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Life cycle assessment of lithium-based batteries: Review of sustainability dimensions

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ABSTRACT

Lithium-based batteries are essential because of their increasing importance across several industries, particularly when it comes to electric vehicles and renewable energy storage. Sustainable batteries throughout their entire life cycle represent a key enabling technology for the zero pollution objectives of the European Green Deal. The EU's (European Union) new regulatory framework for batteries is setting sustainability requirements along the whole battery, including value chains. For a comprehensive assessment of battery technologies, it is necessary to include a life cycle thinking approach into consideration from the beginning.

This review offers a comprehensive study of Environmental Life Cycle Assessment (E-LCA), Life Cycle Costing (LCC), Social Life Cycle Assessment (S-LCA), and Life Cycle Sustainability Assessment (LCSA) methodologies in the context of lithium-based batteries. Notably, the study distinguishes itself by integrating not only environmental considerations but also social and economic dimensions, encapsulating the holistic concept of sustainability. Challenges unique to each assessment method are outlined, including data availability (with 35 % of the reviewed studies having openly accessible inventory data), methodological inconsistencies, uncertainty around future costs and social impacts. Difficulties such as data uncertainty, challenges in cost comparison, and the lack of standardized measures are underscored. The research identifies critical future directions for LCA, including the need for better data quality, adaptation to new technologies, and alignment with Sustainable Development Goals (SDGs). Future research directions are suggested -including the standardization of methodologies, and fostering interdisciplinary collaboration. Overcoming these challenges holds the potential to advance sustainable practices in the battery industry and contribute to a cleaner energy future.

Abbreviation

BESS	Battery Energy Storage Systems
CAPEX	Capital Expenditures
E-LCA	Environmental Life Cycle Assessment
ELCD	European Reference Life Cycle Database
EOL	End-of-life
EOLEX	End-of-life Expenses
EUR	Euro
EV	Electric Vehicle
GHG	Greenhouse Gases
GREET	Greenhouse Gases, Regulated Emissions, and Energy use in Technologies
ISO	International Standard of Organization
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCSA	Life Cycle Sustainability Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Inventory Analysis
LCOE	Levelized Cost of Energy
LFP	Lithium iron phosphate
LIBs	Lithium-ion batteries
MCA	Multi Criteria Analysis
OPEX	Operational Expenses
SDG	Sustainable Development Goal
S-LCA	Social-Life Cycle Costing

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SRHRM	Socially Responsible Human Resources Management
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution

1. Introduction

Within the field of energy storage technologies, lithium-based battery energy storage systems play a vital role as they offer high flexibility in sizing and corresponding technology characteristics (high efficiency, long service life, high energy density) making them ideal for storing local renewable energy. As those available battery energy storage technologies are still too expensive, the development and introduction of new storage technologies are necessary to increase market uptake. Moreover, there is a need to concentrate the majority of the battery manufacturing technology and know-how in Europe and be less reliant on other countries, which currently are dominated by the Asian market. Additionally, there is a drive to improve energy density and safety without compromising on cost or sustainability. With the policymakers in Europe working towards decarbonization of the automobile industry, an anticipated growth in electric vehicle (EV) production is expected. The transition to EVs from an internal combustion engine vehicle, providing an alternative to the existing fossil-based vehicles, could significantly reduce global greenhouse gas (GHG) emissions across the globe. Thus, a surge in sales of electric vehicles is anticipated in Europe and worldwide. With this, the demand for material resources and their consumption by the car manufacturing industries are on the rise. However, mining, processing, production, use-phase, and battery recycling are energy-intensive processes and there arises a need to systematically quantify and evaluate each phase of battery production [1,2]. The life cycle assessment study evaluates the potential environmental impacts of a product within a system boundary. In view of that, several life cycle assessment (LCA) practitioners have used the LCA tool to evaluate the environmental impact of Li-ion battery (LIB) production [3–7]. The technological, cost and social aspects considered illustrate an extensive and a comprehensive picture that is crucial for designing sustainable battery supply chains. Hoogmartens et al. [8], reported that these three sustainable assessment methodology tools were complementary to each other. Further, life cycle sustainability assessment (LCSA) considers these three pillars and provides a platform to assess sustainability studies as one entity.

