

Article

Sustainable Manufacturing and Recycling of Lithium-Ion Batteries: Circular Economy Pathways for Critical Minerals

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Abstract

India's rapid growth in electric vehicles and renewable energy systems is driving strong growth in lithium-ion battery demand. This study provides an India-specific life cycle assessment of manufacturing using imported primary materials with pathways incorporating domestically recycled materials. Two battery chemistries of strategic relevance to India, nickel-manganese-cobalt (NMC 532) and lithium iron phosphate (LFP), were evaluated using a functional unit of 1 kWh battery pack. The ReCiPe midpoint method was used to quantify the environmental impacts, with a focus on major emission indicators (CO₂, NO_x, SO_x, and PM₁₀) in the Indian electricity mix. The results show that NMC 532 batteries exhibit higher emissions than LFP batteries, largely due to the energy-intensive production of nickel and cobalt sulphate precursors. The incorporation of recycled materials substantially reduces emissions for both chemistries. It decreases by 30% for NMC532 and 36% for LFP. Hotspot analysis shows that precursor production, electricity use, and chemical inputs in hydrometallurgical recycling are the main causes of the remaining effects. This study shows that integrating recycling to India's LIB supply chain improves climate and air quality outcomes, enhances critical mineral recovery and supports sustainable manufacturing through circular economy pathways for India's battery and clean energy transition.

Keywords: life cycle assessment; lithium-ion batteries; India electricity-mix recycling; circular economy; critical minerals



Academic Editor: Hyunjung Kim

Received: 14 January 2026

Revised: 25 February 2026

Accepted: 25 February 2026

Published: 27 February 2026

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1. Introduction

India's clean energy transition aims to achieve 500 GW of non-fossil electricity capacity by 2030 and net-zero emissions by 2070 through rapid growth in electric mobility, renewable energy integration, and consumer electronics [1]. This transition has positioned domestic manufacturing to expand from 18 GWh in 2023 to nearly 150 GWh by 2030, aided by Production-Linked Incentive schemes for Advanced Chemistry Cell (ACC) manufacturing [2]. By 2030, India is expected to generate about 128 GWh of end-of-life (EoL) LIBs by 2030, emphasizing recycling as both an environmental and strategic opportunity.

However, India's battery value chain remains highly import-dependent for critical minerals such as lithium, cobalt, nickel, and copper. Cumulative demand for battery-active

materials, including lithium, cobalt, nickel, and manganese, is projected to exceed 250 kt between 2024 and 2030 [3]. Lithium demand is anticipated to rise from 1634 tonnes in 2022 to over 40,000 tonnes by 2030 [4], whereas cobalt supply continues to rely heavily on the Democratic Republic of Congo. Such dependency exposes the sector to supply volatility, price fluctuations, and geopolitical risks, with cumulative import exposure projected between USD 5–11 billion during 2024–2030. Copper, although partially available domestically, remains constrained by rising demand from battery manufacturing and grid infrastructure. India possesses approximately 163.9 million tonnes of copper reserves, yet increasing consumption continues to strain supply chains [5]. Environmentally, primary extraction contributes to groundwater depletion, habitat loss, and greenhouse gas emissions, whereas socially, it perpetuates unsafe mining and recycling practices linked to labour exploitation and health hazards.

Promoting recycling and circular material flows provides a pathway toward environmental sustainability, social equity, and economic resilience within India's battery ecosystem. In contrast, India's formal recycling rate for EoL batteries remains below 5%, with 70%–90% of LIB waste handled by the informal sector, often using unsafe and environmentally damaging practice. Beyond environmental implications, the dominance of informal recycling in India also raises significant social concerns. Informal lithium-ion battery dismantling often occurs without adequate protective equipment, emission controls, or chemical handling protocols, exposing workers to heavy metals, acidic leachates, and toxic fumes. Such practices can lead to occupational health risks, groundwater contamination, and community-level environmental injustice. Recycled battery materials can lower GHG emissions by up to 75% compared to virgin extraction and recover over 95% of lithium, cobalt, nickel, and copper. Expanding formal recycling could meet 30%–40% of domestic lithium demand by 2030, generate skilled employment, and reduce environmental pollution from informal waste processing. Emerging firms, including Attero Recycling, Lohum Cleantech, and Tata Chemicals, have already demonstrated industrial-scale recovery with high efficiency and material purity, signalling the maturation of a sustainable recycling industry. Integrating recycling with domestic manufacturing thus represents a critical step toward achieving India's energy security, resource independence, and sustainability goals. A circular LIB supply chain can enhance economic stability, reduce environmental burdens, and align industrial expansion with national missions such as Aatmanirbhar Bharat and the National Critical Mineral Mission.

Life cycle assessment (LCA) is a comprehensive framework to evaluate environmental impacts across all stages of production and use. It has been widely applied to assess sustainability green energy technologies such as wind turbines [6], wave energy [7], carbon capture and storage [8], battery recycling [9] and smartphones [10].

Ellingsen et al. (2014) [11] applied a process-based LCA to a 26.6 kWh NCM traction battery, reporting 4.6 t CO₂e cradle-to-gate, dominated by cell and electrode manufacturing, with electricity decarbonization identified as the key mitigation lever. Zackrisson et al. (2016) [12] carried out a cradle-to-grave LCA of lithium–air traction batteries, identifying high production impacts and environmental hotspots across the life cycle, with future benefits dependent on technological improvements and improved lithium toxicity modelling. Subsequent studies reveal significant variability in reported emissions. Ellingsen et al. (2017) [13] observed a wide range from 38 to 356 kg CO₂-eq/kWh. Deng et al. (2018) [14] compared next-generation 63 kWh NMC–SiNT EV batteries with NMC–graphite, finding 10%–17% higher global warming but 39%–56% lower toxicity, indicating better overall sustainability potential for the advanced chemistry.

