

## Research paper

# Improving the PSILCA Database Approach for Social Life Cycle Assessment: A Case of End-of-Life Electric Vehicle Policies

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Handling Editor: Kris Hartley

Received: 30.05.2025 / Accepted: 26.07.2025

## Abstract

Social life cycle assessment (S-LCA) is rapidly evolving to complement sustainability assessment beyond environmental impact. This study focuses on improving the Product Social Impact Life Cycle Assessment (PSILCA) database approach through a case study on end-of-life electric vehicle policies in Japan. We show that the social risks associated with acquiring recycled battery materials are lower compared to importing virgin materials, thereby supporting the regulation on electric vehicle battery recycling. The social risks increase when recycling occurs in less developed countries such as Pakistan. Additionally, we point out critical methodological issues when using the PSILCA database. The built-in method weights non-worker stakeholders based on worker hours, and underestimates unavailable inventory data, and inconsistently groups social indicators. We address the issues by proposing a screening method for key supply chain activities and removing inapplicable indicators. The results become more accurate and easier to interpret. Overall, the method guides future S-LCA studies with an improved PSILCA database approach.

**Keywords:** Social Risk Assessment · Reference Scale Assessment · Worker Well-being · Worker Hours · PSILCA Database · Critical Battery Materials · Battery Recycling

## 1. INTRODUCTION

Measuring the sustainability of products, services, and policies is in demand for tracking the transition toward an environmentally safe and socially just society (Costa et al., 2019; Gupta et al., 2024). Among the life cycle sustainability assessment (LCSA) methodologies (Finkbeiner et al., 2010; Guinée et al., 2011), life cycle assessment (LCA) is widely adopted to systematically quantify environmental impact, from raw material extraction to end-of-life treatment (Peters, 2023). The LCA standard for industrial applications, ISO 14040, has been established and updated since 1997, demonstrating its effectiveness in addressing increasingly complex global supply chains. As concerns about the impact of activities expand beyond the environment, such as the well-being of stakeholders (Mármol et al., 2023), social life cycle assessment (S-LCA) is rapidly developing to fill the gap in the social impact assessment.

The first S-LCA guideline was established in 2009, commissioned by the UNEP/SETAC Life Cycle Initiative (UNEP/SETAC, 2009), as the complexity of social impact assessment necessitates rigorous methodologies (Benoît et al., 2010; Huertas-Valdivia et al., 2020). The theoretical framework defined social impacts as “the consequences of social relations weaved in the context of an activity (production, consumption, or disposal), and/or engendered by it, and/or by preventive or reinforcing actions taken by stakeholders” (UNEP/SETAC, 2009). The stakeholders and social impact subcategories that should be safeguarded were proposed as the reference for S-LCA studies and served as the necessary basis for developing databases and software. The

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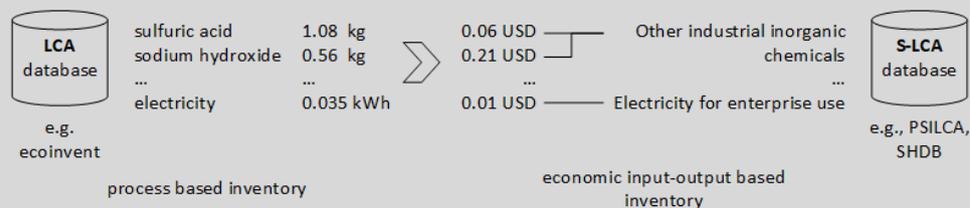
guideline was updated in 2020 (UNEP, 2020), reflecting the methodological advancements over the past decade of studies. In 2024, an ISO14075 standard was published to unify the S-LCA framework, terminology, and other methodological issues for practical application (ISO, 2024; Traverso & Mankaa, 2025).

A milestone in S-LCA development was the launch of social impact inventory databases, including the Product Social Impact Life Cycle Assessment (PSILCA) from GreenDelta (Loubert et al. 2023), and the Social Hotspots Database (SHDB) by New Earth (now NewEarth B) (Bennema et al. 2022). These databases provide social risk inventory data based on country-specific sectoral activities, which are needed to model a globalised production system. Since then, researchers have been able to explore the conceptual development and application of S-LCA through a desk study (Koese et al., 2023; Teah & Onuki, 2017), without requiring resource-intensive stakeholder interviews, questionnaire surveys, and other on-site data collection means (Sánchez et al., 2024). The database-oriented S-LCA aligns with the broader framework of LCSA to assess a product system under a unified framework (Guinée et al., 2011; Valdivia et al., 2021) due to the similarity between the social data structure and the environmental LCA database (van Dulmen et al., 2025). The increasingly popular database approach for S-LCA can be generalised (Koese et al., 2023; Muller et al., 2021; Teah et al., 2024), see Box 1.

### Box 1. The Database Approach for S-LCA

The LCA of a product or service requires extensive data from the upstream processes. Conventional LCA is supported by databases such as ecoinvent. In essence, researchers only need to investigate the foreground processes of interest (e.g., hydrometallurgical recycling from experiments) and model the remaining product system with the inventory in databases (e.g., chemical production and electricity generation).

The database approach for S-LCA leverages the existing LCA infrastructure to perform a quick assessment of social impacts. Since the S-LCA databases compile social indicators for country-specific sectors based on a multi-regional input/output model, a transformation from process-based LCA is necessary. The general approach is first to convert the physical unit (mass and energy) that links the LCA inventory into a monetary unit (USD) that links the S-LCA inventory. Then, the processes in LCA are matched to the closest representative sectoral activities in S-LCA, as depicted below:



The PSILCA database approach is modelled on openLCA software, which automates the weighting and aggregation to generate the social impact result for interpretation. Essentially, the inventory representing the risk level of each activity is weighted by the worker hours required per USD sector output and aggregated for the social impact subcategories.