Due to the increasing recent trend in the development of low-cost and environmentally friendly materials, the life cycle thinking perspective has gained a lot of attention as well. Environmental life cycle assessment (E-LCA) of battery technologies can cover the entire life cycle of a product, including raw material extraction and processing, fabrication of relevant components, the use phase, and, as far as possible, the end-of-life phase/recycling (cradle to grave/cradle to cradle). These methods should be applied already, starting with low technology readiness levels, to enable the analysis and comparison of traditional and emerging products. This approach also provides developers, manufacturers or decision-makers with information about the specific environmental impacts or hotspots of a new product system. They allow for the identification of potential sustainability hotspots and to avoid unintended consequences that might hinder market introduction.

In life cycle costing (LCC), the methodology assesses the cost involved in battery production, maintenance, and end-of-life phase. This gives a comprehensive overview of techno-economic viability and can be a useful tool in establishing a battery choice. For example, one study conducted an LCC evaluation of electric vehicles was conducted on the tangible and non-tangible costs related to the economic and non-economic effects respectively [9]. The LCC analysis delineates the tangible and intangible costs associated with lithium-based batteries, offering critical insights into their economic viability and the broader economic implications of their adoption. This analysis is vital for stakeholders to comprehend the full cost spectrum and make informed decisions that account for long-term economic impacts. In another study, a structure of the LCC of electric vehicles was established based on the acquisition phase, operating phase and disposal phase [10]. Social considerations, often underrepresented in traditional environmental assessments, are brought to the forefront through the incorporation of social life cycle assessment (S-LCA). This paper illuminates the social consequences of lithium battery production, highlighting issues related to labor standards, community impacts, and broader social implications, thus filling a critical research void and enriching the discourse on battery sustainability. The S-LCA is one of the three pillars in achieving sustainable product development. It is considered the most effective methodology to study and comprehend the social impacts of a product, in this context, a lithium-ion battery, in its entire lifecycles [11]. The aim of the review work is to bring together and integrate the three pillars of the sustainability tools in coherence, and through this work a critical overview of previous LCA studies on Li-based batteries is presented. This study presents a review of LCSA for lithium-based batteries, integrating E-LCA, LCC, and S-LCA to provide a comprehensive evaluation of their multifaceted impacts. The key issues of each pillar were studied and analyzed individually. Over the years, LCA has widened its horizon from purely environmental assessments to include the social and economic aspects. This comprehensive work addresses the increasing attention it has received over the past years. The challenges involving procuring primary data, societal issues like labor standards, safety and economy-related issues like the cost of raw materials, and production techniques were addressed.

The originality of this review work lies in its multidisciplinary approach to assessing the sustainability of lithium-based batteries, integrating environmental, economic, and social aspects into a unified framework. The LCSA framework detailed in this paper is intended as a tool for decision-makers across various sectors. By providing a nuanced understanding of the environmental, economic, and social dimensions of lithium-based batteries, the framework guides policymakers, manufacturers, and consumers toward more informed and sustainable choices in battery production, utilization, and end-of-life management.

2. Methodology

The search strategy covers a variety of pertinent keywords and research publications over the past eleven years. Using three significant databases and limiting the search to English-language articles should yield sufficient results that are relevant which is described in Fig. 1. In addition, the inclusion of three sectoral perspectives should aid in capturing research on a variety of Li-based battery applications. The review search protocol for all three dimensions of LCA is focused on conducting a literature review of research articles published between 2012 and 2023. The search was conducted on three academic databases, Web of Science, Scopus and Google Scholar. The sectoral perspective of the search is on three different areas, including E-mobility, grid-scale stationary applications, and portable/wearable electronics. For this extensive search type, keywords related to the specific battery chemistries were used.