Ioakimidis et al. (2019) [15] evaluated second-life LFP EV batteries in Spanish smart buildings, showing that reuse plus PV integration significantly lowers environmental

burdens relative to new battery production. Aichberger and Jungmeier (2020) [16] reviewed 50 LCA studies and reported an average of about 120 kg CO₂-eq/kWh for lithium-ion battery production. Kallitsis et al. (2020) [17] assessed advanced LIBs with nickel-rich cathodes and silicon-graphite anodes, concluding that Chinese-made cells have about 40% higher GWP mainly from metal use, partially offset by higher energy density and efficiency. Sun et al. (2020) [18] used primary Chinese industry data to show that cathode production, aluminium, and electrolytes dominate LIB environmental impacts, whereas recycling and chemistry shifts (NCM622 to NCM811) alter toxicity and other burdens. Yuan et al. (2021) [19] demonstrated via LCA that water-based manufacturing of a 57 kWh NMC-graphite battery cuts manufacturing energy by 43% and reduces cradle-to-gate impacts by up to 88% versus conventional processes. Zhao et al. (2021) [20] synthesized 76 LIB LCAs and reported an average of 187.26 kg CO₂eq/kWh and 42.49 kWh/kg cumulative energy demand, highlighting variability by chemistry and region and stressing repurposing and recycling for sustainability. Rajaeifar et al. (2021) [21] compared three pyrometallurgical LIB recycling routes and found DC plasma with pre-treatment can cut GWP by up to fivefold, making it the most environmentally favourable option.

Chemistry choice and manufacturing geography strongly influence impacts. Yang et al. (2022) [22] modelled BEVs using LFP, NCM, LMO, and LTO chemistries, finding LFP best for GWP and acidification, NCM preferable for fossil depletion and toxicity, and LTO worst overall, with future advances improving BEV performance. Wang et al. (2022) [23] showed in a cradle-to-grave LCA of Chinese LFP EV batteries that second-life use and recycling substantially reduce environmental impacts, fossil depletion, and virgin metal demand. Castro et al. (2022) [24] analysed an industrial LIB recycling chain and identified citric acid as a main impact driver, while whereas its reuse and anode recovery delivered environmental credits and economic feasibility. Tao et al. (2023) [25] built an integrated LCA model for ternary LIBs in China, ranking five recycling technologies and pinpointing key drivers of environmental impact to support sustainable end-of-life and EV policy. Shen et al. (2023) [26] developed a process-based LCA for direct NMC-graphite battery recycling, showing that closed-loop direct recycling can cut impacts by up to 54% relative to conventional open-loop production. Hemmati et al. (2024) [27] evaluated LFP BESS in Lombok and found that manufacturing dominates most impact categories, operations drive global warming, and the system is both environmentally beneficial and economically viable with a short payback time. Kobayashi et al. (2024) [28] proposed an accounting framework for LIB life cycle CO₂ that avoids double counting across manufacturing, reuse, and recycling, demonstrating that extended use and efficient battery-to-battery recycling markedly reduce emissions.

Manjong et al. (2024) [29] used parametric process-based LCA for LFP and NMC811 batteries across 30 supply-chain scenarios, showing that GHG emissions span 27–155 kg CO₂e/kWh and are highly sensitive to ore grade, recovery, and electricity mix. Narimani-Qurtlar et al. (2024) [30] assessed lithium-oxygen cathodes and found that active material synthesis dominates impacts, with rGO/ α -MnO₂/Pd having the highest emissions and underscoring the need for greener production routes. Zhu et al. (2024) [31] compared four potassium-ion battery types to LiFePO₄, concluding that K-ion systems, especially KFeSO₄F, lower toxicity and material scarcity but currently suffer higher GWP and fossil depletion due to low energy density. Tas et al. (2024) [32] combined Statistical Entropy Analysis with LCA to evaluate LIB recycling, revealing trade-offs between critical metal recovery and environmental burdens and providing a decision tool for circular process optimization. Ali et al. (2024) [33] simulated NMC LIB recycling under EU regulations and showed that economic value-based allocation cuts the carbon footprints of cobalt and nickel sulphates by 73.5% and 57.4% while increasing that of lithium carbonate by 20.8%.

Clemente et al. (2025) [34] meta-analysed LIB LCAs and reported a median manufacturing footprint of 17.63 kg CO₂e/kg, emphasizing that clean electricity and large-scale production reduce emissions but full supply-chain decarbonization remains essential. Almahri et al. (2025) [35] showed that the hydrometallurgical remanufacturing of NMC LIBs lowers GHG emissions and costs by about 10%, whereas pyrometallurgical routes are generally uneconomic, with outcomes strongly dependent on chemistry and regional policy.

Chen et al. (2025) [36] linked design features to recyclability using structural models and expert input, finding that cell-to-pack and cell-to-body concepts improve recycling efficiency and cut life cycle impacts despite higher upfront production costs. Pang et al. (2025) [37] integrated LCA and techno-economics for cathode recycling, concluding that hydrometallurgy is environmentally preferable to pyrometallurgy and that regeneration routes can boost recovery, though profitability hinges on context and collection rates. Gaalich et al. (2025) [38] assessed a CO₂-assisted direct recycling process for NMC622 production scrap and showed lower impacts than incineration, pyro-, and hydrometallurgy, with energy and solvent use identified as key optimization targets. Chen et al. (2025) [39] used material flow, LCA, and scenarios to project CO₂ from China's LIB industry, indicating a peak of 44.74 Mt CO₂e in 2023 and a potential decline to 0.12 Mt CO₂e by 2060 under strong technology, energy, and circularity measures. Maruti et al. (2025) [40] applied Remaining Useful Life prediction and a 5R strategy in an industrial case study, showing that coordinated recovery, reuse, repair, remanufacturing, and recycling substantially reduce LIB waste and enhance resource efficiency. Hanna et al. (2025) [41] compared conventional and truncated hydrometallurgy with pyrometallurgy across regions, finding truncated hydrometallurgy minimizes carbon, water, and toxicity impacts and that North American recycling and manufacturing significantly lowers NMC811 footprints.

Kar et al. (2025) [42] evaluated four pretreatment options for spent LIBs and concluded that cryogenic discharge and solvent-free grinding offer optimal technical and environmental performance, whereas NaCl discharge and NMP-based routes pose safety or impact concerns. Zhang et al. (2025) [43] reviewed LIB recycling technologies and stressed that combining advanced pyro-, hydro-, and direct routes with strong regulation and circular-economy policies is key to improving material recovery and environmental outcomes. Gutsch et al. (2024) [44] jointly assessed costs and impacts for NMC811 cathode synthesis, cell manufacturing, and hydrometallurgical recycling, showing material production dominates burdens and that recycling plus clean energy significantly cuts GWP and overall costs.