The database approach facilitated the expansion of LCA studies to encompass environmental and social dimensions, thereby increasing the number of LCSA and S-LCA studies (Huertas-Valdivia et al., 2020). However, methodological and technical issues in S-LCA databases could render some findings from these studies invalid. Database users often overlook the problems inherent in the software provided. For example, when assessing non-worker stakeholders, applying the “worker hours” as a weight is questionable (Arvidsson et al., 2015). Some solutions included aggregation by the weighted average of the “raw value” in PSILCA (Springer et al., 2024) and screening only key activities without aggregation (Teah et al., 2024). Other issues include the representativeness of social indicators to a product system (Haslinger et al., 2024; Martínez-Blanco et al., 2015), as well as the price sensitivity of products affects the weight of activities (Koese et al., 2023; Orola et al., 2024).

Although methodological issues persist, the literature on case studies using the database approach is growing rapidly (Berridy-Segade et al., 2024; Tsalidis et al., 2024; Yu et al., 2025), urging more attention from the S-

LCA community. The improved method in this study explains the common misinterpretations in existing S-LCA studies due to the embedded technical settings and clarifies the influencing factors in the weighting mechanism. This provides more accuracy and transparency when applying the S-LCA results for decision making.

This study aims to address methodological and technical issues (more details in Section 4.1) when utilising the PSILCA database approach for conducting S-LCA. We demonstrate the improvement by evaluating the policy for end-of-life electric vehicles in Japan. Despite being a primary second-hand vehicle exporting country, there is a growing interest in restricting the export of used electric vehicles to secure the critical battery materials. A comprehensive assessment considering environmental, economic, and social impacts is desirable to support the decision-making process (Domingues et al., 2024). Therefore, this study applies the improved PSILCA approach to quantify and semi-quantify the social risks associated with two policy options for battery material security: importing virgin battery materials to Japan and recycling battery materials from electric vehicles.

## 2. METHODS

### 2.1 Goal and Scope Definition

The primary goal was to compare the social risks embodied in the supply chain of acquiring virgin and recycled battery materials in Japan. The assessment aimed to demonstrate the effectiveness of the end-of-life electric vehicle policies in mitigating social impact on domestic and global stakeholders. The secondary goal was to compare the social risks associated with battery recycling activities taking place in Japan and the two primary second-hand vehicle exporting countries: New Zealand and Pakistan. The assessment aimed to clarify the social impact of business-as-usual practice, disregarding the interest of securing critical battery materials in Japan.

The scope of assessment was cradle-to-gate, from sourcing raw materials to obtaining battery materials. The system boundaries for the recycling process and the acquisition of virgin materials are illustrated in Figure 1. The functional unit was defined universally as obtaining the battery materials, specifically 0.111 kg of lithium carbonate, 0.304 kg of nickel sulphate, 0.099 kg of manganese sulphate, and 0.102 kg of cobalt sulphate, which were the yields from recycling one kg of NMC622 batteries (Dai et al., 2019). The functional unit enabled us to compare the scenarios involving the acquisition of recycled and virgin materials. This assessment only considered the cathode active material due to the interest in securing critical battery materials in Japan.

The S-LCA was modelled on openLCA 2.4.1. The inventory data were sourced from PSILCA v3.1 social impact database and ecoinvent v3.11 process-based inventory database. The foreground data for the recycling process and battery material costs were adopted from EverBatt, a publicly available battery recycling model developed by the US Department of Energy (Dai et al., 2019). PSILCA encompasses four stakeholder categories: workers, value chain actors, local communities, and society, and their corresponding social impact subcategories. The total social risk, expressed in a medium-risk-hour equivalent (mrh-eq) unit, was calculated using the openLCA. The calculation of a social risk follows equation (1) (Muller et al., 2021).

$$I = \sum_j A_j \times RF_j \times AV_j - \text{equation (1)}$$

This equation shows a social risk indicator  $I$  equal to the summation of risk across all supply chain activities  $j$ , where  $A$  is the quantity required in the product system (in USD),  $RF$  is the characterization factor in PSILCA (no risk = 0, very low risk = 0.01, low risk = 0.1, medium risk = 1, high risk = 10, very high risk = 100),  $AV$  is the activity variable (in worker hours/USD).

### 2.2 Inventory Analysis

The social risk inventory was derived following the PSILCA database approach, which was also built on our previous work (Teah et al., 2024). The process involved (1) assembling process-based inventory, (2) converting physical flows to monetary flows, and (3) matching the physical processes to PSILCA activities.

First, the hydrometallurgical battery recycling was modelled using data from the EverBatt model (Dai et al., 2019). It included the primary recycling and additional material conversion processes, which convert the recovered nickel and cobalt compounds into nickel sulphate and cobalt sulphate for the production of NMC batteries. The inventory is listed in Figure 1(a). The model assessed the recycling of NMC622 battery type; the composition of the battery and the recycling rate of materials are listed in Tables S1 and S2. The components other than the cathode battery materials were excluded to simplify the social risk assessment.

The acquisition of virgin battery material was modelled using process data from ecoinvent v3.11. A major global battery material supply chain was assessed. Specifically, the lithium carbonate was supplied from Chile; the raw materials of cobalt, manganese, and nickel were mined and refined from DR Congo, South Africa, and



## 2.3 Impact Assessment

After setting up the inventory, a social impact assessment or social risk assessment of a product system can be performed in the openLCA software using the default social impact weighting method. The default mode applied the concept of “worker hours” as an activity variable, or a weight to show the relative importance of an activity, when aggregating the social risks. This study only applied the impact assessment to the worker stakeholder category. This study employed a screening approach (Teah et al., 2024), without aggregating social risk across activities, to the other stakeholder categories.

