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The scarcity of primary data in life cycle assessments of lithium-ion battery manufacturing: A systematic review

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ABSTRACT:
With increasing greenhouse gas emissions, lithium-ion batteries (LIBs) are becoming a promising technology for decarbonization, particularly in the urban mobility sector. However, their production involves critical materials and large energy consumption processes, requiring robust environmental evaluation. Life Cycle Assessment (LCA) plays a key role in assessing the environmental impacts of the manufacturing phase. This study presents a Systematic Literature Review (SLR) focused on identifying the use of primary data in LCAs of LIB manufacturing. The review was conducted using Scopus and SciFinder databases through an iterative search strategy combining keywords related to LIBs, manufacturing, LCA, and primary data. From an initial pool of over 205,000 articles, only four met the inclusion criteria of applying primary data to the manufacturing phase. Most studies focused on LMO and NMC chemistries, primarily in pouch or prismatic formats, and used cradle-to-gate boundaries. Despite being labeled as primary data based, these studies showed strong reliance on secondary datasets, limited geographical coverage, and no recent publications within the last five years. The variability in reported CO_2 emissions further reflects methodological inconsistencies. These findings indicate a literature gap in LCA studies using primary data for LIB manufacturing. Specifically, there is a lack of recent, geographically diverse, and methodologically transparent research, which raises concerns about the reliability of current environmental assessments.

Keywords: Lithium- ion batteries, life cycle assessment, manufacture and primary data

1. Introduction

Multiple lines of evidence indicate a clear increase in global average temperatures (IPCC, 2023). This has prompted international bodies and agreements to aim to reduce this increase (Ongsakul et al., 2025). Multilateral initiatives have focused on establishing collective targets aimed at curbing global warming, as exemplified by climate agreements established in the last decade (Hodgkinson & Smith, 2021). Consequently, the transition to a less fossil fuel dependent energy mix emerges as one of the main challenges, given the significant contribution of the energy and transportation sectors to global greenhouse gas emissions (IEA, 2023).

Lithium-ion batteries have become critical in this transition, facilitating electric mobility technologies and energy storage systems that underpin the broader energy transition (IEA, 2021). These applications are frequently associated with global decarbonization efforts and initiatives to reduce environmental impact (Chandrasekharam

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et al., 2024). However, the increasing demand for these technologies raises concerns about the environmental impacts of extracting critical raw materials, such as lithium, cobalt, and nickel, which are essential for their production chain (Greim et al., 2020).

The battery market has been growing steadily since the 2010s (IEA, 2024). The applications of batteries are wide ranging, from energy storage systems in isolated grids (BESS, Battery Energy Storage System) to electric and hybrid vehicles (Chen et al., 2020; Miao et al., 2019). The diversity of applications and increasing demand, combined with advancements in production capacity, will increase pressure on mining and material processing activities, intensifying the associated impacts (Wolters & Brusselaers, 2024). Therefore, environmental monitoring of this sector is crucial, especially considering the scarcity of strategic minerals critical to the energy transition and technological innovations.

The Life Cycle Assessment (LCA) tool allows for the systematic measurement of these impacts, in accordance with ISO standards 14040 and 14044. From the definition of the goal and scope, an inventory is developed which supports the quantification of the environmental impacts of the assessed processes. With the advancement of battery technologies, applying LCA specifically to the manufacturing phase becomes fundamental, guiding technical development towards reducing the environmental footprint. This phase represents a significant share, currently estimated more than 35% (for NMC batteries) of the total impact associated with battery production (in GHG emissions) and is therefore strategic for the technological and environmental evolution of this sector (Jiang et al., 2024).

Widely used commercial databases in LCA inventory development, such as Ecoinvent, GREET, and GaBi, are built with approximations and linearization that favor their generic application in different contexts (Scrucca et al., 2020). However, to obtain results more representative of reality in LCA studies, the use of primary data is essential, especially for complex industrial processes such as battery manufacturing. The availability of these data is, therefore, a key element in reducing uncertainties and guiding concrete improvements in production processes. Given this, the main objective of this study was to analyse the presence of primary data reported in studies on lithium-ion battery production plants, in the context of LCA aimed at measuring environmental impacts.

