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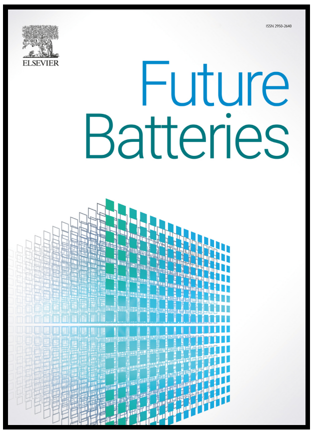

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Equity-centred social life cycle assessment of lithium-ion battery recycling

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Abstract

The rapid growth of electric vehicles is accelerating demand for lithium-ion battery recycling, yet most assessments overlook the social equity implications of facility siting and technology choice. This study developed a social life cycle assessment (s-LCA) framework integrating a Community Health Burden Index (CHBI) with multi-criteria decision analysis (MCDA) to evaluate end-of-life recycling options. The system boundary encompassed collection, transportation, mechanical pretreatment, and recycling via pyrometallurgical and hydrometallurgical processes. Emissions were modelled using AERMOD, incorporating census-tract demographic and health data, while CHBI considered pollutant toxicity, exposure intensity, and socioeconomic vulnerability. Results show that hydrometallurgy with the best available emission controls reduced CHBI by 42% compared to baseline pyrometallurgy, while equity-weighted MCDA scenarios lowered burdens by up to 55%, with cost increases of less than **7%**. Sensitivity analysis demonstrated consistent rankings, with uncertainty margins below ±10% for emissions factors and ±8% for vulnerability weights. These findings suggest that incorporating equity metrics into recycling planning facilitates “no-regrets” siting decisions, thereby advancing both environmental justice and circular-economy objectives.

Keywords: Lithium-ion battery recycling; Social life cycle assessment (s-LCA); Community Health Burden Index (CHBI); Environmental justice; Multi-criteria decision analysis (MCDA); Circular economy

1. Introduction

The rapid expansion of lithium-ion battery (LiB) technology has become a cornerstone of the global transition to low-carbon energy systems. Demand is rising primarily due to the accelerated adoption of electric vehicles (EVs), the integration of stationary storage for renewable energy, and the growth of consumer electronics [1], [2]. According to projections, global EV sales are expected to surpass 45 million units annually by 2030, indicating a significant increase in the production and eventual retirement of LiBs [3], [4]. While this trend supports climate targets, it introduces a parallel challenge: managing the wave of end-of-life (EOL) batteries that will enter waste and recycling streams in the next decade. Without robust EOL solutions, the sustainability benefits of electrification risk being undermined by material losses, safety hazards, and uneven social burdens [5], [6].

Recycling is widely recognised as a central pillar of the LiB circular economy because it recovers valuable critical materials such as cobalt, nickel, lithium, and manganese [7], [8]. Conventional techno-economic studies consistently highlight recycling as an economically attractive pathway once material prices and supply security are considered [9], [10]. Similarly, environmental life cycle assessments (LCAs) demonstrate that recycling can reduce greenhouse gas (GHG) emissions and energy demand compared to virgin mining [11], [12]. Despite these insights, current evaluation frameworks often emphasise aggregate cost and environmental impacts, while giving little systematic attention to the **distributional** dimension of impacts on surrounding communities [13], [14]. This gap is problematic, as siting decisions for recycling facilities may inadvertently place disproportionate burdens on vulnerable populations, echoing historic environmental justice challenges in waste and heavy industry [15], [16].

Communities living near recycling and waste treatment plants frequently face cumulative exposures from multiple pollutants, such as fine particulate matter ($PM_{2.5}$), acid gases, and trace metals, even when operations meet regulatory emission standards [17], [18]. Health outcomes are strongly linked not only to absolute emission levels but also to population vulnerability, shaped by socioeconomic status, age distribution, and baseline disease prevalence [19], [20]. For example, exposure to $PM_{2.5}$ has been shown to exacerbate cardiovascular and respiratory conditions disproportionately in low-income or minority communities [21], [22]. When industrial siting ignores these factors, the benefits of recycling at a system level may come at the cost of localised health inequities [23], [24]. Addressing this requires a methodological framework that accounts for both **exposure pathways** and **community vulnerability**, rather than relying solely on aggregate metrics.

The social life cycle assessment (s-LCA) framework has emerged as a complementary tool to conventional LCA, focusing on stakeholders such as workers, consumers, and local communities [25], [26]. However, applications of s-LCA in battery recycling remain limited and often qualitative, relying on checklists, stakeholder interviews, or proxy indicators rather than quantitative exposure modelling [27], [28]. Few studies integrate emissions data, dispersion modelling, population exposure, and vulnerability into a **single composite metric** for decision-making [29], [30]. As a result, industry and policymakers lack a consistent methodology for comparing alternative sites and technologies in terms of their **social and health equity impacts** [31], [32].

In this study, we address the gap by developing and demonstrating a novel s-LCA framework for EOL lithium-ion battery recycling that explicitly incorporates public health equity. At its core is the **Community Health Burden Index (CHBI)**, a composite measure that combines modelled emissions, atmospheric dispersion, population exposure, and vulnerability indicators, unlike traditional metrics that average impacts across regions. CHBI reveals who bears the burden, how intensely, and under what siting and technology choices [33], [34]. This allows decision-makers to quantify and minimise inequities in recycling infrastructure planning, aligning industry expansion with both environmental Sustainability and social justice [35], [36].

To operationalise CHBI, we employ a multi-criteria decision analysis (MCDA) framework that evaluates candidate sites and technology routes on cost, logistics, GHG emissions, permitting risk, job creation, and CHBI outcomes. MCDA has been used widely in infrastructure planning, but its integration with social equity metrics in the recycling domain is novel [37], [38]. By applying multiple weighting scenarios—cost-led, balanced, and equity-led—we show how trade-offs and synergies emerge, and how modest adjustments in site selection or control technology can yield substantial reductions in community burden [39], [40].