Specifically, the search protocol included using the following keyword sequences used in the title search field (Web of Science, Scopus and Google Scholar): "Life cycle assessment" “AND Li-metal battery” OR “Li-polymer battery” OR ”Li-S battery” OR “Li-air battery” AND "LCA" AND "Li-based battery" OR “Social Life cycle assessment” AND "Social LCA" AND “lithium-based battery” OR “Life cycle assessment AND "LCC" “lithium-based battery” OR "LCSA," AND “lithium-based battery”. (The selection process was strictly - limited to research and review articles.) Additionally, other document types like conference proceedings, project reports and documents from company findings were out of the scope of the selection process. Additional selection criteria included time range (2012–2023), and the language selected was English. A total of 76 articles were found: 31 E-LCA articles, 13 LCC articles, 12 S-LCA articles,

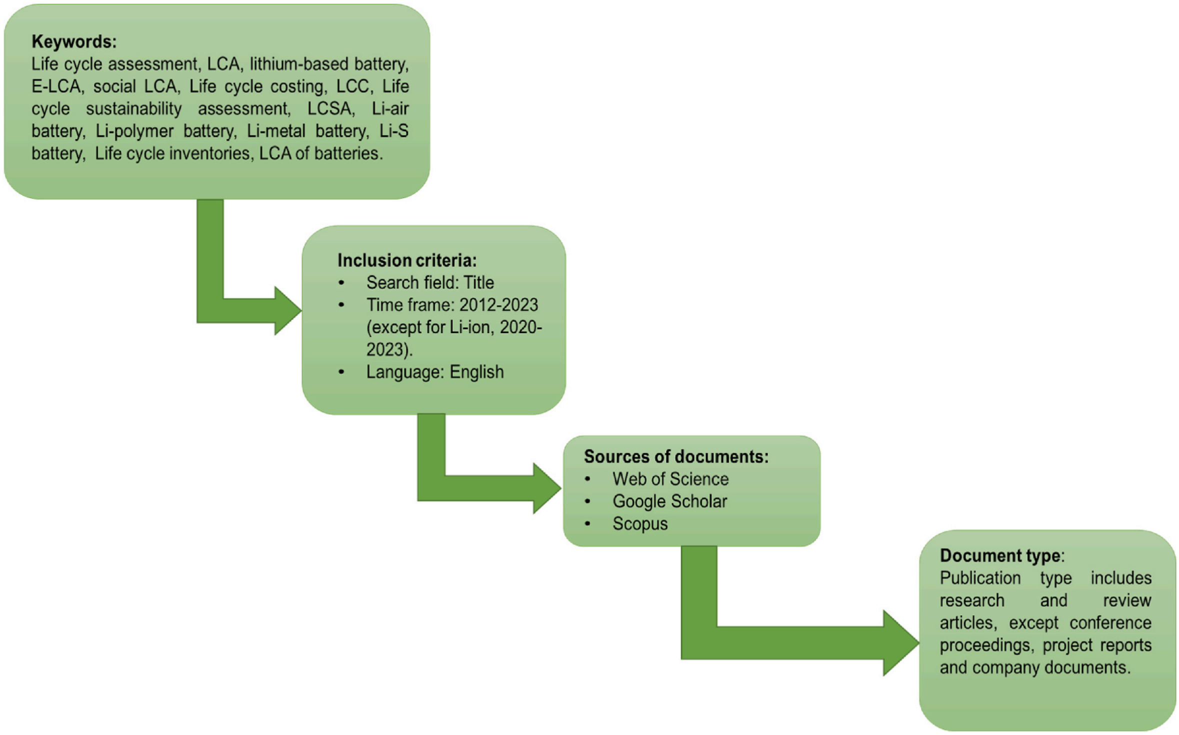

Fig. 1. Review search protocol.

and 6 LCSA articles.

While the paper offers an understanding of sustainability of lithium-based batteries, it is crucial to acknowledge its potential limitations and discuss how these might affect the findings and their interpretation.

The comprehensiveness of the review is contingent upon the range and depth of the literature included. Even with the search criteria carefully and systematically chosen, some important studies might have been overlooked as it is limited to published research articles and do not include other types of works, such as conference proceedings or reports. Additionally, there may be some relevant studies that do not use the exact keywords included in the search protocol, which could result in missing important results. Therefore, it may be helpful to include some additional keywords or conduct a manual search of the literature to ensure that all relevant studies were captured.