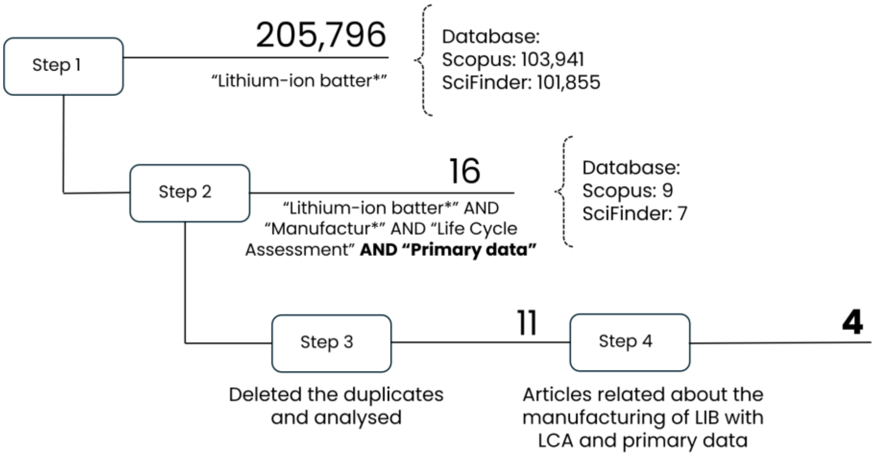
2. Method

This systematic literature review was conducted in accordance with the PRISMA 2020 statement guidelines (Page et al., 2021). We performed literature research using the Scopus and SciFinder-n databases. We chose Scopus for its multidisciplinary scope and citation analysis capabilities, while SciFinder-n was selected for its specialization and depth in chemistry and materials science, fields pertinent to the battery topic. We did not impose any restrictions on language. For general battery searches, searches covered the period from 1996 to 2024, if a specific subtopic yielded no publications in this date range, we extended the search back to the earliest record available. Our most recent literature search update was on May 16, 2025. Only original, peer reviewed scientific articles were included. Review articles, book chapters, and patents were omitted.

The literature search was executed systematically and iteratively, progressively refining the results to identify the most relevant articles. Specifically, for Scopus, keyword searches were performed in the title, keywords, and abstract fields, for SciFinder-n, a similar approach was used. The first search was relatively broad, using the term "Lithium-ion batter*" to map the general research in this area. From an initial analysis of the initial results, a more refined keyword search was applied with the addition of "AND Manufactur*" to focus the search on studies related to the manufacturing processes associated with lithium-ion batteries. The results were then reanalysed, and the search was further refined by adding the term "AND 'Life cycle assessment'" to focus on articles applying LCA methodology. The following search term, "AND 'Primary data'", was incorporated to restrict selection to articles specifying primary data. It should be noted that each search term addition was preceded by an analysis of the partial results to ensure the relevance and focus of the search at each stage.

The screening and selection process, illustrated in Figure 1, was performed by a single reviewer. The reviewer conducted a title and abstract screening followed by a full text review of potentially eligible studies. After removing duplicates, 11 articles were identified. The inclusion criteria were the inclusion of the manufacturing phase within the LCA scope, and a clear statement regarding the origin of the data used (primary or secondary).