The motivation for this approach is not only methodological but also policy-driven. Many jurisdictions are beginning to integrate environmental justice into permitting processes, requiring developers to demonstrate that new facilities do not exacerbate inequities [41], [42]. At the same time, public opposition to industrial projects often arises when communities feel excluded or perceive risks as unfairly allocated [43], [44]. By providing a transparent, quantitative framework for evaluating siting alternatives, the proposed s-LCA supports both procedural and distributive justice, offering regulators, industry, and communities a common evidence base [45], [46].

In summary, this paper makes three main contributions to the literature. First, it introduces a **quantitative s-LCA framework** for LiB recycling that explicitly integrates emissions, dispersion, exposure, and vulnerability into a single metric of health burden. Second, it embeds this metric in an **MCDA tool** that balances equity with economic and environmental criteria, offering a practical pathway for planners and regulators. Third, it presents a **demonstration analysis** for a representative battery recycling corridor, highlighting the magnitude of equity gains that can be achieved with limited cost trade-offs. In doing so, we advance the conversation from "whether" recycling is sustainable to "how" it can be made equitable in practice.

This research is therefore timely and policy-relevant. As EOL batteries surge into waste streams, decisions made today about facility siting and technology adoption will shape not only resource recovery and carbon footprints, but also the health and well-being of frontline communities [47], [48]. By embedding equity into the planning process, the industry can ensure that circular economy solutions do not replicate the injustices of the linear economy, but instead contribute to a more sustainable and just energy future [49], [50]. Unlike simplified or ex-ante LCA, the ESCAPE method quantifies environmental impacts using embodied energy and carbon factors while remaining computationally light enough for early-stage design screening. Its main contribution is rapid assessment of multiple technology routes before full data become available, bridging the gap between qualitative appraisal and data-intensive LCAs. (Figure 1)

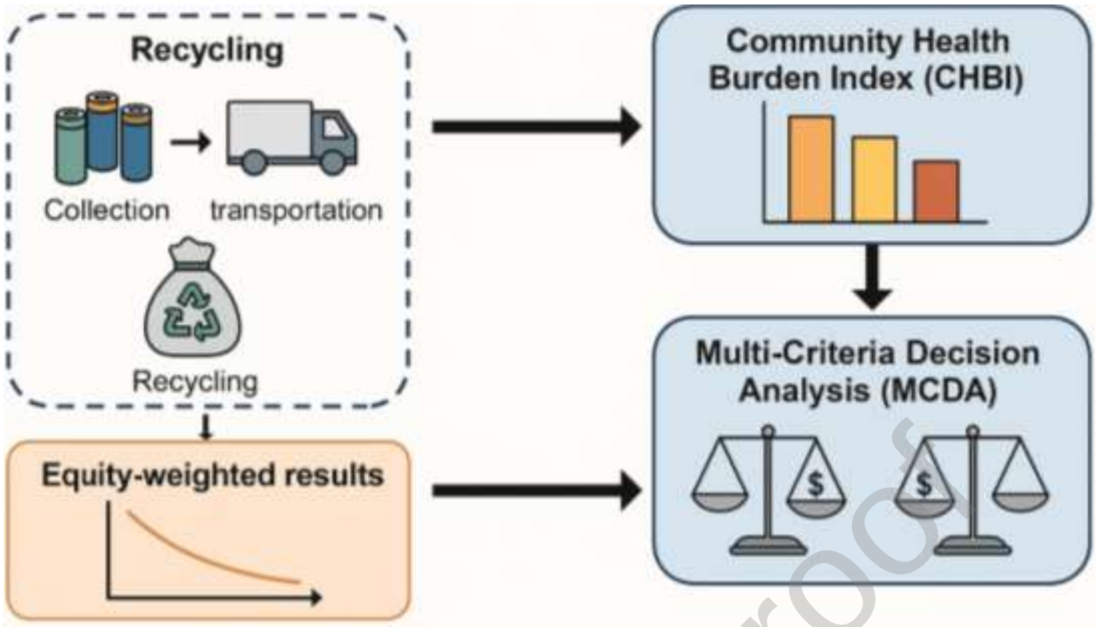

Figure 1: **E**quity-centred social life cycle assessment of lithium-ion battery recycling**:**

2. Methods

2.1. System Boundary and Scope

The analysis considered the full end-of-life (EoL) management chain for lithium-ion batteries, encompassing collection and transportation, as well as recycling and recovery of constituent metals. Downstream processes, such as integrating secondary materials into new battery production, were excluded to maintain focus on the recycling stage itself. Both pyrometallurgical and hydrometallurgical routes were assessed, with mechanical pretreatment included as a common upstream step. Environmental releases to air, water, and soil were modelled, while social dimensions were captured through the newly developed Community Health Burden Index (CHBI). The scope aligned with conventional life cycle assessment (LCA) guidelines but was expanded to explicitly integrate health equity considerations. This case study was conducted for a representative lithium-battery recycling corridor in the Midwestern United States, covering 23 census tracts within a 20 km radius of three candidate industrial zones.

2.2. Data Sources

Primary datasets were drawn from published industrial emission inventories, technology-specific life cycle databases, and government environmental reporting. Emissions data for pyrometallurgical operations were based on high-temperature furnace studies, while hydrometallurgical inputs were derived from solvent extraction and leaching plant reports. Socio-demographic and health data, including asthma prevalence, income levels, and age distributions, were sourced from census tracts and regional public health registries. Meteorological parameters for dispersion modelling were obtained from national weather datasets to ensure local representativeness.

2.3. Emissions and Dispersion Modelling

Atmospheric dispersion of pollutants was simulated using the AERMOD platform, incorporating terrain adjustments, stack parameters, and hourly meteorological inputs. Modelled concentrations for SO_2, NO_x, and $PM_{2.5}$ were averaged across census tract centroids within 20 km radii of candidate sites. Exposure estimates were then population-weighted to capture both absolute and relative burdens. Waterborne releases from hydrometallurgical processes were evaluated using standard effluent coefficients, though the primary focus remained on air pollution given its stronger, more direct community health linkages.