Given the relatively established status of Li-ion battery technology compared to Li-air, Li-metal, Li-polymer, or Li-S, extensive LCA work has been conducted, as evidenced in the web search portal. Specifically, the search targeted the years 2020–2023 for E-LCA Li-ion battery research and 2012–2023 for Li-air, Li-metal, Li-polymer, and Li-S. This approach aimed to prioritize reviewing recent works on the E-LCA of Li-ion batteries, considering several previous LCA studies. The objective was to gain insights into the E-LCA for Li-ion batteries using recent and up-to-date inventory datasets. For Li-air, Li-metal, Li-polymer, and Li-S review was conducted from 2012 to 2023, however very few E-LCA studies were obtained.

The integration of E-LCA, LCC, and S-LCA into a unified LCSA framework presents another methodological challenge, particularly in ensuring consistency and comparability across these dimensions. Differences in methodological approaches, metrics, and data quality across the three assessments could introduce variability and affect the integration of results. The sustainability of lithium-based batteries can vary significantly based on temporal and geographical contexts due to differences in energy mixes, technological advancements, and regulatory environments. The review might not be easily generalizable across different regions and time periods. The reliability of LCSA outcomes heavily depends on the quality and availability of data. Gaps or inconsistencies in data, especially in S-LCA and emerging battery technologies, can lead to uncertainties.

3. Results and discussions

3.1. General information about lithium-based batteries: working Principle and applications

Li-based batteries are a class of electrochemical energy storage devices that have been intensely researched since the 1980s. The effect of charge/discharge rate and prolonged cell cycling on energy and power storage performance is unclear, but they strongly affect the lifetime, cost, and overall quality of a Li-based device [12]. According to Table 1, there are different Li-based batteries, including Li-ion, Li-metal, Li-air, Li-polymer, and Li-S. Li-ion batteries are one of the most popular forms of energy storage commercialized due to their longer cycle life.

Conventional batteries, such as Li-ion batteries, usually consist of negative (anode) and positive (cathode) electrodes, a liquid electrolyte transports Lithium ion between the electrodes, and porous separator functions as electrical insulation between the electrodes, as seen in Fig. 2. Carbon (graphite) and high-capacity carbon alternatives such as silicon, metal oxides, and alloyed metals are being explored as anode materials [13]. The cathode's most critical component of a Li-ion battery

Table 1
Main types and structures of Li-based rechargeable batteries.

Batteries	Anode	Cathode	Electrolyte
Li-ion	Graphitic carbon	Lithiated metal oxide	liquid organic carbonates, polymers, or solids
Li-metal	Li metal/Li alloy metal	Manganese dioxide, Vanadium oxide, Molybdenum disulfide	Nonaqueous solution
Li-air	Li metal	Air	Aqueous, aprotic, or solid
Li-S	Li metal	Elemental sulfur	Liquid organic electrolyte

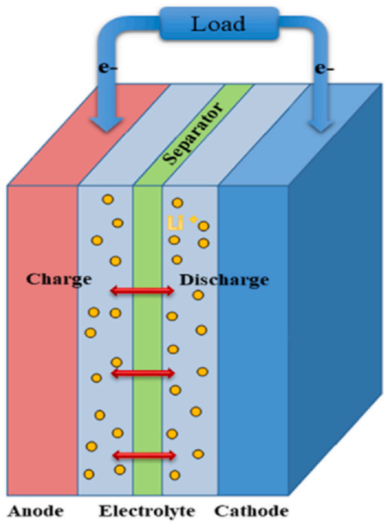

Fig. 2. A graphical representation of working principle of Lithium battery.

is $LiCoO_2$, Li-Mn-O, $LiFePO_4$, and Li-layered metal oxide [14]. Liquid electrolytes integral to cell safety are pure molten salts with low melting points, typically below 100 °C [15]. Salt solubility, ionic conductivity, Li reactivity, and electrochemical stability are fundamental electrolyte properties. Electrolyte wetting of the electrode and separator can also directly impact cell performance [15]. However, the main drawbacks of the conventional Li-ion battery are the chance of leakage of the electrolyte and the formation of dendrites of Li, which make it prone to explosion [16].