Figure 1: *PRISMA Flow Diagram of the Systematic Literature Review process.*

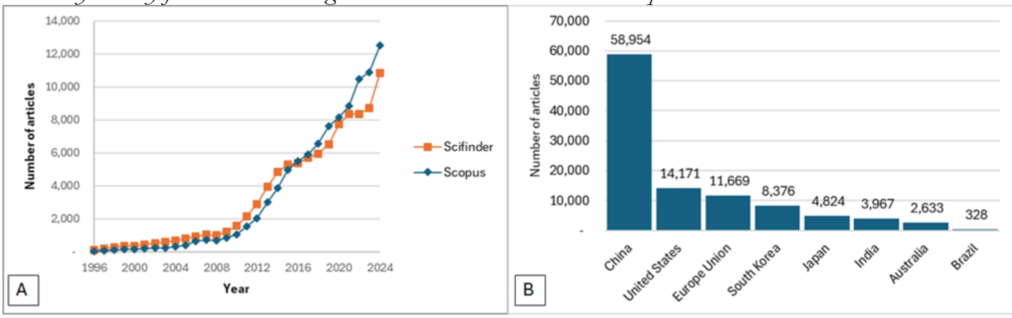


Data extraction was performed manually, systematically and organized based on defined variables: article title, location of the manufacturing process under study, publication year, LCA software, system boundary, functional unit, data source, impact assessment method (LCIA), cathode type, cell format, and the environmental footprint result of the process. The results were synthesized using narrative synthesis and tabular analysis, highlighting the characteristics of the studies. After data extraction was completed, a cross-reference analysis was conducted among the 11 articles to identify inter-citations. As the review was not focused on quantitatively comparing the interventions, a meta-analysis of the articles' results was not conducted, and no statistical methods for heterogeneity, effect measures, or sensitivity analyses were undertaken.

4. Results and discussions

Application of the described structured methodology yielded 205,796 articles after the respective filters were applied. From this total, the data can be processed to observe the distribution of these articles over the years. Figure 2A presents the graph describing this distribution for searches using the string "lithium-ion batter*". The graph clearly shows an increasing trend in the number of publications related to lithium-ion batteries in the Scopus and SciFinder databases between 1996 and 2024, with more significant growth from 2004 onwards.

Figure 2: *(A) Distribution of articles by year for the search string "lithium-ion batter*". (B) Distribution of articles by country for the search string "lithium-ion batter*" based on Scopus data.*



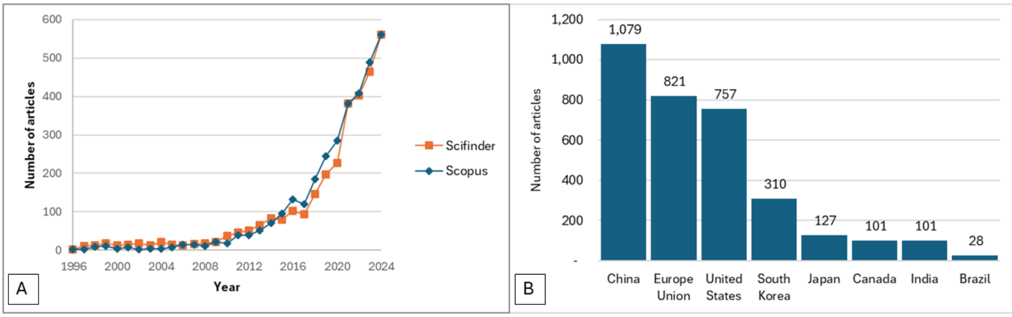
Until approximately 2016, the curves for both databases show similar behaviours, with parallel growth. From this point onwards, a shift in dominance between the databases is observed, with Scopus surpassing SciFinder in recent years, especially in 2023 and 2024, when the Scopus curve shows a more pronounced increase, exceeding 12,000 publications in 2024. Totalling 103,941 articles from Scopus versus 101,855 from SciFinder, a higher number of publications are observed for the Scopus database. This significant growth indicates that the topic has been extensively studied by the academic community.

The Scopus database allows for the separation of publications by country, and Figure 2B presents these data. A significant dominance by China over other countries is observed, with approximately a four-fold lead over the second-placed United States. For the data presented by country, 7 countries were listed in descending order of publication numbers, followed by Brazil, regardless of its publication count. For the "European Union" location, data were aggregated from member states that were among these top 8 publishing countries.