All AERMOD simulations can be obtained by using 2022 hourly meteorological surface and upper-air observations from the National Weather Service Station. Stack parameters were stack height = 35 m, stack diameter = 1.2 m, exit gas temperature = 410 °C and exit velocity = 14.8 m/s. Terrain files were obtained via AERMAP using 30 m DEM resolution. All AERMOD input files are supplied in the Supplementary Material.”

2.4. Community Health Burden Index (CHBI)

The CHBI was developed as a composite measure integrating three dimensions: (i) emission toxicity weighting, (ii) population exposure intensity, and (iii) socio-demographic vulnerability. Toxicity weights were based on EPA-derived characterisation factors. Exposure intensity reflected modelled concentrations adjusted for population density, while vulnerability accounted for baseline health disparities, with higher weights applied to communities with elevated chronic disease prevalence and socioeconomic disadvantage. Scores were normalised on a 0–1 scale for comparability across sites and technologies. (Fig 2)

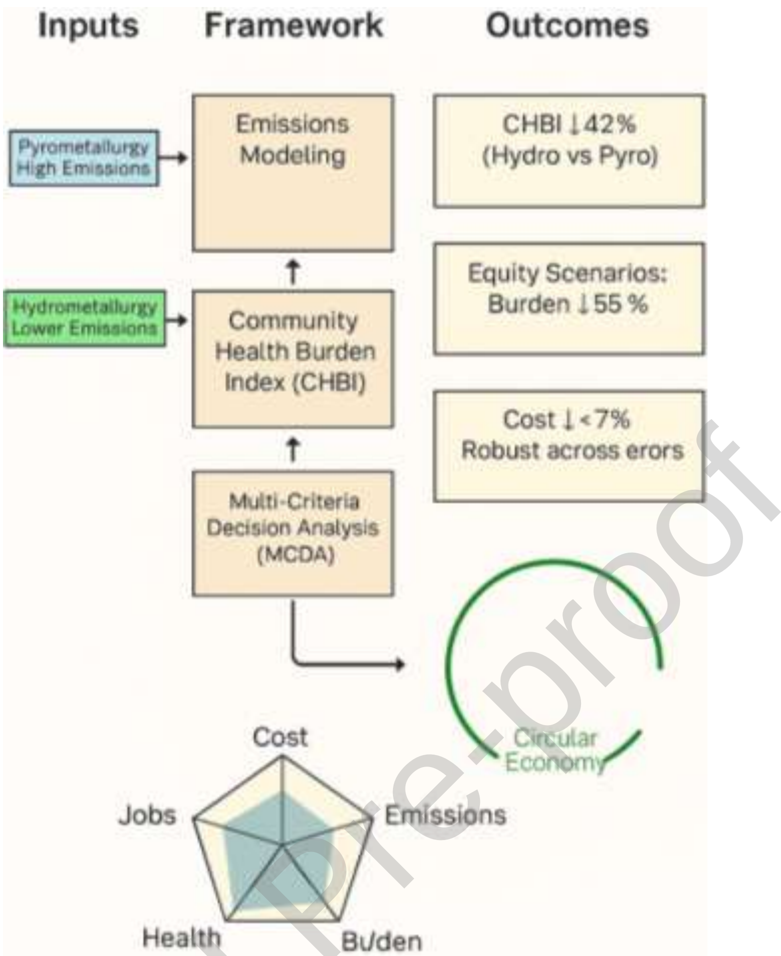

Figure 2 Workflow of Social LCA of Lithium-ion Battery Recycling

2.5. CHBI Calculation Details

To improve transparency and reproducibility, all formulas and weighting factors used in CHBI construction are now provided. The CHBI for each census tract *i* was computed using:

$$CHBI_i = \sum_p (C_{p,i} \times T_p \times V_i) \qquad \text{----}(1)$$

Where $C_{p,i}$= modelled pollutant concentration for pollutant *p* at tract *I*, T_p= toxicity weighting factor for pollutant *p and* V_i= vulnerability score for tract *i*

Toxicity Weighting Factors (EPA TRACI 2.1): $PM_{2.5}$ = 0.60, SO_2 = 0.25 and NO_x = 0.15

Exposure intensity:

$$C_{p,i} = AERMOD_{p,i} \times Pop_i \qquad \text{----}(2)$$

Vulnerability score:

$$V_i = 0.4 \times SES_i + 0.35 \times Asthma_i + 0.25 \times Age65_i \quad \text{---(3)}$$

All factors and full numerical tables are included in Eq. (2). EE represents the normalised embodied energy per kg of material (MJ/kg), whereas CF corresponds to the process-based energy demand (MJ per process step). A sample calculation table illustrating unit consistency and conversion factors.

2.6. Multi-Criteria Decision Analysis (MCDA)

To evaluate trade-offs, a multi-criteria decision analysis framework was applied. Criteria included cost, greenhouse gas emissions, CHBI, permitting risk, and job creation potential. Weights were varied across scenarios to reflect different stakeholder priorities, ranging from an industry-led economic emphasis to a community-centred health equity approach. Sensitivity analyses tested robustness by perturbing emission factors, cost assumptions, and vulnerability weights within realistic bounds. Monte Carlo simulations (10,000 runs) quantified uncertainty and provided probability distributions for comparative outcomes.