Various applications for different type Li-based batteries namely Li-ion, Li-metal, Li-air, Li-polymer and Li-S are described in Table 2.

3.2. *Environmental Life Cycle Assessment (E-LCA) of Li- based batteries*

E-LCA is a time-framed measurement method that evaluates environmental performance over the duration of a product's life cycle. Throughout each stage, calculations are made about the extraction and use of resources (including energy), as well as the emissions to air, water, and soil. It is evaluated and analyzed how much they might contribute to environmental issues, such as climate change, human and ecological toxicity, ionizing radiation, and resource base depletion (such as water, non-renewable primary energy supplies, land, etc.). The development of the life cycle assessment midpoint-damage framework, which theorizes the connections between a product's environmental involvements and the considerable harm it does to human health, resource depletion, ecosystem quality, etc., was greatly aided by the Life Cycle Initiative. Such details are crucial for making decisions [32]. The main components of LCAs are: (1) identifying and quantifying the environmental loads involved, such as the energy and raw material consumption, emissions, and wastes generated; (2) assessing the potential environmental impacts of these loads; and (3) evaluating the options available for reducing these environmental impacts [33,34].

There were numerous attempts to standardize the life-cycle assessment approach. For the purpose of giving comprehensive information on the LCA methodology, the Canadian Standards Association published the first national LCA guideline in the world, Z-760 Environmental Life-cycle Assessment, in 1994. However, the International Standards Organization's (ISO) standards were the ones that were most widely recognized [35].

- ISO 14040 Environmental management, LCA, Principles and framework (1997).
- ISO 14041 Environmental management, LCA, Goal definition and inventory analysis (1998).
- ISO 14042 Environmental management, LCA, Life-cycle impact assessment (2000).
- ISO 14043 Environmental management, LCA, Life-cycle interpretation (2000).
- ISO 14044 Environmental management, LCA, Requirements and Guidelines (2006).
- ISO 14045 Environmental management, LCA, Principles, Requirements and Guidelines (2012).
- ISO 14046 Environmental management, LCA, Water footprint — Principles, requirements, and guidelines (2014)

Among all the ISO frameworks reported about Environmental management, ISO 14040:2006 was last reviewed and confirmed in 2022. Therefore, this version will be considered as the current ISO norms for the LCA study. The guidelines and framework for LCA are outlined in ISO 14040:2006. These guidelines and framework include the following: the definition of the goal and the scope of the LCA, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, the relationship between the LCA phases, and the circumstances for the use of value choices and optional elements [36]. LCA is an efficient tool generally adopted for thorough environmental impact assessment of a product from cradle to grave [37]. Hence, the review of work on E-LCA for Li-based batteries was conducted from 2012 to 2023 and has given emphasis on batteries for electric vehicles. Below is the detailed E-LCA framework.

3.2.1. *E-LCA framework*

The findings of the E-LCA analysis are presented in Table S1 of the supplementary information. A summarized overview is provided below:

Life cycle assessment is a widely used tool to quantify the potential environmental effects of battery production, usage, and disposal/recycling. This framework for the assessment of the environmental impacts consists of four stages. Fig. 3 represents the four stages of LCA for Li-based battery. The most important application for assessing the environmental impact of the battery product over its life cycle lies in dissecting the contributions of individual life cycle stages. Moreover, battery production includes raw material extraction mainly in the form of mining ores, production of battery components, battery modules, and battery packs assembled with a Battery management system (BMS) followed by the transportation of the products, their usage and end-of-life or recycling. The insights and methodologies introduced by (Arshad) [38] have been instrumental in guiding the E-LCA review of batteries, offering a critical evaluation of the environmental impacts stemming from the growing production and application of LIBs. This systematic analysis seeks to examine the studies and conduct a meta-analysis of LCA of batteries, identifying the current state of

Table 2
Application of different types of Li-based batteries.