The selected stakeholders, subcategories, and corresponding indicators are listed in Table S9. The selection was primarily driven by the completeness of the dataset across the activities in the product system to avoid unfair comparison. Some indicators, like the sector average wage for the fair salary subcategory, required recalculation due to the inconsistent aggregation rule in the default weighting method. We elaborate on the methodological and technical issues in the Discussion (Section 4.1).

## 3. RESULTS

### 3.1 Overview of Life Cycle Social Risks of the End-Of-Life Electric Vehicle Policies

Figure 2 shows the overall life cycle social risks to stakeholders associated with Japan's end-of-life electric vehicle policies. The risks of acquiring virgin materials were benchmarked against recycling batteries from the end-of-life electric vehicles. The total risks to workers were assessed in the mrh-eq unit, aggregating the risks in all activities. In contrast, the risks to value chain actors, the local community, and society were assessed semi-quantitatively, focusing on screening only the risk levels in key supply chain activities.

The S-LCA results showed that mandating domestic electric vehicle recycling could help mitigate the social risks associated with acquiring virgin battery materials. The total risks to workers along the supply chain could be reduced, from 158 to 4 mrh-eq, due to the lower risks of violating collective bargaining rights and forced labour. The risks to value chain actors were reduced, from very high to medium risk levels, due to the less severe risks in corruption, fair competition, and the promotion of social responsibility. Also, the risks to the local community and society were reduced. However, the opportunities for economic development in society along the supply chain were deprived; it negatively impacts developing countries, China, and the DR Congo.

The S-LCA results also showed that the social risks of recycling electric vehicles vary depending on the countries, which had a significant impact on regulating the export of used electric vehicles from Japan. On the one hand, the social risks associated with recycling in New Zealand were similar to those in Japan, except for the issues affecting migrants and indigenous people. On the other hand, the social risks associated with recycling in Pakistan were worse than those in Japan, particularly regarding the well-being of workers in the supply chain. From the examples, the policy to regulate the export of used electric vehicles, initially motivated by national resource security concerns, would also indirectly impact the social risks faced by stakeholders overseas.

Sections 3.2 and 3.3 elaborate on the interpretation of S-LCA results on acquiring virgin battery materials and recycling battery materials using the improved PSILCA database approach.

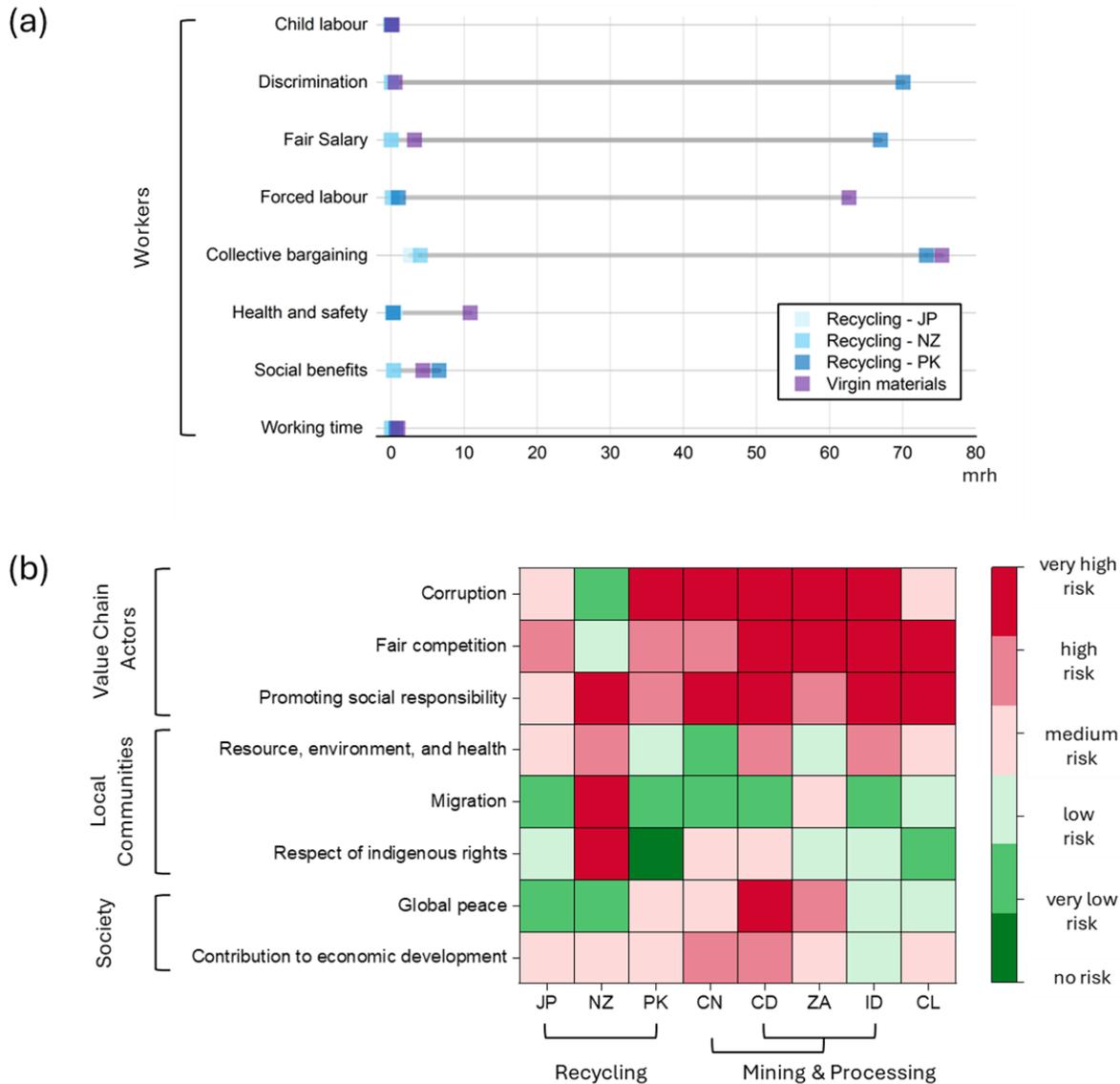


Figure 2. Life Cycle Social Risks to the Stakeholders Associated With Japan's End-Of-Life Electric Vehicle Policies: (a) Workers in Medium Risk Hours (Mrh-Eq per Functional Unit) and (b) Value Chain Actors, Local Communities, and Society. The "contribution to economic development" is a positive exception indicator; where red colours represent high opportunities. (JP: Japan, NZ: New Zealand, PK: Pakistan, CN: China, CD: the DR Congo, ZA: South Africa, ID: Indonesia, CL: Chile)