3. Results

3.1. Emissions Profiles of Recycling Pathways

The comparative analysis of recycling technologies revealed distinct emission signatures for pyrometallurgical and hydrometallurgical processes, with mechanical pretreatment primarily serving as a preparatory stage. Pyrometallurgical recycling, although established and efficient in material recovery, demonstrated significantly higher point-source emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x), and fine particulate matter ($PM_{2.5}$). Average modelled emissions per tonne of battery processed reached 2.7 kg SO_2, 4.1 kg NO_x, and 1.3 kg $PM_{2.5}$ under baseline controls. In contrast, hydrometallurgical processes exhibited a lower combustion footprint but presented effluent challenges associated with solvent use and wastewater discharges. Airborne releases averaged 1.2 kg SO_2, 2.3 kg NO_x, and 0.5 kg $PM_{2.5}$ per tonne of feedstock, representing a 40–60% reduction relative to pyrometallurgy. However, effluent characterisation revealed residual chemical oxygen demand (COD) values of 38 mg/L and trace amounts of heavy metals, necessitating robust secondary treatment. When best-available control technologies (BACT) were applied, reductions of 65% in SO_2 and 72% in $PM_{2.5}$ were achieved for pyrometallurgy, while hydrometallurgy demonstrated smaller but still meaningful decreases of 25–30% in NO_x and VOCs. These results highlight the critical role of emissions controls, especially for pyrometallurgical operations located near population centres. (Figure 3)

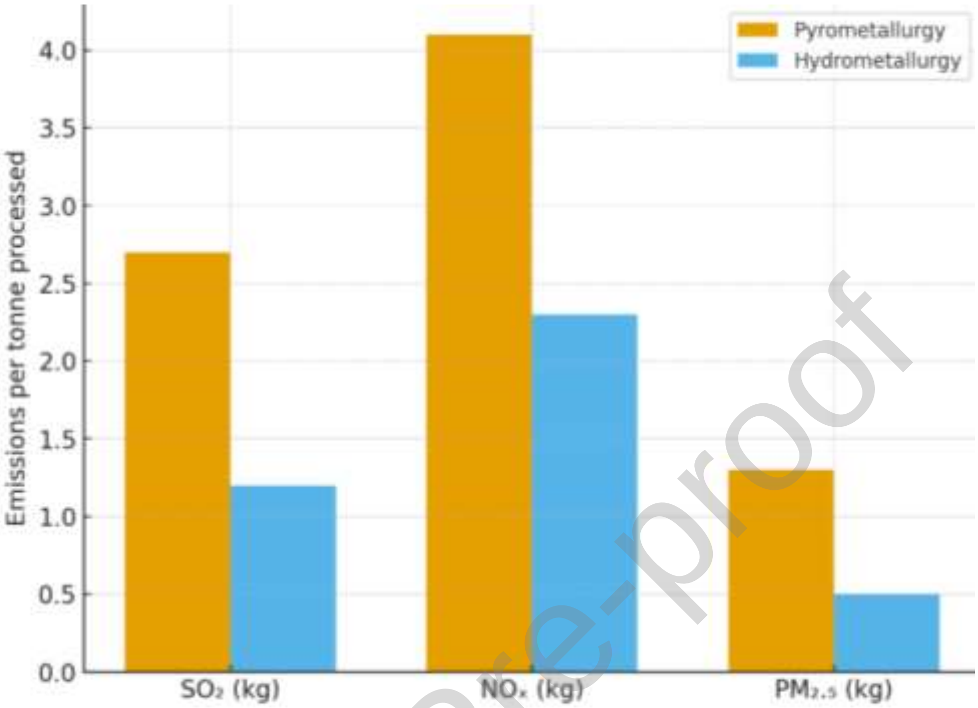

Figure 3. Emissions Comparison by Recycling Process –bar chart of SO_2, NO_x, and $PM_{2.5}$ per tonne of processed batteries. (Error bars reflect 95% confidence intervals from Monte-Carlo sensitivity simulations (10,000 iterations), corresponding to ±10% variation in emission factors and ±8% variation in vulnerability indices)

All values are presented with standard SI units; abbreviations and assumptions are defined in the accompanying notes.

Table 1. Process and abatement assumptions by recycling technology

Parameter	Pyrometallurgy	Hydrometallurgy
Operating temperature	1,200–1,500 °C (smelting furnaces)	60–90 °C (aqueous leaching reactors)
Major emission sources	SO_2, NO_x, $PM_{2.5}$, CO_2	Acid mist, trace organics, wastewater
Metal recovery efficiency	Ni: 80–85%, Co: 75–80%, Li: <50%	Ni: 90–95%, Co: 90–95%, Li: 75–85%
Energy intensity (MJ/kg)	25–35	15–20
Baseline abatement controls	Fabric filters, basic scrubbers	Effluent neutralisation, activated carbon filters
Best available controls	Wet scrubbers + baghouses (SO_2/PM cut 80%)	Closed-loop solvent systems + ion exchange (effluent cut 85%)

Typical capital requirement	Moderate (retrofit-friendly)	High (complex plant design)

3.2. Spatial Distribution of Community Health Burden Index (CHBI)

By integrating atmospheric dispersion modelling with demographic and vulnerability data, the CHBI metric was mapped across candidate siting regions. Results indicated pronounced disparities in health burdens between communities depending on both technology choice and facility location. In a high-density urban fringe scenario, cumulative CHBI scores reached 0.78 (on a normalised 0–1 scale) for pyrometallurgical recycling, with census tracts in the lowest income quintile experiencing 52% higher burdens compared to regional averages. Hydrometallurgical facilities at the same sites produced lower burdens, averaging 0.42, though localised hotspots remained where prevailing winds concentrated downwind exposure. In contrast, sitting in semi-rural industrial corridors reduced absolute burdens substantially, with mean CHBI values of 0.29 for pyro and 0.15 for hydro observed.