The largest share of global battery production is concentrated in China, which is considered the country with the world's largest installed capacity for production of LIBs for electric vehicles application (IEA, 2024). In second place, the USA leads compared to the rest of the world, surpassing the European Union (in third position) by approximately 18%. There are substantial investments in the lithium-ion battery sector in the countries leading these results (Moreno-Brieva & Merino-Moreno, 2021), this investment is linked to the technological maturation of research and development so that the manufacturing stage can then be more economically and environmentally efficient. At the end of the search, Brazil, intentionally included, does not hold a prominent position. Brazil still lags in the synthesis and assembly of lithium-ion batteries compared to the rest of the world for scientific publications, highlighting a significant local opportunity for studies to encourage the national chain.

Given the large number of publications from the previous step, the research was further refined to find the desired niche of publications more closely related to the battery manufacturing process. As can be observed in Figure 3A, the graph represents the number of publications when the string "Manufactur*" is included as a search delimitation criterion. In this graph, the number of publications is drastically reduced, from 205,796 to 6,879, an approximate 97% reduction in the number of articles, with 3,502 in Scopus and 3,377 in SciFinder.

Figure 3: *(A) Number of articles per year for the search string "Lithium-ion batter*" AND "Manufactur*". (B) Distribution of articles by country for the search with the same string (Scopus data).*



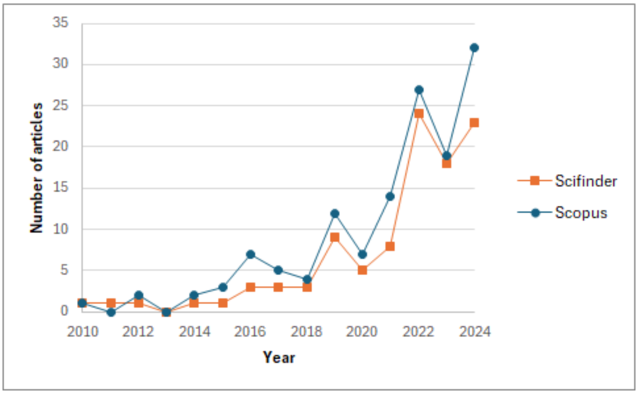
A distinct dynamic over the years is observed between the two data search sets. Although the previous graph (Figure 2A) showed a recent dominance of the Scopus database, this more specific selection (Figure 3A) reveals a more balanced distribution of publications between the two platforms. This more refined search, by including the term "manufacturing," poses a point for consideration to the academic community, as it addresses a life cycle stage strongly associated with semi-industrial or industrial environments. In this context, it is important to recognize that the disclosure of technical information via scientific articles is not always common or feasible in industry, as the requirement for methodological transparency can conflict with issues of commercial secrecy and intellectual property protection. This cultural and strategic barrier between industrial and academic environments may partly explain the significant reduction in the number of publications found at this stage of the review. The discussion around this industrial-academic divide shows how proprietary concerns hinder environmental transparency. This begs the question of whether a standard framework for anonymized primary data sharing could be the solution.

After categorizing this search group by country, Figure 3B shows that China remains dominant as the location with the highest number of publications. For this search, there was a significant reduction in China's lead over the second-largest country, indicating that publications in this niche are more restricted. There was also a reversal of the second and third positions, indicating that the European Union has a higher number of publications on lithium battery manufacturing processes than the USA.

The European Union has demonstrated a strong commitment to reducing its dependence on Asian battery manufacturers and to developing a robust and sustainable local battery value chain. Since 2017, initiatives like the "European Battery Alliance" have sought to promote collaboration between industry and research institutions (Conor McCaffrey & Niclas Frederic Poitiers, 2024). Public and private investments have been made in R&D, development of gigafactories, and training of a qualified workforce. This mature and coordinated effort can naturally be identified in the increase in scientific production. In Brazil, there are only 28 studies that fit this group of search strings. Although Brazil possesses vast reserves of lithium and other strategic minerals for battery production, the lack of clear, long-term industrial policies aimed at developing a national battery value chain may discourage applied research and interaction between universities and industry in this sector.