Battery Type	Applications	References
Li-ion	Grid-level energy storage	[17]
	Portable electronic devices	[18]
	Aerospace applications	[18]
	Satellite and Aviation	[19]
	Medical Devices	[20]
	Electric Vehicles (EVs)	[21]
Li-metal	Next-generation energy storage systems	[22]
	Medical Devices	[23]
Li-air	Automotive applications	[24]
	Smart grid	[25]
Li-polymer	Drones	[26]
	EV and HEV	[27]
	UPS	[28]
Li-S	Electric Vehicle	[29]
	Portable electronic device	[30]
	Aerospace applications	[31]

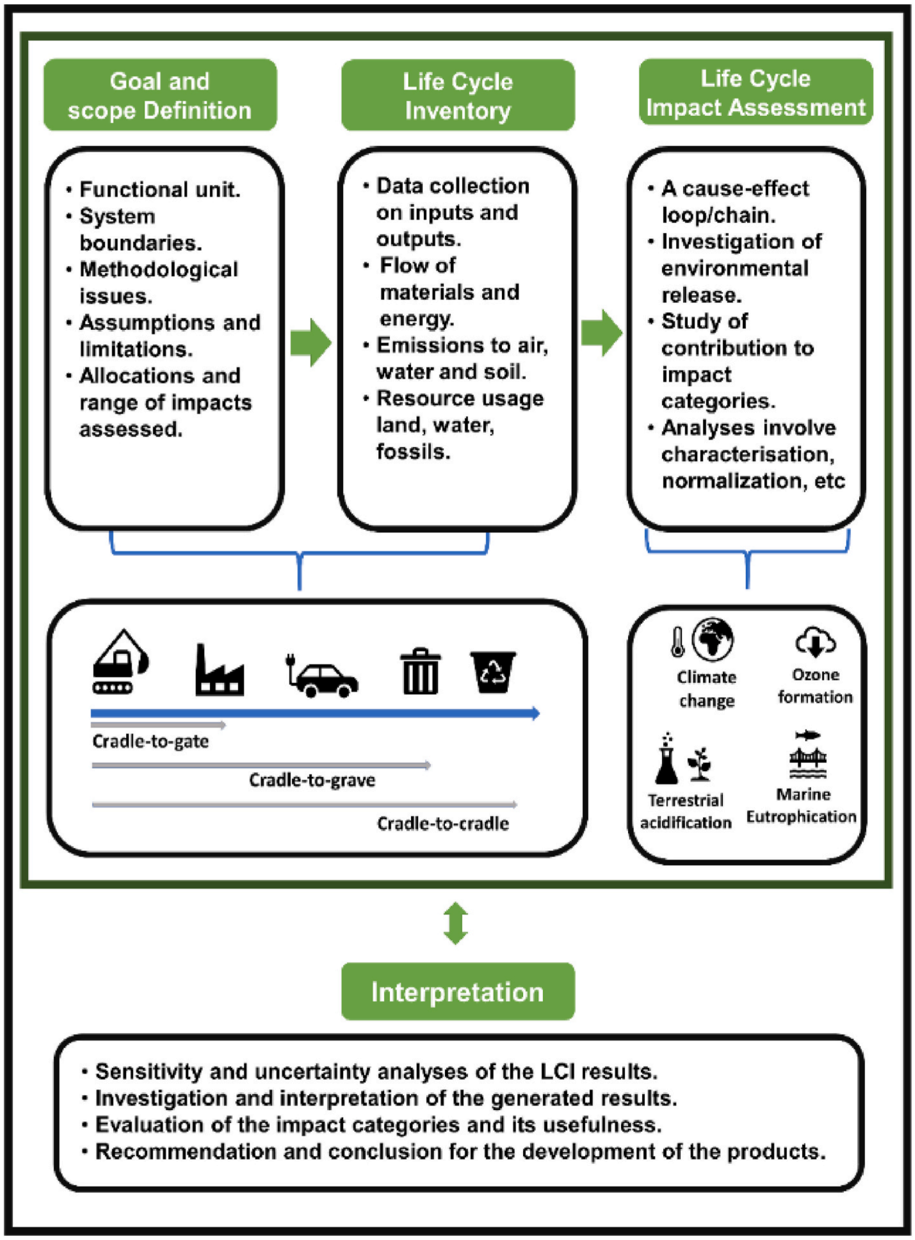

Fig. 3. Life cycle assessment of Li-based battery.

research and providing crucial insights into the life cycle assessments of emerging technologies.