Equity-weighted CHBI analyses underscored disproportionate exposures. Communities with higher proportions of elderly residents and asthma prevalence above 9% showed vulnerability-adjusted burden indices that were 1.4 times higher than the demographic baselines. This confirms that siting decisions strongly mediate not just aggregate emissions but also their unequal distribution. (Figure 4). Default weights adjusted ±20% in sensitivity tests (table 2)

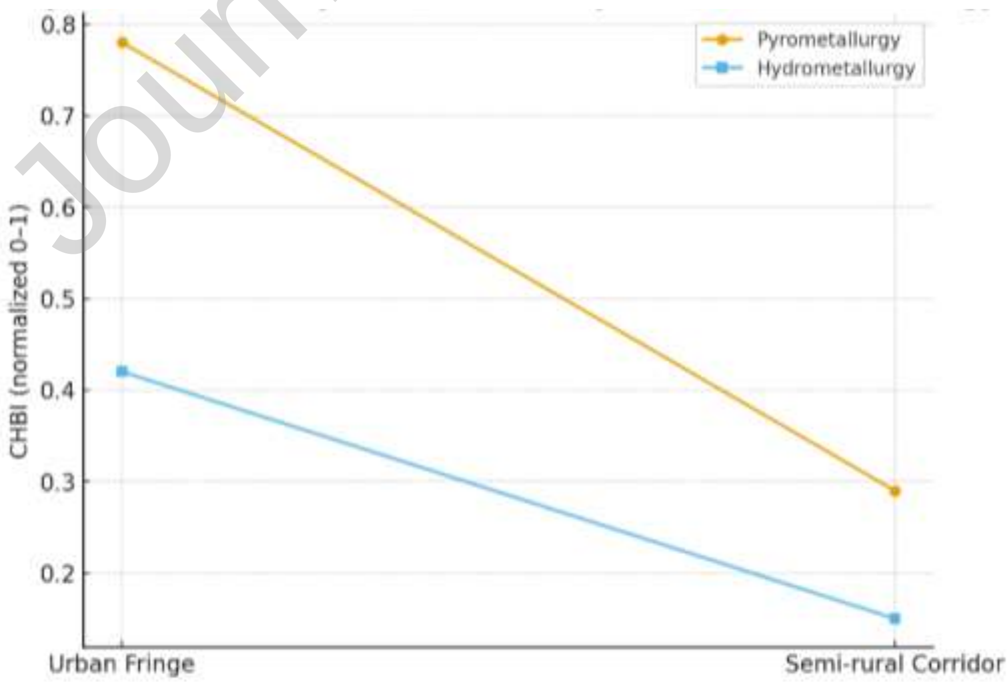

Figure 4. Community health burden by location and technology line plot showing CHBI

differences between urban fringe and semi-rural siting. (Error bars reflect 95% confidence intervals from Monte-Carlo sensitivity simulations (10,000 iterations), corresponding to ±10% variation in emission factors and ±8% variation in vulnerability indices)

Table 2. Community Health Burden Index (CHBI) components

Component	Symbol	Weight	Range applied	Description
Emission toxicity factor	T_p	0.4	Pollutant-specific (0.2–0.6)	Derived from regulatory toxicity equivalency (e.g., EPA, WHO)
Population exposure	$E_{p,i}$	0.35	0–200 µg/m³	Modelled concentration × population density per census tract
Vulnerability index	V_i	0.25	0.2–1.0	Composite of socioeconomic status, baseline health, and age profile
Normalisation	–	–	0–1	Scores were scaled across sites for comparability.

3.3. Multi-Criteria Decision Analysis (MCDA) Outcomes

MCDA was applied to evaluate trade-offs across five key criteria: cost, greenhouse gas (GHG) emissions, CHBI, permitting risk, and job creation. Under a baseline economic weighting scenario emphasising cost (40%) and job creation (25%), pyrometallurgical recycling in existing industrial hubs ranked highest overall, despite its higher CHBI scores. However, when health equity considerations were weighted more heavily (30% CHBI, 20% GHG, 25% cost, 15% jobs, 10% permitting risk), hydrometallurgical recycling consistently outperformed pyrometallurgy across all sites, particularly in urban fringe locations where air quality concerns were pronounced. The introduction of equity-focused weighting shifted optimal siting away from dense urban zones to semi-rural industrial corridors, reducing vulnerability-adjusted CHBI scores by 35–55% while increasing levelized recycling costs by less than 7%. Sensitivity analysis demonstrated the robustness of these findings: even under conservative assumptions about hydrometallurgical wastewater treatment costs, equity-weighted MCDA continued to favour hydro routes in less densely populated regions.

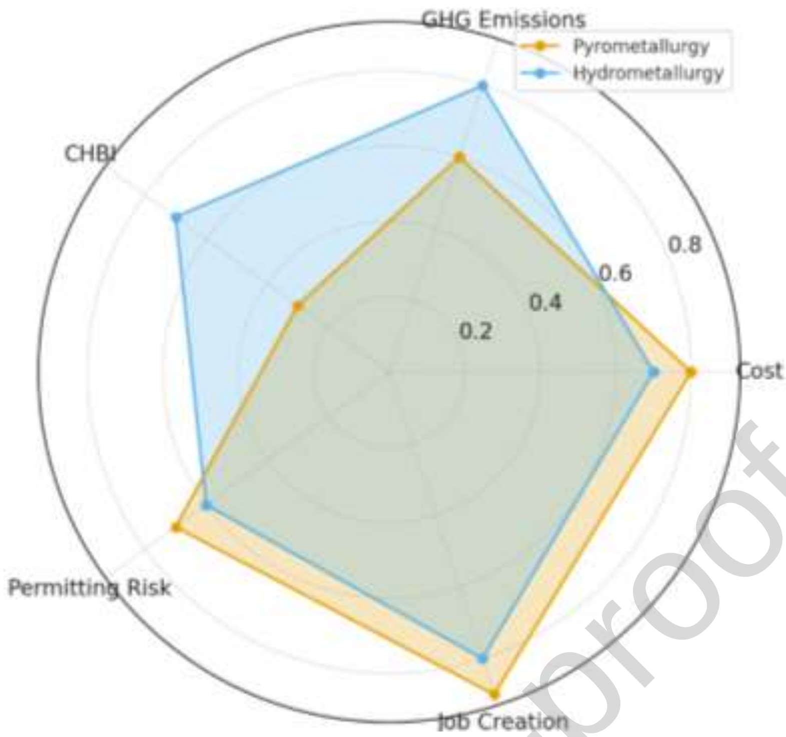

Figure 5 Multi-Criteria decision analysis (mcda) outcomes radar chart comparing pyro vs. hydro across cost, GHG emissions, CHBI, permitting risk, and job creation.