### 3.2 Social Risks of Acquiring Virgin Battery Materials

The investigated virgin battery materials imported to Japan were based on the predominant global supply chain applicable to other resource-importing countries. A standalone S-LCA revealed the hotspot of this representative supply chain, as a complete contribution tree analysis based on the mrh-eq approach was available in the openLCA software. Briefly, the risks of violating collective bargaining rights were pronounced in the DR Congo, Indonesia, and Chile, which were associated with mining and refining activities. The risks of forced labour were pronounced in the DR Congo and China, which were associated with mining and battery material processing activities. The risks to workers' health and safety were concerning in China. The risks to fair salary were concerning in the DR Congo and Indonesia.

*Table 1. Total Social Risks to Workers in the Supply Chain of Virgin Battery Materials (mrh-eq), and the Share of the Risks Attributed to the Activities in China (Nickel, Cobalt, and Manganese Sulphate Production), the DR Congo (Cobalt Mining), South Africa (Manganese Mining), Indonesia (Nickel Mining), and Chile (Lithium Carbonate Production). The foreground risk level refers to the screening of the primary activity without aggregating auxiliary inputs, such as the production of materials and energy. Note that the share of mrh-eq in fair salary, health and safety, and social benefits categories does not add to 100% due to the methodological issues in the PSILCA weighting method*

	Total risk (mrh-eq)	China		DR Congo		South Africa		Indonesia		Chile	
		Share of mrh-eq--	Foreground risk level	Share of mrh-eq	Foreground risk level						
Child labour	0.16	1%	No Risk	92%	Very Low	2%	Very Low	2%	Very Low	3%	Very Low
Discrimination	0.54	1%	Very Low	16%	Very Low	41%	High	8%	Very Low	34%	Low
Fair Salary	3.19	-	Very Low	-	Medium	-	Very Low	77%	High	-	Low
Forced Labor	62.64	16%	Very High	82%	Very High	1%	High	1%	Medium	0%	Low
Collective Bargaining	75.34	0%	Medium	69%	Very High	1%	High	25%	Very High	5%	Very High
Health and Safety	10.82	78%	Very High	-	No Data	-	Very Low	-	Very Low	-	Low
Social Benefits	4.34	-	Medium	54%	High	-	Medium	-	Medium	-	Medium
Working time	0.91	11%	Medium	59%	Medium	1%	Low	22%	Medium	7%	Medium

To clarify the aggregated mrh-eq results, we summarise the foreground social risks associated with the key supply chain activities in Table 1. This study defined the “foreground risk” as primary activity risk without linking it to upstream activities, akin to Scope 1 emissions in the GHG Protocol. The mrh-eq value had no risk threshold, i.e., no specific value to categorise one result as high or low risk, because it was an artificial unit created using worker hours as an activity variable. The analysis confirmed that the total mrh-eq of most indicators correlated well with the number of very-high-risk activities within the supply chain, specifically those related to forced labour, collective bargaining, and health and safety. This implied that screening the risks of key activities in the foreground could sufficiently inform the S-LCA results for a preliminary survey.

However, the representativeness of the activities, as indicated by the share of mrh-eq, showed that the weighting of activities significantly influenced the S-LCA result. We clarified the steps for weighing and normalising activities in the PSILCA database, as shown in Table 2. The product value, measured in USD per functional unit, and the worker hours required for each activity, measured in hours per USD, determined the weight in Equation 1. The resulting weight, measured in worker hours per functional unit, was normalised against the minimum value across the activities for easier comparison. The ranking, in descending order, was as follows: activities in the DR Congo (13.7), Indonesia (12.0), China (6.6), South Africa (2.8), and Chile (1.0). The social risks associated with DR Congo and Indonesia activities were two to ten times more significant than the rest.

*Table 2. Weighting and Normalisation of Social Risks Associated With Main Activities in the Virgin Battery Material Supply Chain, as Represented by Countries Where These Activities Occur*

	China	DR Congo	South Africa	Indonesia	Chile
Product value (USD)	3.15	2.08	0.31	2.17	0.81
Worker hours (hour/USD)	0.024	0.075	0.104	0.062	0.014
Weight of activity (hours)	0.08	0.16	0.03	0.14	0.01
Normalised weight of activity	6.6	13.7	2.8	12.0	1.0

In addition, the normalised weight also showed that, despite the high added value in Chinese battery materials processing, the lower worker hours required, an indication of higher productivity, resulted in a reduced overall weight. The normalised weight of DR Congo and Indonesia showed that the unit cost of the product and the required input were critical factors when the industrial productivity was similar. The weight of cobalt was attributed to its higher unit cost of mineral, while the weight of nickel was attributed to the larger input amount required for NMC622 batteries.