Das et al. (2022) [45] compared the life cycle GHG emissions of EVs and ICEVs in India, finding that EVs emit more (0.32–0.37 kg CO₂eq/km) than ICEVs (0.24–0.27 kg CO₂eq/km) due to India's carbon-intensive grid. Cleaner electricity, efficient production, and recycling are needed to cut emissions. Singhal et al. (2025) [46] assessed the life cycle and techno-economic performance of grid-scale storage options in India. Pumped hydro showed the lowest cost and environmental impact, whereas vanadium redox-flow systems were the least sustainable and most costly. Abhiraman et al. (2025) [47] evaluated the life cycle impacts of NMC and LFP EV batteries via OpenLCA[®] and ReCiPe 2016. NMC had almost double the emissions and six times higher water use than LFP, affirming LFP's environmental advantage and the need for better recycling infrastructure.

Most existing LIB LCA studies are based on supply chains in Europe and China, where electricity systems are comparatively less carbon-intensive and recycling infrastructure is well established. In contrast, India's grid remains largely coal-dependent, significantly influencing the emission intensity of energy-intensive processes such as precursor synthesis and hydrometallurgical recycling. Additionally, India's recycling ecosystem is still

emerging, with substantial informal-sector participation and limited industrial-scale closed-loop capacity.

Furthermore, India lacks domestic mining and refining of key battery minerals, resulting in high reliance on imported battery-grade materials. These structural differences are rarely reflected in international LCA models. To address this gap, the present study develops an India-specific cradle-to-gate LCA framework that compares imported primary material pathways with domestically recycled pathways under realistic electricity and supply-chain conditions.

This study's goal was to use a life cycle assessment (LCA) approach to assess the environmental performance of lithium-ion battery production in India, with an emphasis on circular economy pathways for critical minerals. This study compares manufacturing based on imported primary materials and domestically recycled materials for NMC 532 and LFP battery chemistries in light of the lack of domestic raw material extraction. The evaluation looked at the impact of the Indian electricity mix and a decarbonized grid scenario and quantified important air emission indicators (CO_2 , NO_x , SO_x , and PM_{10}) per functional unit of a 1 kWh battery pack.

2. Materials and Methods

This study used LCA approach in accordance with ISO 14040–ISO 14044 [48–52] standards to investigate the environmental impact of lithium-ion battery manufacturing in India. The assessment used cradle-to-gate system boundaries, excluding raw material mining due to the lack of domestic extraction, and examined production using imported primary materials and domestically recycled resources. The functional unit is described as a 1 kWh lithium-ion battery pack for two chemistries: NMC 532 and LFP. Life cycle inventory (LCI) data were gathered from the literature, industry reports, and GREET databases [53–57], with power modeled using the Indian grid mix. The ReCiPe Midpoint technique was used to assess the life cycle impact, with an emphasis on key air emission indicators such as CO_2 , NO_x , SO_x , and PM_{10} , and findings were compared across primary and recycled material pathways, as well as electricity scenarios.

2.1. Goal and Scope of the Study

The purpose of this Life Cycle Assessment (LCA) study was to statistically assess and compare the environmental implications of lithium-ion battery (LIB) manufacturing in India utilizing (i) primary materials and (ii) recycled materials within a circular economy framework. This study attempts to assess the environmental impact of LIB production in India and determine the possible environmental benefits of using recycled materials into the battery production supply chain.

The scope included a cradle-to-gate life cycle study of lithium-ion battery manufacturing in India, including two comparable scenarios.

Scenario 1 (Primary Material Pathway): Batteries are manufactured with imported refined primary materials.

Scenario 2 (Recycled Material Pathway): Batteries are manufactured utilizing secondary materials collected from end-of-life LIBs via recycling methods.

2.1.1. Functional Unit

The functional unit for this LCA is specified as the production of 1 kWh of lithium-ion battery capacity, allowing for direct comparisons between supply chains employing imported primary materials and domestically recycled resources.

2.1.2. System Boundary

The life cycle evaluation used a cradle-to-gate system boundary, as shown in Figure 1, beginning at the battery-grade material stage and extending to battery pack manufacturing in India. Upstream mining, beneficiation, and the primary refining of lithium, nickel, and cobalt were excluded, as these processes occur outside India and fall beyond the national manufacturing system under study. The objective was to evaluate India-specific manufacturing and recycling pathways under the Indian electricity-mix and industrial conditions. Including global extraction would introduce geographical and methodological variability, reducing comparability. Defining the boundary at the battery-grade material stage ensures consistency between primary and recycled pathways while isolating the effects of Indian energy intensity, recycling technologies, and industrial practices.

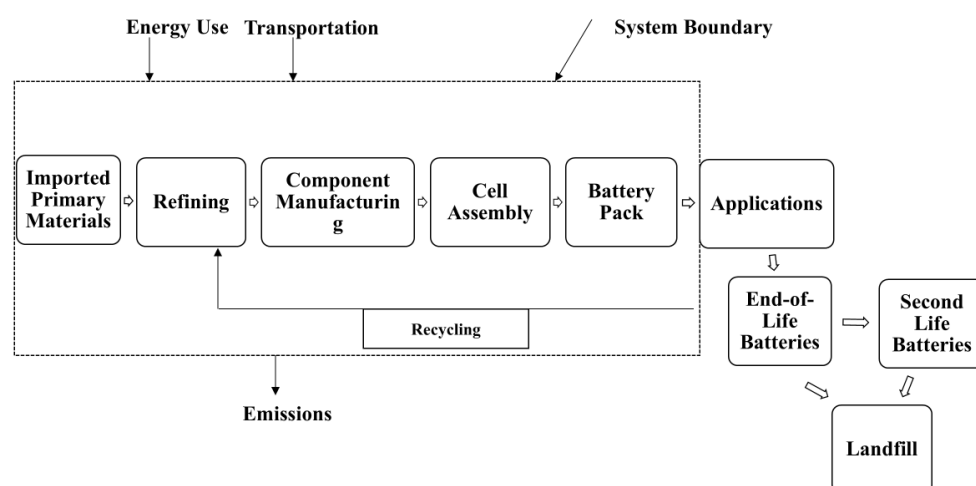


Figure 1. System Boundaries for the LIB manufacturing and recycling supply chain.