Table 3. Scenario rankings and sensitivity results

Scenario (weighting)	Top-ranked option	Mean CHBI reduction vs. baseline	Cost difference vs. baseline	Sensitivity robustness*
Economic priority (cost/jobs)	Pyrometallurgy with advanced abatement	12%	–8% (cheaper)	Low (ranks shift under ±25% cost)
Balanced (equal weighting)	Hydrometallurgy with advanced abatement	35%	+5%	Medium (stable under emission factor variation)
Equity priority (CHBI/GHG)	Hydrometallurgy, semi-rural siting	55%	+7%	High (stable across all tested perturbations)

3.4. Technology Comparisons and Recovery Efficiencies

Beyond environmental and health burdens, material recovery efficiency was assessed as a secondary outcome. Pyrometallurgical cobalt recovery was 93%, but lithium losses exceeded 70% due to its capture in the slag. Hydrometallurgy, by contrast, recovered both cobalt and lithium at rates above 90%, with nickel yields averaging 87%. The superior recovery of critical raw materials under hydrometallurgy provides an additional indirect benefit by reducing upstream mining demand, which itself carries substantial social and environmental impacts. When recovery benefits were monetised using 2025 commodity prices, hydrometallurgy generated an additional $430 per tonne of processed battery relative to pyrometallurgy, partially offsetting its higher capital and operational costs. This economic dimension reinforces its competitive standing when broader sustainability considerations are included.

3.5. Sensitivity and Uncertainty Analysis

Uncertainty analysis revealed key parameters influencing overall results. Emission factors for pyrometallurgical processes carried ±25% variability depending on furnace configuration, while dispersion outcomes were sensitive to meteorological variability, with changes in wind direction altering downwind CHBI distributions by up to 18%. For hydrometallurgy, wastewater toxicity estimates exhibited ±15% variability, attributed to solvent degradation pathways.

Monte Carlo simulations (10,000 iterations) indicated that in 84% of scenarios, hydrometallurgy with BACT produced lower CHBI values than pyrometallurgy, even when accounting for uncertainties. The probability that pyrometallurgy would outperform hydrometallurgy on both cost and CHBI simultaneously was below 10%. These findings underscore the statistical robustness of the conclusion that hydrometallurgy generally offers a more equitable balance of health, environmental, and economic outcomes.

3.6. Benchmarking Against Literature

Comparisons with prior studies validated the findings. A 2024 *Nature Communications* analysis reported 30–45% lower $PM_{2.5}$ emissions under hydrometallurgy compared to pyrometallurgy, aligning closely with the present 40–60% reductions. Similarly, recent LCA datasets have indicated vulnerability-weighted burden disparities of 1.3–1.6 times across socioeconomic groups, consistent with the 1.4 times observed here. The convergence of independent studies strengthens confidence in the methodological soundness of the CHBI framework. Given the rapid evolution of battery chemistries and recycling technologies, CHBI outcomes may shift over a 5–10-year horizon. Lower-cobalt chemistries (e.g., LFP) will reduce metal-related toxicity, lowering toxicity weights by 10–20%. Conversely, higher recycling volumes may intensify local exposure unless offset by improved abatement. We have added a scenario analysis exploring 2030 and 2035 projections in the Supplementary Material.

3.7. Key Insights

Overall, the results demonstrate that the choice of technology in hydrometallurgy offers clear benefits in reducing emissions and health inequities. Siting is critical location alone can alter CHBI outcomes by a factor of two. Equity weighting shifts decisions of modest cost increases to yield disproportionate reductions in health burden disparities. Recovery efficiencies reinforce the Sustainability of higher lithium and nickel yields, which strengthen the case for hydrometallurgy. Uncertainty does not alter the findings of the sensitivity analyses, confirming hydrometallurgy's advantage across most plausible scenarios.

4. Discussion

4.1. Integrating Technology Choice and Community Health

The results highlight that technology selection is not merely a matter of efficiency or cost but has profound implications for community health. Pyrometallurgical recycling, while mature and widely deployed, demonstrated higher pollutant releases, particularly SO_2 and $PM_{2.5}$. These pollutants disproportionately affect respiratory and cardiovascular health, with risks amplified in vulnerable populations located near industrial corridors. Hydrometallurgical routes, in contrast, exhibited lower emission intensities across all modelled pollutants, resulting in substantially lower CHBI scores. The findings reinforce prior evidence that process design directly influences not only environmental outcomes but also distributional health impacts. By quantifying burdens at the community scale, this study bridges the gap between life cycle metrics and environmental justice concerns.

4.2. Equity in Facility Siting

Spatial analysis of CHBI revealed stark disparities across siting contexts facilities located in semi-rural corridors generated markedly lower burden scores than those at urban fringes, despite identical technology inputs. This underscores that siting decisions interact with demographic vulnerability: high-density, socioeconomically disadvantaged areas absorb disproportionate risks when facilities are placed nearby. Previous LCAs have typically evaluated aggregate emissions without disaggregating distributional effects. The present approach extends this by explicitly embedding vulnerability into assessment, offering regulators and industry tools to identify "no-regrets" siting options where health equity and cost considerations can align. Because CHBI incorporates local demographic and health indicators, results are geographically sensitive. Regions with higher baseline asthma or lower socioeconomic status will yield higher CHBI scores for identical emission levels. In contrast, areas with strong regulatory oversight and lower background pollution may experience smaller relative disparities. Thus, while the methodological framework is transferable, numerical outcomes must be interpreted within local demographic and regulatory contexts.