Apart from the workers, the social risks to the value chain actors, local communities, and society were pronounced (Figure 2b). The high-risk indicators included public sector corruption, anti-competitive behaviour, and violations of antitrust and monopoly legislation, promoting social responsibility, certified environmental management systems, and the global peace index. The risks were attributed to the global battery supply chain, primarily in developing countries. Although the social risks were high, the economic opportunities were substantial compared to their country’s GDP, which was the only assessed positive social indicator. Some studies argue that economic growth in developing countries is necessary to improve the social foundation, which is much needed, as they transition towards a society with lower social risks (Hansen, 2022). We caution that results from S-LCA must not be overinterpreted. We should focus on managing risks to prevent undesired social impacts, rather than encouraging hasty divestment from the regions.

### 3.3 Social Risks of Battery Recycling in Japan and Overseas

In 2024, Japan exported 20,119 used electric vehicles, including 1,962 units to New Zealand and 1,142 units to Pakistan. Considering the rate of battery degradation, an end-of-life battery recycling will soon be needed. The battery recycling process investigated was based on hydrometallurgical treatment, which was recognised as an environmentally friendlier and practical solution due to the recovery of lithium (Asokan et al., 2023; Ciez & Whitacre, 2019). The treatment primarily involved separation, acid leaching, and

solvent extraction; therefore, the social risks associated with the recycling activity was represented by the chemical industry in each country.

The overall social risks to workers and value chain actors were greater in developing countries, such as Pakistan, than in developed countries, including Japan and New Zealand. Specific issues were observed in certain countries, including collective bargaining rights (trade unionism) in Japan, migration, and indigenous rights in New Zealand (Figure 2).

Using the mrh-eq assessment approach, the aggregated risks were heavily weighted on the foreground chemical industry. In the case of recycling in Japan, the value of the recycled products (3.96 USD) was much higher than the cost of material and energy input (0.61 USD). Therefore, it was weighted six times more than the combined weight of all other activities. Moreover, the social inventory for the material input was primarily attributed to inorganic chemicals, such as sulfuric acid, sodium hydroxide, and hydrogen peroxide, which were represented with the same chemical industry activity in the PSILCA database. The social hotspots identified through the mrh-eq approach were trade unionism and public sector corruption.

The supply chain activity screening approach required subjective judgments to determine the cutoff point for upstream activities. Compared to the hotspot identified earlier, the risk of trade unionism was recognised, but not public sector corruption (rated as medium risk in the foreground activity), as shown in Figure 2. The former was attributed to the activities in Japan, while the latter was significantly attributed to overseas activities.

The breakdown of public sector corruption embedded in the recycling activity was presented in a Sankey diagram (Figure 3) to clarify the S-LCA result. Approximately 90% of the risk was attributed to the acquisition of inorganic chemicals. The chemical industry in Japan had been depending on the input from upstream activities in Japan (24% of the risk), China (26% of the risk), and other countries to produce the chemicals. A notable drawback of the screening approach was that one might not immediately recognise Japan's chemical industry's dependency on upstream activities in China, without the interlinkage of activities embedded in the PSILCA input-output database.

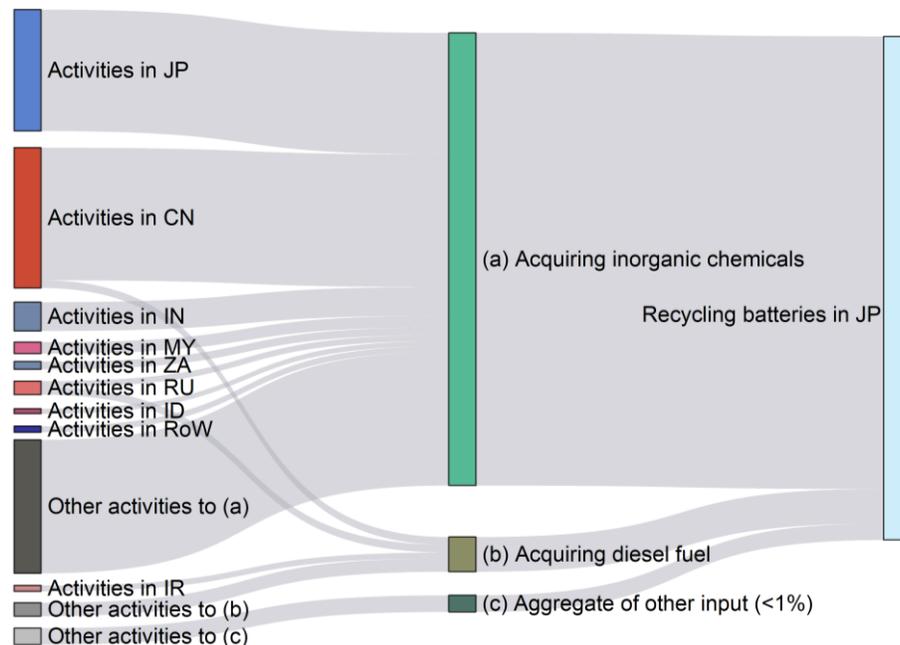


Figure 3. The Attribution of Social Risks (in mrh-eq Unit) Associated with Public Sector Corruption in Battery Recycling in Japan, as Reflected in the Material and Energy Inputs to Hydrometallurgical Treatment and Their Upstream Activities

## 4. DISCUSSION

### 4.1 Improving the PSILCA-Based S-LCA Methodology

The framework proposed in this study modified the PSILCA database-based S-LCA approach to correct inconsistencies and other issues in the database, adjust the social impacts weighting method, and enhance the interpretability of results. We outline the methodology changes and findings to inform future research.

First, we found that treating missing data as “low risk” or a factor of 0.1 in PSILCA underestimated the social impact. Data was frequently missing in less developed countries, which typically face higher social risks. An example is the missing health and safety risk data associated with activities in DR Congo, which was measured by violations of mandatory health and safety standards. If the missing data were interpreted as low risk, then the mining activity in DR Congo would be rated unreasonably safer than the processing activity in China (see Table 1). We excluded indicators with excessive missing data, as they were deemed less relevant to the study. Another option was to subjectively adjust the characterisation factor to high risk or a factor of 10.