Table 1 presents the scope of the current study, defining the inclusion and exclusion criteria of the life cycle stages in the analysis. Global mining, beneficiation, refining, and the international transportation of imported battery-grade materials were excluded to maintain a consistent India-focused system boundary. Inclusion of these upstream stages may increase the environmental intensity of the primary material pathway.

Table 1. System boundary conditions.

Life Cycle Stage	Primary Material Pathway	Recycled Material Pathway
Raw material extraction	Excluded (no mining in India)	Excluded
Material refining	Included (imported battery-grade materials)	Included (recycling and purification)
Transportation	Included (average)	Included
Cell manufacturing	Included	Included
Module and pack assembly	Included	Included
Use phase	Excluded	Excluded
End-of-life	Excluded	Recycling considered as input
Infrastructure	Excluded	Excluded

2.2. Key Inventory Inputs

Battery-grade lithium compounds such as lithium carbonate, as well as nickel, cobalt, and manganese salts needed for the production of cathode precursors and active materials, were included in the life cycle inventory for the primary material pathway. For the production of anodes, natural or synthetic graphite was taken into consideration. Current

collectors and structural elements are made of metallic materials, such as copper and aluminum foils. Energy inputs included process heat delivered by electricity or natural gas, depending on the manufacturing step, and electricity modeled using the Indian grid mix. End-of-life LIBs collected in India were the primary input for the recycled material pathway. Electricity and process chemicals needed for recycling operations were specifically considered, particularly for hydrometallurgical processes such as pretreatment (discharge and dismantling and shredding and separation), leaching, purification, and precipitation. The inventory accounts for the management of slag, residues, and other process wastes, as well as the water consumption related to recycling and material recovery procedures. The life cycle inventory for precursor and active material production, cell, module and pack components, recycling and recovery processes are presented in Tables 2–5 and all inputs are normalized per kWh of battery capacity. The data in Tables 2 and 3 were extracted from secondary data from the GREET model. For the production of the NMC532 precursor corresponding to 1 kWh of battery pack capacity, approximately 1.6211 kg of precursor was required. Table 2 presents the data for the material input (NiSO_4 , CoSO_4 , MnSO_4 , NaOH , NH_4OH , Li_2CO_3 , Fe_3O_4 , di-ammonium phosphate), along with utility consumption (water and energy). Table 3 presents the material inputs for cell, module and pack manufacturing. Tables 4 and 5 presents the inventory data for chemical use, water consumption and energy inputs for pretreatment and hydrometallurgical recycling.

Table 2. LCI for manufacturing from imported primary materials.

NMC532 Precursor Production		LFP Cathode Material Production	
Material inputs	kg/kWh Battery pack	Material inputs	kg/kWh Battery pack
NiSO_4	1.4071	Li_2CO_3	0.4749
CoSO_4	0.8008	Iron oxide	1.0118
MnSO_4	0.5674	Diammonium phosphate	1.7345
NaOH (100%)	1.4428	Energy consumption	MJ/kWh Battery pack
NH_4OH (100%)	0.2010	Natural gas	20.4
Water consumption	L/kWh Battery pack	Electricity	64.6
Water	1.0346		
Energy consumption	MJ/kWh Battery pack		
Natural gas	66.0497		
NMC532 Cathode material Production via Calcination			
Material inputs	kg/kWh Battery pack		
NMC532 Precursor	1.6211		
Li_2CO_3	0.6536		
Energy consumption	MJ/kWh Battery pack		
Electricity	39.2201		
Non-combustion process emissions	kg/kWh Battery pack		
CO_2	0.3577		

In the present study, hydrometallurgical recycling was selected as the representative end-of-life pathway because it is the most commercially established and industrially deployed technology in India. Leading recyclers, such as Attero Recycling, Lohum Cleantech, SungEel India Recycling, and Tata Chemicals, predominantly utilize hydrometallurgical processes for the recovery of lithium, nickel, cobalt, and manganese in battery-grade form, enabling reintegration into precursor and cathode production. Therefore, hydrometallurgy was adopted as a realistic industrial baseline.

In this study, recycled materials recovered through hydrometallurgical processes are assumed to meet battery-grade purity requirements and are therefore modelled using the same downstream precursor synthesis and cathode manufacturing configurations as

primary materials. This assumption reflects current industrial practice, where recycled lithium carbonate and transition metal salts are refined to equivalent specifications before reintegration into cathode production. Recycling-specific stages, including pretreatment and hydrometallurgical recovery, are explicitly modelled with dedicated energy, chemical, and water inputs (Tables 4 and 5). Thus, this approach enables consistent comparison between primary and recycled scenarios while accounting for recycling-stage burdens.

Table 3. Cell, module, and pack manufacturing inventory.

Components	Quantity (kg/kWh Battery Pack)	
	NMC 532	LFP
Material input		
Cell components		
Cathode	1.7154	2.0649
Anode (Graphite)	0.8792	1.0544
Carbon black	0.0357	0.0431
Binder (PVDF)	0.0537	0.0646
Copper	0.3112	0.4660
Aluminium	0.1754	0.2620
Electrolyte: LiPF ₆	0.0585	0.1024
Ethylene Carbonate	0.1633	0.2860
Dimethyl Carbonate	0.1633	0.2860
Plastic: Polypropylene	0.0351	0.0458
Polyethylene	0.0079	0.0102
Polyethylene Terephthalate	0.0082	0.0116
Module components		
Copper	0.0059	0.0068
Aluminium	0.1666	0.2285
Plastic: Polyethylene	0.0018	0.0018
Insulation	0.0016	0.0017
Electronic part	0.0159	0.0159
Pack components		
Copper	0.0013	0.0014
Aluminium	0.4293	0.5152
Steel	0.0259	0.0384
Insulation	0.0137	0.0164
Coolant	0.1204	0.1550
Electronic part	0.0598	0.0637

Table 4. LCI for the recycling of domestic materials—pretreatment stage (per kWh Battery pack).

Input	NMC 532	LFP	Unit
Nitrogen	0.2225	0.2872	kg
Lime	0.1424	0.2009	kg
Diesel	2.6702	3.4440	MJ
Natural gas	8.9008	11.4800	MJ
Electricity	0.8900	1.1480	MJ
Process water	1.6843	2.1726	L
Output			
Black mass	2.8347	3.5129	kg
Aluminium	0.3026	0.4305	kg
Copper	0.4005	0.5740	kg
Steel	0.1780	0.2066	kg
Flue dust	0.0045	0.0057	kg
Solid waste	0.6542	0.9012	kg
Waste water	1.6866	2.1755	kg

Table 5. Hydrometallurgical recycling inventory (per kWh Battery pack).