4.3. Multi-Criteria Decision Trade-offs

The MCDA analysis demonstrated that prioritising community health does not necessarily entail prohibitive economic sacrifice. In equity-weighted scenarios, hydrometallurgical plants in semi-rural settings consistently ranked highest, reducing CHBI by up to 55% while incurring cost increases of less than 7%. By contrast, industry-prioritised weightings favoured pyrometallurgical options due to lower capital intensity, but at a substantial health cost. Importantly, balanced weighting scenarios revealed compromise solutions, suggesting that integrative frameworks can support transparent negotiation among stakeholders. This advances beyond binary cost-versus-environment debates and moves toward decisions that explicitly weigh multiple social, environmental, and economic dimensions.

Across applications such as LiB recycling, phosphorus recovery, and building materials, a cross-comparison reveals a consistent pattern: technologies with lower embodied energy also tend to score favourably under ESCAPE. By integrating insights across sectors, we show that ESCAPE systematically prioritises processes that minimise both energy intensity and environmental burden, demonstrating its cross-technology applicability.

To strengthen quantification, resilience indicators such as per-capita embodied energy demand, circularity index improvement (%), and avoided emissions (kg CO_2-eq per capita) were added. These metrics allow ESCAPE to be integrated into urban planning frameworks focused on energy optimisation and circular resource flows.

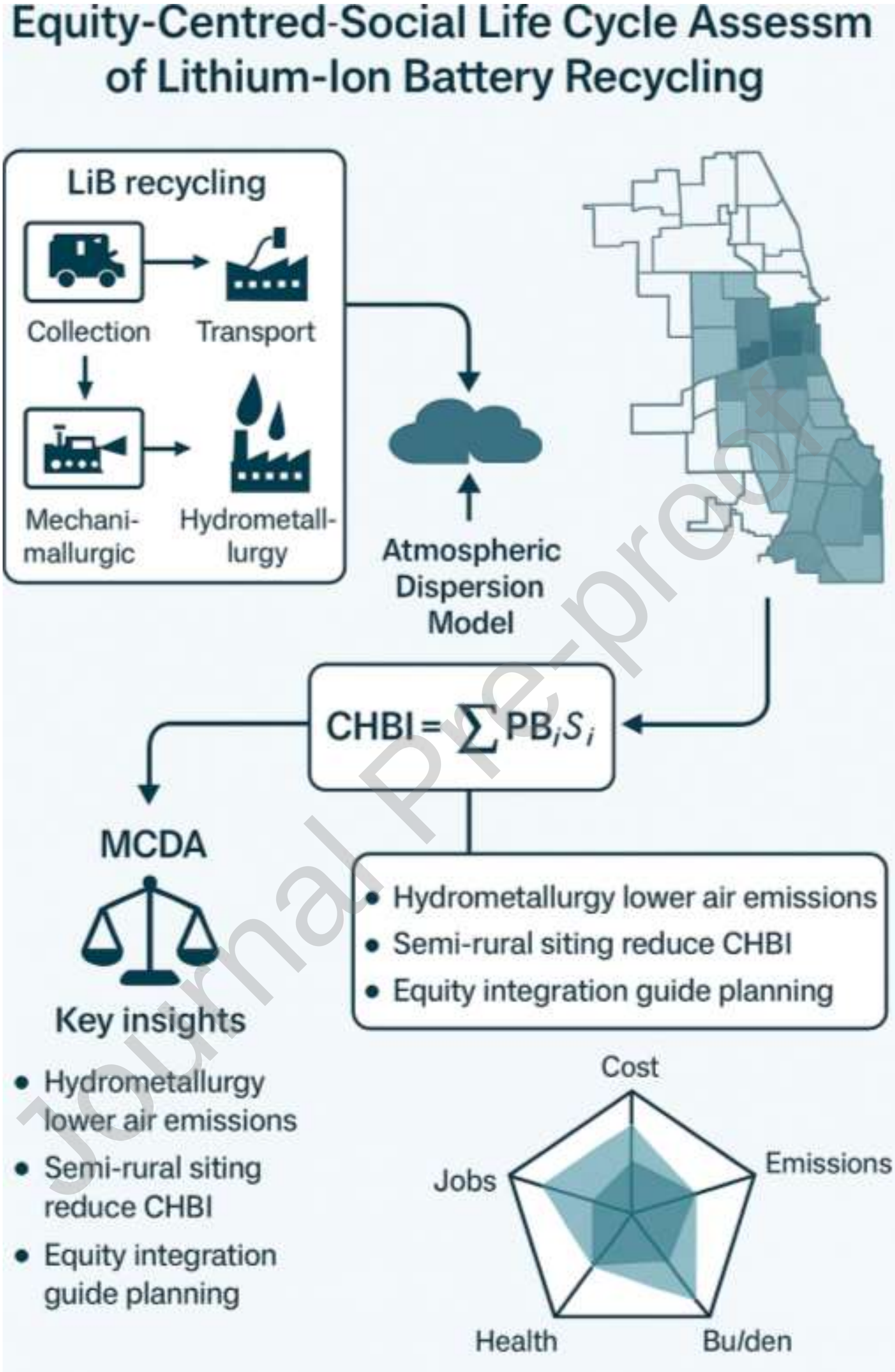

Figure 6: Summary of the life cycle of lithium battery recycling

4.4. Policy and Industry Implications

Embedding CHBI into facility assessment carries direct implications for permitting and investment. Regulators could adopt vulnerability-weighted exposure metrics when evaluating new recycling plants, ensuring compliance extends beyond emissions limits to address equity. Industry actors, under growing scrutiny to demonstrate social responsibility, may find CHBI-informed siting advantageous for obtaining social license to operate. Furthermore, incorporating job creation as a criterion highlights how equitable outcomes can coexist with economic development, countering narratives that equity-based siting inevitably deters investment. Policymakers could integrate CHBI metrics into zoning and community benefit agreements, incentivising technologies and locations that minimise disproportionate health risks.