Second, we recalculated the S-LCA result (in mrh-eq unit) for selected indicators due to the inconsistent weighting in the default method. In PSILCA v3.1, the inventory included 70 indicators, whereas the impact assessment comprised only 55. Some indicators were grouped into a single “indicator category” (Table S10). The openLCA software presents the results of these indicator categories and individual indicators side by side. The elevated value in the indicator category was frequently misinterpreted as a hotspot. However, this was simply due to the value being an aggregation of multiple indicators. An example was the “fair salary category”, which was misinterpreted as the highest risk for battery production (Koese et al., 2023). An appropriate comparison would require disaggregating the impact from the three indicators: living wage, minimum wage, and sector average wage.

Third, we selected only 16 out of the 70 indicators to provide a concise interpretation of the S-LCA results. Although the rich collection of indicators in PSILCA was based on international conventions and standards, the incomplete dataset for many indicators, as noted earlier, rendered the results difficult to interpret accurately. In this study, we iteratively analysed the S-LCA results and selected only one relatively complete and representative indicator for each subcategory. This approach was sufficient to cover the social impact subcategories comprehensively, while avoiding the need to treat multiple indicators for each subcategory.

Fourth, we adopted a screening approach, only on key supply chain activities, for social risk assessment of stakeholders other than workers. It was motivated by the irrelevance of worker hours to stakeholders such as local communities. Although not all upstream activities were screened, the S-LCA findings were consistent with the mrh-eq assessment, as shown in Table 1. The consistency was due to the weighting mechanism based on product value, as shown in Table 2. In industrial processes, the foreground activity and the economic flow often have significantly higher added value (Machala et al., 2025); therefore, screening these activities would likely yield similar findings.

### 4.2 Limitations of This Study

The S-LCA presented here has some limitations due to the scope of assessment, methodological subjectivity, and data uncertainty. The scope considered only the precursor materials for the NMC cathode, which accounted for 80% of the value acquired from battery cell recycling. The copper from the current collector was a major component that was excluded, therefore underestimating the benefits of social risk mitigation from battery recycling. The selection of social risk indicators from the PSILCA database was based on data availability and subjective judgment of their representativeness. Future improvement of the dataset might affect the selection and the S-LCA results. But, to date, there is no consensus on social indicator selection from S-LCA guidelines and ISO14075. The data variability and uncertainty were another limitation. This study analysed the major raw material suppliers for nickel, manganese, and cobalt; however, there were other smaller suppliers from different regions, such as the Philippines, that were not discussed. The data also only represents a country-specific sector performance; the actual social impact on the activities would depend on the individual companies' performance (see more discussion in Section 4.4).

### 4.3 Comparison with Other S-LCA Literature

A few studies have examined the S-LCA of battery production, as well as one on battery recycling. Despite the differences in specific battery types and the scope of assessment, we compared the main findings from studies that applied a database-oriented reference scale approach to conduct preliminary cross-checking of the validity of the S-LCA approach.

- Popien et al. 2022 assessed the recycling processes encompassing discharging, dismantling, mechanical, and hydrometallurgical processes. They highlighted that effectively managing the number of employees, or labour required, was critical to mitigate the social risk. The social impact of dismantling and mechanical pretreatments, which were not considered in this study, could potentially double the risk due to the increased working hours required. The study did not identify more prevalent social risks.
- Koese et al. 2023 assessed the NMC battery production in China. The social risks for workers were higher than for other stakeholders. The hotspot subcategories were fair salary, collective bargaining, social benefits, and forced labour. The fair salary had an exceptionally high mrh-eq, which disagreed with the findings in our study. It was most likely due to the inconsistent weighting pointed out in Section 4.1. The latter three hotspots agreed well with the findings in our study.
- Orola et al. 2024 assessed the NMC cathode production in the global supply chain. The social impact categories differed due to the use of the SHDB database. The social risks for health and safety were most pronounced among the categories. The health and safety of workers were a hotspot in our study, but not in the earlier study (Koese et al., 2023). It was likely due to the underestimation of health and safety risk where data was unavailable, as pointed out in Section 4.1.

### 4.4 Comparison with Actual Company Performance

The S-LCA results were based on country-specific sectoral average performances, which might differ between the companies in practice. We compared four selected companies involved in battery recycling in Japan and one chemical production company in China, to contrast their workers-related risks with the social risks identified in S-LCA. The indicators of companies were adopted from TERRAST, a commercially available ESG database (Sustainable Lab Inc. 2025).

Table S11 summarises the comparison. Two indicators were compared for discrimination against female workers. The gender wage gap was severe, ranging from 17% to 39%, among companies in Japan. The finding agreed with the PSILCA inventory, which had a very high risk, or 31%. The women's participation ratio, or female employees ratio, was as low as 9 to 25% among the companies. This finding disagreed with the PSILCA inventory, which had a low risk, or about 40%. For the other indicators, we also found some disagreements that warrant future investigation, such as the very high risk indicated in the living wage in Japan.

Comparing the actual company performance and S-LCA results, we found that the performance of individual companies varies depending on their overall practices and operational strategies. The risk level of inventory in PSILCA helped identify areas of concern. We noted that the risk level determined in PSILCA did not always align with the company's performance. The reasons could be the choice of indicators, the resolution of data, and other methodological issues. We also caution against overinterpreting the results due to the small sample sizes discussed in this section.