Input	NMC 532	LFP	Unit
Sulfuric Acid	4.3739	0.70258	kg
Hydrogen Peroxide	0.3033	-	kg
Sodium Hydroxide	2.8602	-	kg
Soda Ash	0.9411	0.7588	kg
Lime	0.0016	0.0021	kg
Water	21.4609	26.5955	L
Diesel	1.70082	2.1077	MJ
Natural gas	5.4653	5.6347	MJ
Electricity	2.5512	3.1616	MJ
Output			
Lithium Carbonate (crude)	0.6435	0.5199	kg
Co ²⁺ in product	0.2069	-	kg
Ni ²⁺ in product	0.5159	-	kg
Mn ²⁺ in product	0.2891	-	kg
Graphite	0.9241	1.0152	kg
Solid Waste	0.6775	2.0515	kg
Wastewater	29.0925	27.9135	kg

3. Results and Discussion

This section presents the life cycle assessment results for lithium-ion battery manufacturing in India, comparing primary material-based and recycled material-based pathways for NMC 532 and LFP chemistries. The analysis focuses on key air emission indicators, including CO₂, NO_x, SO_x, and PM₁₀, evaluated per functional unit of 1 kWh battery pack. The results are discussed at both the process and life cycle stage levels to identify major environmental hotspots and the influence of material sourcing and electricity mix. The implications of integrating recycling into domestic battery manufacturing are subsequently examined from a circular economy perspective.

3.1. Emissions from NMC532 and LFP Cathode Active Material Production

Emissions were calculated using a process-based approach according to Equation (1), where emissions of pollutant were obtained by summing the contributions from material inputs and energy consumption.

$$\text{Emission}_i = \sum [(MI_j \times EF_{i,j}) + (EI \times EF_i)] \quad (1)$$

where Emission is the total emission of pollutant I over the system boundary; i represents the type of pollutant; j represents each individual material and chemical input; MI is the material input; EF_{i,j} is the emission factor of pollutant I for the material j; and EI is the energy input.

Figure 2 represents the emissions associated with the production of NMC532 and LFP cathode active material production and demonstrates that NMC532 exhibits 49 kg CO₂-eq/kWh, whereas LFP shows a substantially lower value of about 27.6 kg CO₂-eq/kWh, indicating nearly 44% lower carbon intensity for LFP. For gaseous pollutants, NMC 532 also demonstrates consistently higher emissions. NO_x emissions were 0.074 kg No_x-eq/kWh for NMC 532 compared to 0.040 kg No_x-eq/kWh for LFP. Similarly, SO_x emissions were about 0.096 kg SO_x-eq/kWh for NMC 532 and 0.051 kg SO_x-eq/kWh for LFP. PM₁₀ emissions were comparatively small in magnitude but followed the same trend, with NMC 532 emitting around 0.009 kg PM₁₀-eq/kWh, nearly double that of LFP at 0.004 kg PM₁₀-eq/kWh. Overall, the results demonstrate that NMC 532 consistently imposes higher climate and air pollution burdens per kWh than LFP, primarily due to the energy- and sulphate-intensive

production of nickel and cobalt-based precursors. This difference primarily arises from the higher material intensity and energy demand associated with nickel- and cobalt-rich precursor synthesis, which have greater embodied emissions than LFP compounds, and the higher calcination energy required for NMC processing under India's coal-dominated electricity mix. A $\pm 10\%$ variability was also applied to key inventory inputs, including energy consumption and emission factors, reflecting data uncertainty

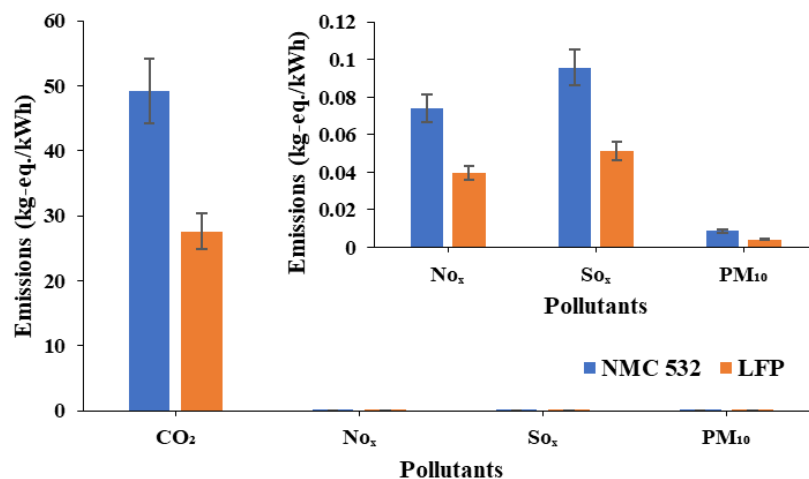


Figure 2. Comparison of emissions between NMC532 and LFP cathode active material production.

3.2. Emissions from the Cell, Module and Pack Components for NMC532 and LFP

Figure 3 presents the total emissions from cell, module and pack manufacturing for NMC532 and LFP batteries. CO₂ emissions dominate the impact profile, with NMC 532 emitting 72 kg CO₂-eq/kWh, compared to about 56 kg CO₂-eq/kWh for LFP, representing nearly a 22% higher carbon intensity for NMC 532. A similar trend was observed for gaseous pollutants. NO_x emissions were approximately 0.11 kg NO_x-eq/kWh for NMC 532 and 0.09 kg NO_x-eq/kWh for LFP. SO_x emissions were around 0.146 kg SO_x-eq/kWh for NMC 532, compared to 0.127 kg SO_x-eq/kWh for LFP. PM₁₀ emissions were lower in magnitude but remained higher for NMC 532 (≈ 0.015 kg PM₁₀-eq/kWh) than for LFP (≈ 0.020 kg PM₁₀-eq/kWh), showing comparable particulate burdens. Overall, the results indicate that NMC 532 imposes consistently higher climate and air pollutant emissions across manufacturing stages, primarily due to its greater material intensity, higher nickel and cobalt content relative to LFP.

