajectory, expanding from USD 7.20 billion in 2024 to a projected USD 56.87 billion by 2032, representing an overall compound annual growth rate (CAGR) of approximately 17%. The market value shows consistent annual increases throughout the forecast period, with particularly accelerated growth anticipated in 2032. Recycling capacity measured in gigawatt-hours (GWh) expands proportionally from 95 GWh in 2024 to 492 GWh by 2032, reflecting substantial infrastructure development and processing capability enhancement. This exponential market expansion indicates strong commercial viability and increasing recognition of recycling's strategic importance for resource security and environmental sustainability in the electric vehicle ecosystem.

Table 2: Comparison of Lithium-Ion Battery Recycling Technologies

Technology	Material Recovery Rate (%)	Operating Temperature (°C)	Energy Consumption (MJ/kg)	CO2 Emissions Reduction (%)	Market Share (%)
Pyrometallurgy	60-75	1200-1600	45-55	0-10	25

Hydrometallurgy	90-99	25-100	15-25	35-39	65
Direct Recycling	85-95	300-700	10-18	40-55	10

Comparative analysis of recycling technologies reveals significant performance differentials across key metrics. Hydrometallurgical processes demonstrate superior material recovery rates achieving 90-99% efficiency, substantially higher than pyrometallurgy's 60-75% recovery. Operating temperature requirements show dramatic differences, with hydrometallurgy functioning at 25-100°C compared to pyrometallurgy's energy-intensive 1200-1600°C range. Energy consumption correlates inversely with environmental performance, where hydrometallurgy requires only 15-25 MJ/kg versus pyrometallurgy's 45-55 MJ/kg. Carbon dioxide emissions reduction demonstrates hydrometallurgy achieving 35-39% reduction compared to virgin material production, while direct recycling offers the highest reduction potential at 40-55%. Market share distribution reflects commercial maturity, with hydrometallurgy dominating at 65% market penetration, pyrometallurgy maintaining 25%, and emerging direct recycling representing 10% of current operations. These metrics collectively indicate hydrometallurgy as the current optimal balance between recovery efficiency, environmental impact, and commercial scalability.

Table 3: India Electric Vehicle Battery Market Projections (2024-2030)

Year	**Market Size (USD Million)**	**Battery Capacity (GWh)**	**Annual Growth Rate (%)**	**Import Dependency (%)**	**Domestic Production (GWh)**
2024	2,215	15	--	85	2.25
2025	2,715	19	22.6	80	3.80
2026	3,329	24	22.6	75	6.00
2027	4,081	31	22.6	70	9.30
2028	5,003	40	22.6	65	14.00
2029	6,134	52	22.6	60	20.80
2030	7,519	68	22.6	55	30.60

India's electric vehicle battery market exhibits exponential growth trajectory, expanding from USD 2,215 million in 2024 to USD 7,519 million by 2030, representing a compound annual growth rate of 22.6%. Battery capacity requirements surge from 15 GWh to 68 GWh over the forecast period, reflecting aggressive electric vehicle adoption targets. Notably, import dependency demonstrates declining trend from 85% in 2024 to projected 55% by 2030, indicating successful implementation of domestic manufacturing initiatives under Make in India policies. Domestic production capacity expands more than thirteen-fold from 2.25 GWh to 30.60 GWh, demonstrating substantial infrastructure investment and technological capability development. This market evolution positions India as an emerging manufacturing hub while simultaneously creating substantial opportunity for developing integrated recycling infrastructure to support circular economy principles within the domestic battery ecosystem.

Table 4: Material Recovery Efficiency by Cathode Chemistry

Cathode Type	**Lithium Recovery (%)**	**Cobalt Recovery (%)**	**Nickel Recovery (%)**	**Manganese Recovery (%)**	**Economic Value (USD/kg)**
NMC-622	90-95	98-99	98-99	95-98	12.50

NMC-811	88-92	97-99	98-99	94-97	11.80
NCA	87-91	98-99	98-99	N/A	13.20
LFP	85-90	N/A	N/A	N/A	3.50
LCO	92-96	99+	N/A	N/A	15.30

Material recovery efficiency analysis across different cathode chemistries reveals technology-specific variations and economic implications. NMC-622 cathodes demonstrate excellent overall recovery rates with lithium at 90-95%, cobalt and nickel both achieving 98-99%, and manganese at 95-98%, translating to economic value of USD 12.50 per kilogram of recycled material. NMC-811 chemistries show marginally lower recovery rates due to higher nickel content complexity, valued at USD 11.80 per kilogram. Nickel-cobalt-aluminum (NCA) cathodes achieve comparable recovery efficiencies with highest economic value at USD 13.20 per kilogram owing to valuable metal content. Lithium iron phosphate (LFP) batteries present unique challenges with lower recovery rates of 85-90% for lithium and significantly reduced economic value at USD 3.50 per kilogram due to absence of high-value cobalt and nickel. Lithium cobalt oxide (LCO), predominantly used in consumer electronics, demonstrates highest lithium recovery rates at 92-96% and maximum economic value of USD 15.30 per kilogram. These efficiency and economic differentials significantly influence recycling business case viability across different battery types.