With ongoing concerns about the environmental footprint of lithium-ion battery manufacturing processes, Figure 4 shows the temporal distribution of scientific articles relating to these themes. With the inclusion of the keyword “Life cycle assessment” in the search for lithium battery manufacturing processes, an even greater reduction in the number of articles is observed, another significant decrease of approximately 96%. From 6,879 total articles to 252, with 144 from Scopus and 108 from SciFinder. These articles begin in 2010, unlike the other research conducted so far, due to the reduced quantity of studies in the databases, no time filter was applied to this search.

Figure 4: *Distribution of articles by year for the search string “Lithium-ion batter*” AND “Manufactur*” AND “Life cycle assessment”.*



The graph indicates that before 2016, the use of LCA in lithium-ion battery manufacturing was practically absent, suggesting that this tool was still in its developmental stages within the sector. It is important to highlight that LCA is not the only tool for environmental calculation of lithium-ion battery manufacturing processes, and the absence of articles in this area does not indicate that there were no environmental concerns until 2016. This upward curve consolidates in 2024, indicating that the topic is gaining traction, as the environmental assessment of the manufacturing stage becomes a focus for the sustainable development of the battery sector.

To find articles that genuinely apply this life cycle assessment methodology with primary data in the lithium-ion battery manufacturing process, the string "Primary data" was applied. This step further restricted the search, reducing the number of articles by approximately 94% compared to the previous search, from 252 articles to 16, with 9 from Scopus and 7 from SciFinder. With these data, the overview of the systematic literature search can be elaborated, as shown in Figure 1. From these 16 articles, an individual review was performed to verify adherence to the topic in question.

Of the 11 articles that passed duplicate screening, 7 were excluded after a full-text review because they did not use primary data for the complete battery cell manufacturing process, despite containing relevant keywords. Five of these articles used primary data exclusively for other life-cycle stages. For instance, the study by Jasper et al. (2022) analyzed a residential energy storage system, but its manufacturing inventory relied on secondary data from the Ecoinvent database. Similarly, Mayanti (2024) assessed electrified buses using primary data for the operational (use) phase but not for the battery production itself. Another excluded study focused on the end-of-life stage, using primary data from recyclers to assess how cell design characteristics impact the sustainability of the recycling process. Finally, the article by Engels et al. was excluded because its scope was limited to a single input material. Although it used valuable primary industrial data from a Chinese manufacturer, this data was for the beneficiation of natural graphite for anodes, not the manufacturing of the complete battery cell. These exclusions highlight the importance of precise screening to isolate studies that provide primary data for the entire manufacturing process, from slurry mixing to cell finishing.

Other studies, such as that assess the influence of cell format on the recycling process, with primary data for the end-of-life stage. The analysis is based on primary data collected from manufacturers and recyclers, especially for the end-of-life phase, highlighting how design characteristics impact the performance and sustainability of the recycling process. Finally, the last excluded article, by Engels et al. (2022), studied the life cycle assessment of natural graphite production for lithium-ion battery anodes, using primary industrial data from a Chinese manufacturer for its beneficiation.

From this review, four articles were identified as fully adherent to the topic of life cycle assessment with primary data obtained from lithium-ion battery manufacturing processes. From these articles that adhere to the theme, information was extracted as cited in methodology, and then Table 1 was compiled for comparison purposes between the articles and for subsequent advancement in studies developed on this topic. The analysis of the articles demonstrates considerable heterogeneity in terms of geographical location, publication year, and cathode chemistries. This methodological and technological variation, although reflecting diverse production realities, makes any type of comparison almost impossible. Consequently, establishing a valid and representative reference value for the environmental impact of lithium-ion battery manufacturing becomes a difficulty.