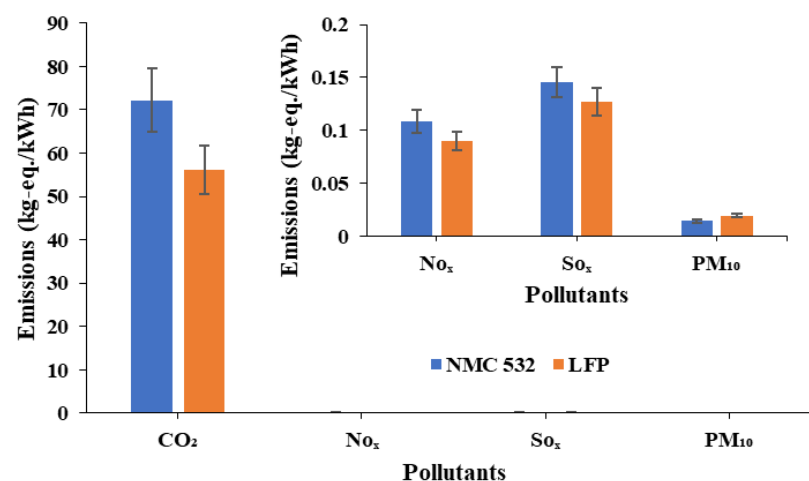


Figure 3. Comparison of emissions: NMC532 and LFP cell, module and pack components.

3.3. Validation with Previous Studies

Table 6 presents the validation of the results of the present study from previous studies. In the present study, the projected cradle-to-gate carbon intensities of 72.22 kg CO₂-eq/kWh for NMC532 and 56.2 kg CO₂-eq/kWh for LFP correlate with values reported in the LCA literature review, demonstrating the validity of the evaluation. Ellingsen et al. (2017) [13] found a range of 38–356 kg CO₂-eq/kWh, where both values fall comfortably, with the LFP value close to the lower bound. The NMC532 result falls slightly below the average of ~120 kg CO₂-eq/kWh reported by Aichberger and Jungmeier (2020) [16] and significantly lower than the aggregated average of ~187 kg CO₂-eq kWh^{−1} reported by Zhao et al. (2021) [20], indicating differences in system boundaries, electricity mix, and data vintage. Recent reviews by Manjong et al. (2024) [29] reported 27–155 kg CO₂-eq/kWh, with LFP consistently showing lower emissions than NMC due to its simpler chemistry and the absence of Ni and Co. Overall, the agreement with multiple review studies and the reproduction of established chemistry-dependent trends demonstrate that the present results are robust and well justified for journal publication. These differences may be due to the differences in system boundary definition, electricity-mix assumptions, battery and technological assumptions and variations in functional units.

Table 6. Validation of the present results with previous literature.

Literature Review	kg CO ₂ -eq/kWh
Present study	72.22 for NMC532 and 56.2 for LFP
Ellingsen et al. (2017) [13]	38–356
Aichberger and Jungmeier (2020) [16]	120
Zhao et al. (2021) [20]	187.26
Manjong et al. (2024) [29]	27–155
Patil et al. (2025) [58]	95.49 (coal-powered); 76.27 (electricity mix)

3.4. Emission Potential of Recycled Materials for NMC532 and LFP Batteries Manufacturing

Figure 4a illustrates the effect of incorporating recycled materials on total emissions of NMC532 and LFP batteries. Without recycling, CO₂ emissions were approximately 72 kg CO₂-eq/kWh, which decreased to about 50 kg CO₂-eq/kWh when recycled inputs were integrated, representing a reduction of nearly 30%. A similar declining trend was observed for other air pollutants. NO_x emissions decreased from around 0.11 kg NO_x-eq/kWh to 0.08 kg NO_x-eq/kWh, whereas SO_x emissions reduced from approximately 0.145 kg SO_x-eq/kWh to 0.10 kg SO_x-eq/kWh. PM₁₀ emissions also declined from about 0.014 kg PM₁₀-eq/kWh to roughly 0.009 kg PM₁₀-eq/kWh, indicating nearly a 34% reduction in particulate emissions. Overall, the results demonstrate that integrating recycling into the NMC 532 supply chain substantially lowers GHG and air pollutant emissions by avoiding energy-intensive primary metal refining and reducing upstream material production burdens under the Indian electricity mix.

Figure 4b presents the influence of recycling on the environmental performance of LFP batteries per 1 kWh. In the absence of recycling, CO₂ emissions were approximately 56 kg CO₂-eq/kWh, which decreased to nearly 36 kg CO₂-eq/kWh when recycled materials were incorporated, reflecting a reduction of about 36%. Similar trends were observed for other air pollutants. NO_x emissions declined from around 0.09 kg NO_x-eq/kWh to 0.06 kg NO_x-eq/kWh, whereas SO_x emissions decreased from approximately 0.127 kg SO_x-eq/kWh to 0.08 kg SO_x-eq/kWh. PM₁₀ emissions were comparatively lower in magnitude but showed a notable reduction from about 0.019 kg PM₁₀-eq/kWh to 0.014 kg PM₁₀-eq/kWh. Overall, the integration of recycling substantially reduced greenhouse gas and air pollutant

emissions for LFP batteries by lowering dependence on energy-intensive primary material production and mitigating upstream processing burdens.