## 5. CONCLUSION

This study proposed to improve the PSILCA database approach for S-LCA to address some of the critical methodological and technical issues, including the treatment of missing data, the consistency of weighting across indicators and subcategories, the selection of representative indicators, and the avoidance of the worker hours activity variable for non-worker stakeholders. These are significant issues as the database approach is gaining popularity in the field of S-LCA. The above issues were often unintentionally overlooked in S-LCA literature, due to the abundance of social risk indicators and the lengthy S-LCA results, which would be difficult to discuss in a single paper. However, some technical issues were embedded in the PSILCA database, and the problem would spread further as the number of users increased. Therefore,

this study would serve as a timely reminder to the S-LCA communities. In the case of battery production and recycling, we demonstrated that the above issues indeed led to some errors in calculating and interpreting the S-LCA results.

Apart from the methodological improvements, this study evaluated the social impact of the end-of-life electric vehicle management policies in Japan. When comparing battery production from virgin and recycled materials, mandating domestic battery recycling significantly improved the overall social risk to workers and value chain actors. Using the screening approach, we can more clearly identify the social risks associated with the foreground activities and compare them with the actual company performance. We emphasised that social risk was not an unavoidable consequence; it could be mitigated through individual management efforts within companies. The PSILCA approach for S-LCA at the macro-scale was suitable for systematically presenting social risks to inform policy support.

Finally, we recommend future research on S-LCA to harmonise and improve the interpretation of the numerous social risk indicators to reflect societal values. Currently, the indicators are synthesised into  $m_{rh}$ - $eq$ , which is problematic for non-worker indicators and meaningless when the result is presented as standalone figures. Some suggestions, including conducting surveys to understand the people's willingness to pay in mitigating social risks in each country or region, would enhance the applicability and usefulness of the S-LCA methodology.

## ACKNOWLEDGEMENTS

This work was supported by JSPS KAKENHI Grant Number 24K15399. This work contains the results of projects supported by the New Energy and Industrial Technology Development Organization (NEDO, Grant number JPNP21026), JST COI-NEXT JPMJPF2003, and JST Social scenario research program towards a carbon-neutral society Grant Number JPMJCN2301. The activities of the Presidential Endowed Chair of the “Platinum Society” at the University of Tokyo are supported by Mitsui Fudosan Corporation, Sekisui House, Ltd., East Japan Railway Company, and Toyota Tsusho Corporation.

## AUTHOR CONTRIBUTIONS

**Heng Yi Teah:** Conceptualisation, methodology, formal analysis, visualisation, writing, review & editing, funding acquisition.

**Suyi Yang:** Formal analysis, writing.

**Jiaqi Yang:** Formal analysis, writing.

**Eri Amasawa:** Conceptualisation, review & editing.

**Yasunori Kikuchi:** Conceptualisation, funding acquisition.

## DECLARATIONS

**Competing interests** The authors declare no competing interests.

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## SUPPORTING INFORMATION

Table S1. Battery Composition of a NMC(622) Cell (data source: EverBatt model)

Material	Composition (kg/cell)	
Active cathode material	0.25	
Li		0.02
Ni		0.09
Mn		0.03
Co		0.03
O		0.08
Graphite	0.16	
Carbon black	0.02	
Binder - PVDF	0.02	
Copper	0.12	
Aluminum	0.06	
Electrolyte - LiPF <sub>6</sub>	0.02	
Electrolyte - EC	0.05	
Electrolyte - DMC	0.05	
Plastic - PP	0.01	
Plastic - PE	0.00	
Plastic - PET	0.00	
Total cell mass	0.77	

Table S2. Recovery Rate of Materials via Hydrometallurgical Treatment (Data Source: EverBatt Model)

Material	Recovery rate
Copper	90%
Steel	90%
Aluminum	90%
Graphite	90%
Plastics	50%
Lithium	90%
Ni <sup>2+</sup> in output	98%
Mn <sup>2+</sup> in output	98%
Co <sup>2+</sup> in output	98%
Electrolyte solvents	50%

Table S3. Cost of Utilities and Other Materials for Recycling 1 Kg Spent Battery Cell (Data Source: EverBatt Model, and Statista for Electricity Price in Japan)

	Amount	Unit	Cost (USD2015)
<b>Utilities</b>			
Water	3.79	kg	0.00421
Electricity	0.03	kWh	0.00796
Diesel (combusted)	0.02	L	0.0201
Natural gas (combusted)	2.50	MJ	0.0231
<b>Materials</b>			
Ammonium hydroxide	0.03	kg	0.0132
Hydrochloric acid	0.01	kg	0.00167
Hydrogen peroxide	0.37	kg	0.251
Sodium hydroxide	0.56	kg	0.208
Sulfuric acid	1.08	kg	0.0600
Soda ash	0.02	kg	0.00278
Sulfuric acid (conversion)	0.26	kg	0.0142
Water (conversion)	0.31	kg	0.00034

Table S4. Price of Battery Materials (Functional Unit Abbreviated as f.u.; Data Source: EverBatt Model)

	Amount (kg/f.u.)	Price (USD2019/kg material)	Price (USD2015/f.u.)
Nickel sulfate	0.304	4.29	1.208
Manganese sulfate	0.099	1.13	0.105
Cobalt sulfate	0.102	19.51	1.834
Li carbonate	0.111	7.90	0.813

Table S5. The Inventory Matching From Ecoinvent Database's Processes to PSILCA Database's Activities, to Recycle 1 KG of Spent Battery Cell Using the Hydrometallurgical Treatment at Three Countries

<b>Activities in PSILCA</b>	<b>Input (USD2015)</b>
<b>Recycling activity in Japan</b>	
<b>Input</b>	
Industrial water supply	0.005
Electric power for enterprise use	0.008
Petroleum refinery products (inc. greases)	0.020
Crude petroleum and natural gas	0.023
Industrial soda chemicals	0.003
Other industrial inorganic chemicals	0.548
<b>Output</b>	
Other industrial inorganic chemicals	3.959
<b>Recycling in New Zealand</b>	
<b>Input</b>	
Water	0.005
Electricity	0.008
Petroleum products	0.020
Crude petroleum and natural gas	0.023
Manufacture of other chemical products	0.551
<b>Output</b>	
Manufacture of other chemical products	3.959
<b>Recycling in Pakistan</b>	
<b>Input</b>	
Electricity, gas, and water supply	0.013
Petroleum, Chemical and Non-Metallic Mineral Products	0.594
<b>Output</b>	
Petroleum, Chemical and Non-Metallic Mineral Products	3.959