Table 1: Analysis of the four selected articles most relevant to the search objective

Author	Localization	Year	Software	System boundary	Functional unit	Dataset	LCIA	Cathod	Cell format	Results
Kim et al.	South Korea and USA	2016	Not specified	Cradle-to-gate	1 kWh	Primary data, Ecoinvent and GREET	GHG emissions	LMO/ NCM_{111}	Pouch	140 kg $CO_{2\text{-eq}}$/ kWh
Dai et al.	USA	2019	GREET	Cradle-to-Gate	1 kWh	Primary data, Ecoinvent and GREET	GREET, IPCC	NMC_{111}	Prismatic	73 kg $CO_{2\text{ eq}}$/ kWh
Cusenza et al.	Japan	2019	Not specified	Cradle to grave	11.4 kWh	Primary data and Ecoinvent	IPCC and PEF	LMO-NMC_{442}	Not specified	313 kg $CO_{2\text{ eq}}$/ kWh
Ellingsen et al.	Norway	2013	Not specified	Cradle-to-gate	1 traction battery, kWh e Kg	Primary data and Ecoinvent	ReCiPe	NMC_{111}	Not specified	172-487 kg $CO_{2\text{ eq}}$/ kWh*

*Margin considering different energy matrix.

The literature analysis presented in Table 1 reveals important trends and gaps in research on battery life cycle assessment. Several publications are concentrated between 2013 and 2019, with 2019 being prominent with two publications, and an absence of studies in the most recent five-year period. This lack of more recent research is a significant point, given the technological advancement of batteries and the growing urgency for cleaner manufacturing solutions. Regarding geographical distribution, the studies cover South Korea, the USA, Japan, and Norway, showing global interest in the topic, but the representation of major production locations is significantly low.

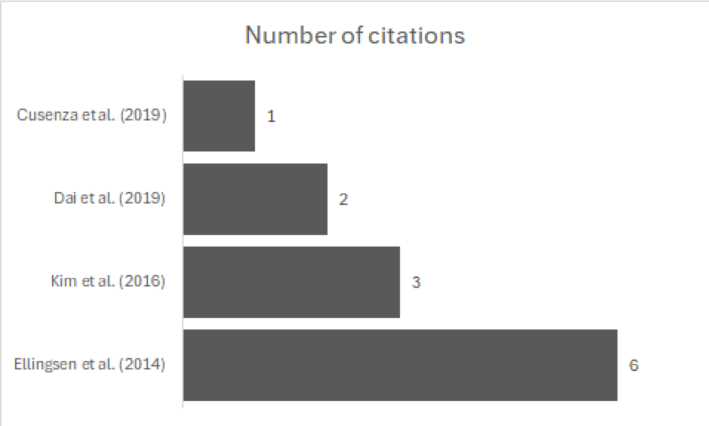
The absence of studies with primary data from China, the world's largest academic producer (as per Figure 2B), indicates a critical gap, suggesting that a significant portion of global production likely operates under life cycle inventory conditions that are not yet sufficiently transparent in the literature. Therefore, more studies with primary data are an urgent demand for the sector. Greater methodological standardization is necessary, especially in leading production regions, to build a more reliable profile useful for decision making and policy development in favor of sustainability.

Almost all studies use a cradle-to-gate system boundary, except for the study by Cusenza, et al. (2019), which considers the battery's end-of-life. This approach, while useful for focusing on manufacturing impacts, excludes the end-of-life phase, which is crucial for a holistic understanding of sustainability. A consistent trend towards using kWh as the functional unit is observed, which is an important point for comparing studies generated in this area. Most studies use the Ecoinvent and GREET databases to supplement the generated and analysed primary data, which can introduce further imprecision to the primary data due to the approximations in these databases.

Most of the selected studies focus primarily on GHG emissions, using secondary datasets to supplement their primary data. While this aligns with broader literature trends, the heavy reliance on databases like GREET and Ecoinvent introduces known uncertainties. This imbalance between carbon metrics and broader environmental impact assessments, such as mineral resource depletion or water use, reflects a significant gap that should be prioritized in upcoming reviews to provide more holistic evaluations. In all studies, the cathode chemistry is focused on LMO and NMC. These two chemistries are likely linked to use in electric vehicles (NMC) (Miao et al., 2019) and electronic devices (LMO) (Zhang et al., 2023). The cell format was predominantly pouch cell and prismatic, the pouch cell model may be applied in studies with LMO chemistry, as it is a possible model for application in notebooks and portable electronics (Zhang et al., 2023). The environmental impact, expressed in all studies in kg CO2eq, fluctuated between 73 and 313, a range indicating significant variation, mainly due to differences in the studies, particularly related to the energy source considered for the manufacturing stage.