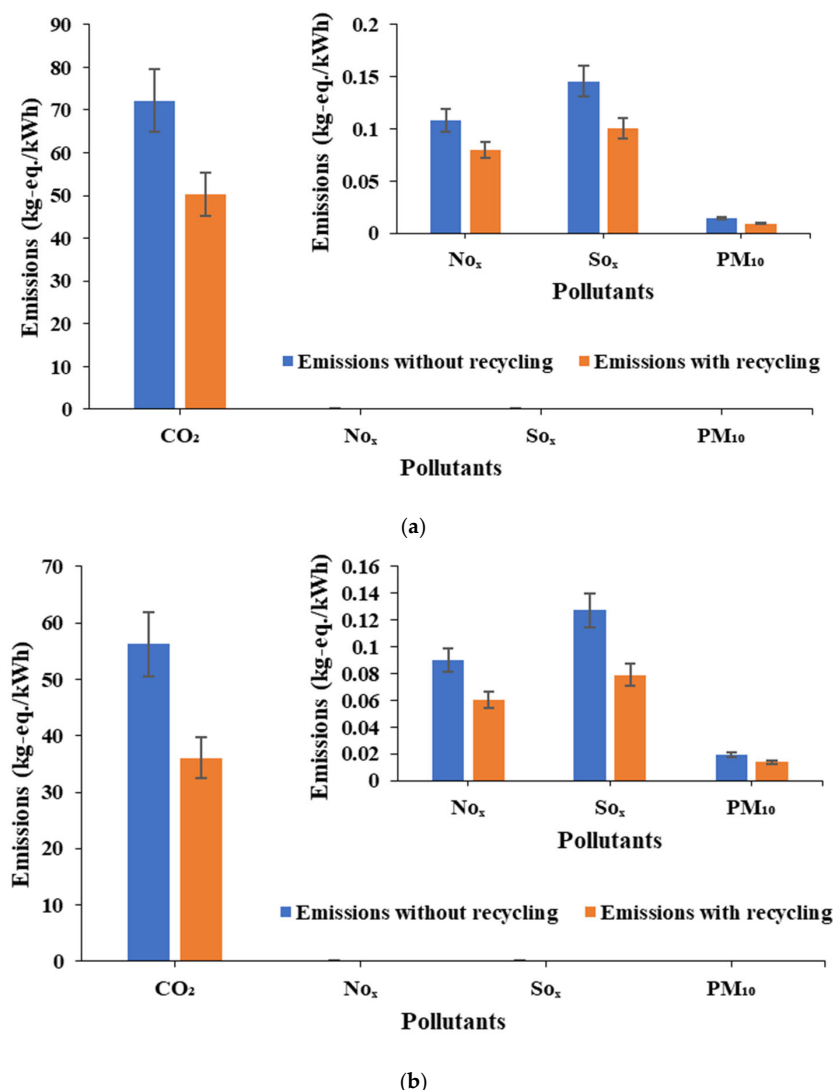


Figure 4. (a) Pollutant emissions from NMC 532 battery manufacturing with and without recycling. (b) Pollutant emissions from LFP battery manufacturing with and without recycling.

The error bars shown in Figure 4 represent a $\pm 10\%$ variability applied to the emission estimates to account for uncertainties in energy consumption, material inputs, and process efficiencies. This sensitivity range reflects possible fluctuations in operational conditions and data sources.

Figure 5 presents the avoided emission credits. It quantifies the environmental benefits achieved through recovery of the materials. For NMC 532, recycling results in avoided emissions of 29.78 kg CO₂-eq/kWh, 0.046 kg NO_x-eq/kWh, 0.067 kg SO_x-eq/kWh, and 0.0074 kg PM₁₀-eq/kWh. Similarly, LFP demonstrates avoided emission credits of 23.49 kg CO₂-eq/kWh, 0.036 kg NO_x-eq/kWh, 0.054 kg SO_x-eq/kWh, and 0.0062 kg PM₁₀-eq/kWh. The higher avoided emission credits for NMC 532 reflect the greater environmental burden associated with primary nickel and cobalt production, indicating stronger emission mitigation potential through recycling compared to LFP.

Although NMC532 achieves a smaller absolute CO₂ reduction due to the avoidance of carbon-intensive nickel and cobalt refining, LFP exhibits a higher percentage reduction (36%) because its baseline precursor emissions are lower and more directly influenced by

process energy inputs. In the case of LFP, recycling significantly offsets energy-related emissions associated with lithium carbonate production, resulting in a larger proportional decrease relative to its initial footprint. Therefore, the higher percentage reduction reflects relative baseline differences rather than greater absolute mitigation.

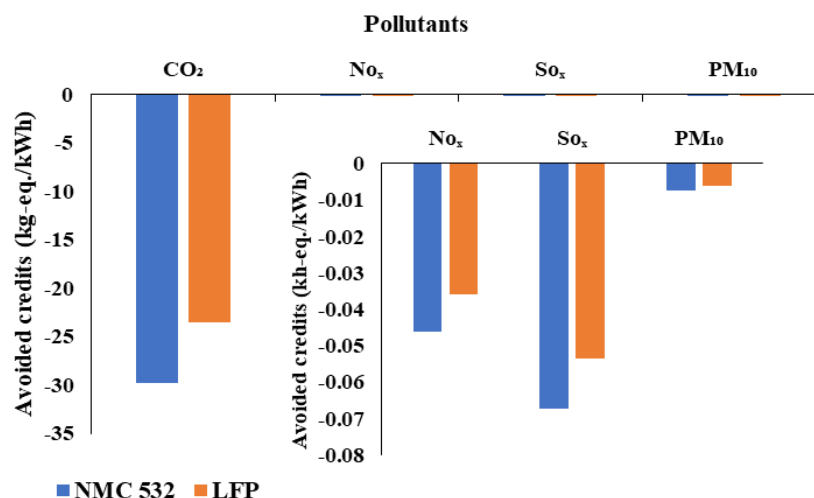


Figure 5. Avoided emission credits from the recovery of NMC 532 and LFP Batteries.

After incorporating recycling and avoided emission credits, CAM production remains the dominant contributor to overall emissions for both NMC532 and LFP systems. Although hydrometallurgical recovery significantly offsets precursor-related impacts, residual emissions are primarily associated with energy-intensive processes such as cathode precursor synthesis, calcination, and electricity consumption under India's coal-dominated electricity-mix grid. In NMC532, nickel and cobalt refining stages continue to contribute substantially, whereas in LFP systems, lithium carbonate production and electricity use remain the principal sources of emissions post-recycling.

3.5. Transportation Sensitivity Analysis

The transportation sensitivity analysis for lithium-ion batteries defined key assumptions of 1000 km of road freight for domestic distribution, 300 km by diesel truck for recycling collection, and hybrid sea–road routes, with a global average of 5000 km by sea and 1000 km by road for imports. A deterministic sensitivity analysis, as shown in Figure 6, was performed with varying parameters of distance and payload. The GHG emissions from transportation accounted for nearly 9% of total GHG emissions.