*Table S6. The Inventory Matching From Ecoinvent Database's Processes to PSILCA Database's Activities, to Acquire 1Kg Nickel Sulfate*

<b>Activities in PSILCA</b>	<b>Input (USD2015)</b>
Electricity and steam production and supply - CN	0.129
Other metallic ores - ID	7.14
Raw chemical materials - CN	0.0602
Construction - CN	3.03E-09

*Table S7. The Inventory Matching From Ecoinvent Database's Processes to PSILCA Database's Activities, to Acquire 1Kg Manganese Sulfate*

<b>Activities in PSILCA</b>	<b>Input (USD2015)</b>
Electricity and steam production and supply - CN	0.0964
Other mining - ZA	0.00377
Manufacture and distribution of gas - CN	0.0838
Construction - CN	3.03E-09

*Table S8. The Inventory Matching From Ecoinvent Database's Processes to PSILCA Database's Activities, to Acquire 1KG Cobalt Sulfate*

<b>Activities in PSILCA</b>	<b>Input (USD2015)</b>
Electricity and steam production and supply - CN	0.329
Petroleum Refineries - CN	0.00760
Mining and Quarrying - CD	20.4
Raw chemical materials - CN	0.601
Construction - CN	3.03E-09

Table S9. Selected Social Risk Indicators for the Stakeholders Subcategories Based on the PSILCA Database

<b>Stakeholders Subcategories</b>	<b>Indicators</b>
<b>Workers</b>	
Child labour	Children in employment, total
Discrimination	Women in the sectoral labour force
Fair salary	Sector average wage, per month
Forced labour	Trafficking in persons
Collective bargaining	Trade union density
Health and safety	Violations of mandatory health and safety standards
Social benefits	Evidence of violations of laws and employment regulations
Working time	Weekly hours of work per employee
<b>Value Chain Actors</b>	
Corruption	Public sector corruption
Fair competition	Anti-competitive behaviour or violation of anti-trust and monopoly legislation
Promoting Social responsibility	Promoting social responsibility
<b>Local Communities</b>	
Resource, environment, and health	Certified environmental management system
Migration	International migrant stock
Respect of indigenous rights	Indigenous rights
<b>Society</b>	
Global peace	Global peace index
Contribution to economic development	Contribution of the sector to economic development

Table S10. A List of Social Indicators That Contains the Aggregation of Multiple Indicators After the Default Social Impact Weighting in PSILCA. The authors suggested to avoid or manually disaggregate these indicators for a fair comparison

<b>Subcategory</b>	<b>Indicators (at social-LCIA step)</b>	<b>Multiple Sub-Indicators (at inventory step)</b>
Fair Salary	Fair Salary	Living wage, per month
		Minimum wage, per month.
		Sector average wage, per month
Freedom of association and collective bargaining	Association and bargaining rights	Right of Association
		Right of Collective bargaining
		Right to Strike
Social benefits, legal issues	Violations of employment laws and regulations	Violations of mandatory health and safety standards
		Evidence of violations of laws and employment regulations
	Biomass consumption	Extraction of biomass (related to area)
		Extraction of biomass (related to population)
	Minerals consumption	Extraction of industrial and construction minerals
		Extraction of ores
	Industrial water depletion	Level of industrial water use (related to renewable water resources)
		Level of industrial water use (related to total withdrawal)
GHG footprints	GHG Footprints	Embodied CO2 footprint
		Embodied CO2-eq footprint
Migration	Migration flows	Emigration rate
		Immigration rate
		Asylum seekers rate
Respect of indigeneous rights	Indigenous rights	Indigenous People Rights Protection Index
		Presence of indigenous population
Health and safety	Health expenditure	Health expenditure, domestic general government
		Health expenditure, external resources
		Health expenditure, out-of-pocket
		Health expenditure, total

Table S11. Comparison of Worker Well-Being and Environmental Management of Five Companies in Corresponding to PSILCA Sectoral Risk Levels (Data Source: The Five Companies Data Is Obtained From TERRAST Database, <https://www.terrast.biz/Terrast>)

Company	Country	100-Gender Pay Gap Including Management in percentage (%)	Percentage of Female Employees (%)	Average annual salary/12m (JPY/person/month)	Average annual salary (industry average)/12m (JPY/person/month)	Occupational accident frequency rate (person/M hours)	ISO 14001/EMS certified
Sumitomo Metal Mining Co.,Ltd.	Japan	36.2	20.0	686,250	559,734	1.48	Yes
Mitsubishi Materials Corporation	Japan	39.9	15.3	591,417	559,734	0.21	Yes
Sumitomo Chemical Co.,Ltd.	Japan	24.0	25.0	702,040	569,404	0.10	Yes
Kanto Denka Kogyo Co.,Ltd.	Japan	17.0	9.4	628,313	569,404	-	Yes
Wanhua Chemical Group Co.,Ltd.	China	-	14.0	97,714	-	-	-
Country		Gender wage gap	Women in the sectoral labour force	Living wage, per month	Sector average wage, per month	Rate of fatal accidents at workplace	Certified environmental management systems
Japan	Risk level	Very high risk	Low risk	Very high risk	Low risk	Very low risk	Medium risk
	Raw data	30.92	0.68	1,164	2,686	3.11	0.01
China	Risk level	No data	Very low risk	Medium risk	Very low risk	No data	Very low risk
	Raw data	-	0.89	240.08	842.92	-	48.33