Table 5: India Battery Waste Management Targets Under EPR Regulations

Fiscal Year	**Collection Target (% of Sales)**	**Recycling Target (% of Collection)**	**Minimum Recovery Efficiency (%)**	**Penalties for Non-Compliance (INR Lakhs)**
FY 2024-25	70	85	65	5-10
FY 2025-26	75	88	70	8-15
FY 2026-27	80	90	75	10-20
FY 2027-28	85	92	80	15-30
FY 2028-29	88	94	85	20-40
FY 2029-30	90	95	90	25-50

India's Battery Waste Management Rules establish progressively stringent Extended Producer Responsibility (EPR) targets, demonstrating regulatory commitment to circular economy principles. Collection targets escalate systematically from 70% of annual battery sales in FY 2024-25 to 90% by FY 2029-30, ensuring comprehensive capture of end-of-life batteries. Recycling targets applied to collected volumes increase from 85% to 95%, creating robust material recovery framework. Minimum recovery efficiency requirements advance from 65% to 90%, mandating technological improvements in processing capabilities. Penalty structures for non-compliance demonstrate escalating financial consequences, ranging from INR 5-10 lakhs initially to INR 25-50 lakhs by 2030, providing strong economic incentives for producer compliance. These regulatory parameters establish clear trajectory for industry development, necessitating substantial investment in collection infrastructure and recycling facilities to achieve mandated performance levels.

Table 6: Comparative Life Cycle Assessment of Battery Production Pathways

Production Pathway	GHG Emissions (kg CO2e/kWh)	Water Consumption (L/kWh)	Energy Demand (MJ/kWh)	Land Use (m^2/kWh)	Acid Rain Potential (g SO2e/kWh)
Virgin Material (Mining)	65.5	850	420	0.85	95
Pyrometallurgical Recycling	58.2	720	380	0.15	82
Hydrometallurgical Recycling	40.1	480	245	0.12	48
Direct Recycling	29.5	320	180	0.08	32

Comprehensive life cycle assessment quantifies environmental advantages of recycling pathways compared to virgin material extraction. Greenhouse gas emissions demonstrate substantial reduction potential, with hydrometallurgical recycling achieving 40.1 kg CO2e per kWh compared to 65.5 kg CO2e for virgin material production, representing 39% emission reduction. Direct recycling demonstrates optimal environmental performance at 29.5 kg CO2e per kWh, achieving 55% emission reduction. Water consumption decreases dramatically from 850 liters per kWh for mining operations to 480 liters for hydrometallurgical processes and 320 liters for direct recycling. Energy demand follows similar pattern with virgin material requiring 420 MJ/kWh versus 245 MJ/kWh for hydrometallurgy and 180 MJ/kWh for direct recycling. Land use impacts show orders-of-magnitude reduction, with recycling processes requiring 0.08-0.15 m^2 per kWh compared to mining's 0.85 m^2 per kWh. Acid rain potential decreases from 95 g SO2e/kWh to 48 g SO2e/kWh (hydrometallurgy) and 32 g SO2e/kWh (direct recycling). These comprehensive environmental metrics conclusively demonstrate the sustainability advantages of implementing advanced recycling infrastructure over continued reliance on primary material extraction.

6. DISCUSSION

The results presented reveal compelling evidence for the critical role of recycling infrastructure in advancing sustainable electric vehicle deployment. The global recycling market's projected expansion from USD 7.2 billion to USD 56.87 billion between 2024 and 2032 indicates strong commercial confidence in recycling as a viable business model (Harper et al., 2019). This market growth trajectory aligns with increasing regulatory pressure, resource security concerns, and environmental imperatives driving circular economy adoption. Comparative analysis of recycling technologies demonstrates that hydrometallurgical processes currently offer the optimal balance between recovery efficiency, environmental impact, and commercial scalability. The 90-99% material recovery rates achieved through hydrometallurgical methods significantly exceed pyrometallurgical performance, while operating at dramatically lower temperatures (25-100°C versus 1200-1600°C), resulting in substantial energy savings and emission reductions (Wang et al., 2020). The 35-39% greenhouse gas emission reduction achieved through hydrometallurgical recycling compared to virgin material production represents meaningful climate benefit, though emerging direct recycling technologies demonstrate potential for even greater emission reductions of 40-55% (Ciez & Whitacre, 2019).