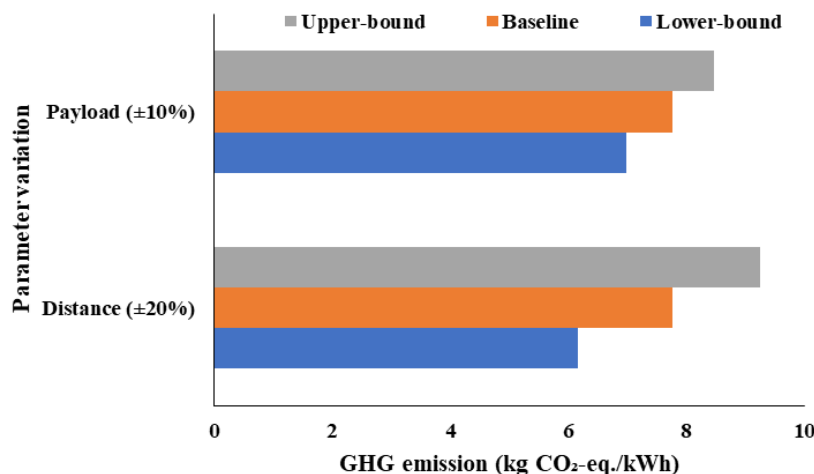


Figure 6. Transportation sensitivity analysis.

3.6. India-Specific Factors: Coal Grid, PLI Policy, Informal Recycling, and Chemistry Strategies

India's electricity mix, dominated by coal (~75% share), amplifies emissions in energy-intensive stages such as precursor, CAM synthesis and hydrometallurgical recycling. The Production-Linked Incentive (PLI) scheme for Advanced Chemistry Cells (targeting 50 GWh by 2030) and the proposed recycling PLI incentivise formal hydrometallurgical capacity, enabling 30%–36% of domestic lithium needs via recycling while reducing import reliance. As shown in Table 7, a comparative assessment of NMC 532 and LFP batteries in the Indian context highlights key challenges, decarbonization strategies, feasibility, and expected emission reduction outcomes.

Table 7. Comparison of NMC 532 and LFP in India: challenges, decarbonization pathways, and feasibility.

Chemistry	Key Challenges	Decarbonization Strategy	Feasibility (India Context)	Expected Outcome
NMC 532	High Ni/Co energy use; complex recovery	Prioritise hydrometallurgy (95% metal recovery); PLI funded closed loop with imports	Medium: Emerging (Lohum/Attero scale); leverage 100 GWh manufacturing target;	30% emission cut; Ni and Co security
LFP	Simpler but Li focused; reuse potential	Extend reuse; low temperature hydrometallurgy; pair with rooftop solar	High: lower tech barrier; aligns PLI for stationary storage	36% cut; faster via reuse

For NMC532, deploying PLI-funded hydrometallurgical plants with a Ni/Co focus is feasible via current 20 GWh pilots scaling up to 100 GWh. For LFP, reuse in ESS paired with solar (grid-independent systems) should be prioritised, leveraging simpler tech for rapid deployment. Policymakers should enforce EPR, subsidise grid-flex, and invest in recycling infrastructure for 45% emission alignment by 2030. These measures enhance India's self-reliance, cut imports and hazards, and guiding clean energy transition.

4. Limitations of This Study

The present study adopts a cradle-to-gate boundary beginning at the battery-grade material stage and excludes upstream mining, beneficiation, and the international transportation of imported materials. Although this approach allows for focused evaluation of India-specific manufacturing and recycling impacts under the national electricity mix, it does not capture the full global supply-chain footprint associated with primary material extraction. Given the energy-intensive nature of lithium, nickel, and cobalt mining and refining, inclusion of these upstream processes would likely increase the overall environmental burden of the primary material pathway. Future work could extend the boundary to a full global cradle-to-gate assessment, incorporating mining and transport stages for greater completeness.

5. Conclusions

This study created an India-specific cradle-to-gate life cycle assessment to compare lithium-ion battery manufacture utilising imported primary materials vs. domestically recycled resources for NMC 532 and LFP chemistries using the Indian energy mix.

- The chemical composition of batteries has a significant impact on their environmental performance. NMC 532 batteries have consistently greater emissions than LFP across all metrics (CO₂, NO_x, SO_x, and PM₁₀), principally due to the energy-intensive manufacturing of nickel and cobalt sulphate precursors.

- This study reveals that NMC 532 has higher emissions (72 kg CO₂-eq/kWh) than LFP (56 kg CO₂-eq/kWh), amplified by India's coal-dominated electricity grid mix, but recycling reduces the burden by 30% for NMC 532 and 36% for LFP.
- CAM production is a dominant source of environmental impact.
- The avoided emission credits is 30 kg CO₂-equation/kWh for NMC 532 and 23 kg CO₂-equation/kWh for LFP.
- NMC 532 has a stronger mitigation potential since it avoids carbon-intensive nickel, cobalt, and manganese refining, as well as the long-distance international transit of battery-grade ingredients.
- PLI-supported formal hydrometallurgy counters informal recycling pollution, enabling circularity for critical minerals amid 128 GWh EoL waste by 2030.
- Although this study models hydrometallurgical recycling as the representative pathway for India, future research should conduct a full techno-environmental comparison of pyrometallurgical, hydrometallurgical, and direct regeneration technologies using India-specific industrial inventory data to support optimal technology selection under evolving electricity decarbonization scenarios.

Overall, recycling in India's lithium-ion battery value chain can be a critical enabler of sustainable manufacturing. By closing material loops for critical minerals, recycling not only reduces greenhouse gas emissions and air pollutants but also enhances resource security and lowers dependence on imported raw materials. These outcomes directly align with circular economy pathways, reinforcing the role of sustainable manufacturing and the recycling of lithium-ion batteries as a strategic approach for managing critical minerals in India's clean energy transition.

Author Contributions: Conceptualization: S.V., P.S. and A.R.P.; methodology: S.V. and P.S.; validation: S.V.; formal analysis, S.V.; investigation: S.V., A.R.P. and S.R.; data curation: S.V. and P.S.; writing—original draft preparation: S.V. and P.S.; writing—review and editing: S.V., P.S., A.R.P. and S.R.; visualization: S.V., P.S. and A.R.P.; supervision: A.R.P., W.B. and N.H.; project administration: A.R.P. and N.H.; funding acquisition: A.R.P. and N.H. All authors have read and agreed to the published version of the manuscript.

Funding: The present study received financial assistance from a research project entitled “Synergistic Supply Chain Assessment of Critical Minerals involving Australia and India” (2024010135) funded by Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia under the India Australia Critical Minerals Research Partnership (IACMRP) Programme.

Data Availability Statement: The data presented in this study are available on request from the corresponding authors.

Conflicts of Interest: The authors declare no conflicts of interest.

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