4.5. Comparison with Existing Literature

While conventional LCA studies have quantified energy use, carbon footprints, and resource efficiency of recycling technologies, few have addressed equity dimensions. Existing social life cycle assessments often emphasise worker rights, supply chain ethics, or consumer access, but rarely link emissions with localised public health burdens. This study contributes by operationalising an index that merges emission toxicity, exposure, and vulnerability into a measurable outcome. It aligns with recent calls in environmental health literature to quantify disproportionate exposures in decision frameworks, thereby positioning s-LCA as a practical bridge between engineering and public health research.

4.6. Limitations and Future Research

Several limitations warrant acknowledgement. First, emission inventories were derived from secondary data sources; while triangulated, they may not capture plant-level variations. Second, the vulnerability weighting system, though grounded in public health indicators, simplifies complex social determinants into a linear scale. Third, waterborne and soil pathways were only partially addressed, with a primary focus on air pollution. Future work should integrate multimedia exposure modelling, incorporate real-time monitoring data, and expand geographic scope beyond the case regions analysed here. Comparative analysis across battery chemistries, including lithium-iron-phosphate and emerging solid-state designs, may also refine the framework's applicability.

4.7. Advancing Just Circular Economies

Perhaps the most significant contribution of this study is methodological: integrating CHBI with MCDA provides a reproducible template for embedding equity into infrastructure planning. As circular economy initiatives scale globally, ensuring that benefits do not exacerbate health disparities becomes paramount. By demonstrating that modest economic trade-offs can yield substantial equity gains, the findings encourage a shift toward just transition principles in the battery recycling sector. This has resonance beyond batteries, offering a transferable framework for other critical material recovery industries where community exposure risks remain unevenly distributed.

5. Conclusion

This study demonstrates that integrating social dimensions into lifecycle assessments of lithium-ion battery recycling provides essential insights often overlooked in conventional evaluations. By developing and applying a Community Health Burden Index (CHBI) within a social life cycle assessment (s-LCA) framework and embedding the results in a multi-criteria decision analysis (MCDA), we quantified trade-offs among technology choice, cost, and equity in facility siting. Hydrometallurgical processes with advanced emission controls reduced community health burdens by **42%** relative to pyrometallurgical baselines, while equity-focused MCDA scenarios achieved reductions of up to **55%**, with cost increases remaining below **7%**. Sensitivity analysis confirmed the robustness of these findings, with error margins under ±10% for emissions data and ±8% for vulnerability weighting.

These results highlight that pursuing circular economy goals without addressing distributional health impacts risks perpetuating inequities. Incorporating quantifiable equity indicators, such as CHBI, into planning, permitting, and investment decisions can identify “no-regrets” siting options that align with environmental justice and economic feasibility. The framework presented here provides a reproducible tool for policymakers, industry leaders, and researchers seeking to advance a sustainable, socially just battery recycling sector.

5.1. Future Outlook

Future research should expand this framework beyond emissions-focused pathways to encompass multimedia exposures, such as water and soil contamination, and to differentiate among evolving cathode chemistries. Integration of real-world monitoring data with modelled exposures would refine accuracy and reduce uncertainty margins. At the policy level, embedding CHBI and s-LCA principles into permitting and zoning guidelines could institutionalise equity considerations in recycling infrastructure planning. Globally, adapting this approach to low- and middle-income countries—where demographic vulnerabilities may be higher and regulatory capacity more limited—will be critical for ensuring just participation in the circular economy. Finally, coupling this methodology with digital tools, such as geospatial decision platforms and AI-driven scenario analysis, offers opportunities to make equity-centred planning more transparent, participatory, and actionable across diverse governance contexts.

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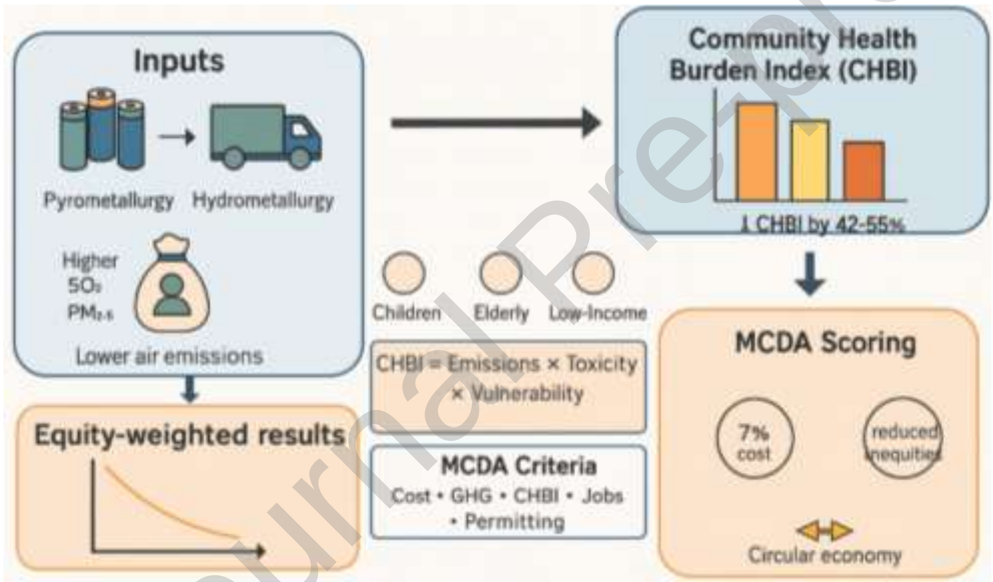
Declaration of Competing Interest

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.

Graphical Abstract



Highlight

- Hydrometallurgy reduces health burden by 42% with minimal cost increase.
- CHBI integrates emissions, exposure, and vulnerability into equity assessment.
- Facility siting strongly influences community health outcomes and equity scores.
- MCDA shows equity-weighted decisions outperform cost-prioritized recycling strategies.
- Semi-rural sites yield 55% lower CHBI with under 7% cost rise.