Finally, to evaluate the impact of the four studies with primary data in relation to the others, a cross-reference analysis was performed among the 11 reviewed articles. Figure 5 presents the quantity of identified cross citations, allowing visualization of the centrality and relative influence of these studies within the analysed set.

Figure 5: *Graph illustrating the cross-reference analysis for the 4 selected articles within the context of the 11 reviewed articles.*



The article by Ellingsen et al. (2024) was cited by 6 of the 11 studies analysed, appearing in about 55% of the sample. The four articles with primary data, considered the most adherent to the review's scope, also stand out as the most cited among themselves. On the other hand, seven articles show no cross reference. It is worth noting that this is an intra set analysis, that is, the absence of citations here does not imply low relevance in the broader LCA literature but merely reflects the lack of connection among the articles selected in this study. This allows us to understand that the intra set citation analysis indicates that the articles by Ellingsen et al. and Kim et al. served as foundational works for other studies within this specific group. However, the limited cross referencing among the broader set of selected articles suggests a fragmentation in the field. This lack of methodological continuity limits comparative insights and slows the consolidation of a robust knowledge base.

6. Conclusions and further research

The main objective of this study was to conduct a systematic literature review on the LCA of lithium-ion battery manufacturing, aiming to identify publication trends, data sources, and methodological approaches. A remarkable and continuous growth in the volume of publications on lithium-ion batteries was observed in recent years (Figure 2A), with China demonstrating consistent leadership in scientific production (Figure 2B). In this analysis, China emerged as a leader not only in the overall publication landscape for lithium-ion batteries but also specifically in research on lithium-ion battery manufacturing. However, when the search was refined to LCA studies focusing specifically on the manufacturing phase, a significant drop in the number of articles was observed. This sharp decrease suggests that while broad research on batteries is extensive, investigation into the environmental sustainability of production processes remains considerably under explored, offering substantial opportunities for further research and scientific advancement. Following the points above, creating a harmonized methodological framework is essential. Such a framework would not only benefit future LCA studies by ensuring consistency but is also critical for better policy alignment and the practical application of research findings by industry.

This literature review identified a significant lack of studies using primary data for lithium-ion battery manufacturing, with only four articles meeting the established criteria. This severe scarcity of primary data poses a significant constraint. The fact that only four articles out of over 205,000 met the inclusion criteria raises concerns about the comprehensiveness of current LCAs. This limitation not only undermines the accuracy of environmental assessments but also highlights a potential industry reticence in data sharing, likely driven by commercial secrecy and a lack of transparent reporting methodologies. This highlights the difficulty in accessing industrial data, which are generally scarce and often confidential. Primary data are important in LCA inventory research for technological development and understanding credible environmental footprints in the manufacturing stage of LIB. Nevertheless, this study's major contribution is to identify key gaps that need follow up research.

In order to generate advances in knowledge and practice on this issue, future research should focus on the collection of primary data on the manufacturing phase, and its reporting for transparency in research papers. Specifically, the underrepresentation of China, despite being the global leader in LIB production and research, suggests a vital direction for future work. Researchers should investigate how Chinese production chains can provide accessible and verifiable primary data, potentially bridging the gap between industrial confidentiality and scientific openness to foster global sustainability initiatives. Exploring such a framework deserves further attention, especially since methodological transparency is essential for reliable environmental evaluations and for enabling cross comparative LCA studies across different battery chemistries and formats. The conclusion reinforces the urgent need for transparent primary data. While publication volumes grow, meaningful data on environmental footprints remain sparse. Therefore, encouraging industry collaboration through regulatory incentives and standardized reporting platforms is critical. Addressing these data and methodological challenges is an academic obligation and a necessary first step to ensure that global decarbonization efforts are supported by responsible and sustainable technological advancement.

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