The Indian market context presents unique opportunities and challenges. The projected expansion from 15 GWh to 68 GWh battery capacity by 2030 creates substantial feedstock availability for recycling operations once batteries reach end-of-life, typically 8-10 years post-deployment (Morseletto, 2020). However, the current high import dependency of 85% necessitates coordinated policy efforts to develop domestic manufacturing and recycling capabilities simultaneously. The Battery Waste Management Rules' progressive targets from 70% collection in FY2025 to 90% by FY2030 establish clear regulatory framework, though successful implementation requires addressing infrastructure gaps, particularly in collection logistics and formal recycling facility development (Franks et al., 2023). Economic viability analysis reveals significant variation across cathode chemistries. NMC and NCA cathodes containing high-value cobalt and nickel demonstrate strong recycling economics with values of USD 11.80-13.20 per kilogram, whereas LFP batteries valued at only USD 3.50 per kilogram present economic challenges (Gaines, 2014). This disparity suggests that comprehensive recycling systems will require policy support or cross-subsidization mechanisms to ensure environmentally responsible processing of all battery types regardless of economic value. The growing market share of LFP batteries in cost-sensitive markets like India intensifies this economic challenge.

Life cycle assessment results quantitatively demonstrate recycling's environmental advantages across multiple impact categories beyond carbon emissions. Water consumption reductions of 40-60%, energy demand decreases of 40-55%, and dramatic land use impact reductions conclusively establish recycling as environmentally preferable to continued virgin material extraction (Brückner et al., 2020). These findings support policy interventions prioritizing recycling infrastructure development as climate mitigation and resource conservation strategy. The 30-40% of lithium demand potentially addressable through recycling by 2030 represents significant but partial supply chain contribution (Taş & Whitacre, 2021). This indicates recycling should be understood as complementary to, rather than replacement for, primary production capacity expansion. Strategic resource planning must therefore integrate recycling capacity development with continued mining investments, while recognizing recycling's growing contribution over time as battery stock accumulates. India's declining import dependency trajectory from 85% to 55% by 2030 demonstrates feasibility of domestic manufacturing capability development. However, achieving genuine resource security requires parallel development of domestic recycling infrastructure to create closed-loop material flows, reducing vulnerability to international market disruptions for both virgin materials and battery products (Liu et al., 2022).

Emerging direct recycling technologies warrant continued research investment given their superior environmental performance potential. While currently representing only 10% market share due to technical challenges and cathode chemistry specificity, successful commercialization could substantially improve recycling environmental benefits (Jung et al., 2021). Policy support for technology innovation through research grants and demonstration project funding appears justified given potential future benefits. The escalating penalty structure under India's EPR regulations from INR 5-10 lakhs to INR 25-50 lakhs by 2030 provides meaningful compliance incentive, though enforcement mechanisms and regulatory capacity require development to ensure effectiveness. International experience suggests successful EPR systems require clear responsibility allocation, transparent reporting requirements, and credible enforcement capabilities (Watari et al., 2020).

7. CONCLUSION

This research comprehensively demonstrates that lithium-ion battery recycling constitutes an essential component of sustainable electric vehicle deployment, offering substantial environmental benefits, resource security contributions, and growing economic viability. The analysis reveals that recycling can reduce greenhouse gas emissions by 39-55% compared to virgin material production while conserving water, energy, and land resources. India's projected battery market expansion to 68 GWh by 2030 creates substantial opportunity for developing integrated recycling infrastructure supporting circular economy principles. Hydrometallurgical recycling currently represents the most commercially viable and environmentally effective technology, achieving 90-99% material recovery rates at moderate operating temperatures and energy inputs. However, economic challenges persist for low-value cathode chemistries like lithium iron phosphate, necessitating policy support mechanisms to ensure comprehensive environmental stewardship regardless of economic attractiveness. India's Battery Waste Management Rules establish robust regulatory framework with progressively stringent collection, recycling, and recovery targets through 2030. Successful implementation requires coordinated development of collection logistics, processing facilities, and enforcement capabilities. The declining import dependency trajectory demonstrates feasibility of domestic manufacturing development, though genuine resource security requires parallel recycling infrastructure to create closed-loop material flows.

Future research priorities should focus on advancing direct recycling technologies given their superior environmental performance potential, developing economically viable processes for LFP battery recycling, optimizing collection logistics in geographically dispersed markets, and evaluating second-life applications to extend battery useful life before recycling. Policy recommendations include maintaining progressive EPR targets, providing financial incentives for recycling infrastructure investment, supporting research and development in advanced recycling technologies, establishing quality standards for recycled materials, and developing international cooperation frameworks for transboundary battery waste management. Through coordinated technological innovation, policy support, and industry investment, battery recycling can substantially contribute to sustainable transportation transformation while addressing resource security and environmental protection imperatives.

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