Goal and scope: The ISO 14000 series have a structured and standardized method of LCA frameworks and principles, and this calls for smooth functioning of the life cycle assessment of a battery. Accordingly, the LCA assessment starts by defining the goal and scope of the study. In this phase, the objectives, functional unit of a battery (e.g., kWh or kg of battery), system boundaries (cradle-to-gate, cradle-to-grave, cradle-to-cradle) [39], methodologies, allocation procedure and impact categories are defined. This step forms a basis where the LCA study is generated. In the reviewed articles given in the Supplementary file Table S1, most of the functional units considered were either 1 kWh of the nominal energy capacity (for example [40–42]: or one vehicle kilometre (for example: [43–45]). The determination of the functional unit is guided by the specific objectives of the study, including the comparative evaluation of environmental performance across different vehicles or different battery chemistries, investing in the battery efficiency or examining different phases of battery production.

The generation of system boundaries makes LCA of batteries a mutually iterative process, as the study conducted can be modified and adjusted based on the results generated. The three system boundaries that were frequently used in the reviewed articles to represent the entire life cycle of an electric vehicle were cradle-to-gate, cradle-to-grave, and cradle-to-cradle. This is explained in detail in the supplementary file (Section 1.4)

Life Cycle Inventory: In the following step, LCI is the data collection step, which requires entering data of all the processes included in the battery production. The inventory collection is of utmost importance in the LCI study as it is an exhaustive phase of LCA. Moreover, the LCI inventory data collection demands complete and well-grounded information with a better picture of each step in the battery manufacturing and usage phase. As the LCA study is dependent on data availability, data collection is one of the most demanding tasks. There are two types of data: foreground data and background data. The foreground data or primary data is procured directly from a battery manufacturer. This type of inventory is highly confidential and challenging to acquire. On the contrary, background data / secondary data is mostly generated by estimations and from the LCA software databases like EcoInvent, European Reference Life Cycle Database (ELCD), GREET, etc., and also includes the data from the studies [29,41,42,45–54].

The reviewed articles on E-LCA revealed that only 45 % of them utilized a combination of primary data (obtained from laboratory or industrial sources) and secondary data (drawn from databases/software). The primary data encompassed various aspects such as battery production materials, energy consumption during production and use phases, as well as waste and recovered materials. The remaining studies relied solely on secondary data sourced from existing studies. Additionally, it was found that only 35 % of the reviewed studies had openly accessible inventory data, while 38 % lacked open inventory data. The remaining articles provided only partial inventory data. Significant challenges may arise in ensuring transparency, developing methodologies, and validating life cycle assessments, particularly when open inventory data is not available. Inconsistent data sources make it difficult to compare environmental impacts accurately and may lead to skewed conclusions. These aspects are crucial for enhancing the reliability of such assessments.

Life Cycle Impact Assessment: The LCIA stage assesses the environmental impacts and puts into perspective the contribution from each impact category. The purpose of this phase is to provide a quantitative and comparative evaluation of potential environmental impacts based on the insights obtained from the LCI stage. A comparison of these impacts revealed significant variability, which can be attributed to differences in concepts, databases, and the battery chemistries that are being studied.

Although LCIA methodologies vary, they aim to provide insights into the environmental significance of a product or system across its entire life cycle. SimaPro modeling software was used in many works to assess and evaluate the environmental impacts of materials and energy used in manufacturing and assembly processes. This was followed by OpenLCA, an open-source LCA software developed by GreenDelta. Fig. 4 (b) shows the choice of software for the assessment by the reviewed articles. Also, in the articles there were various impact assessment methods and tools were used to quantify and evaluate the environmental impacts associated with battery production and use. Fig. 4 (a) shows the different tools that were employed by the studies in the assessment.

This phase mainly has two types of impact categories: the midpoint impact category and the endpoint impact category. The former is a parameter in a cause-effect chain before the endpoint is reached and the latter is basically the aggregate from the midpoint categories. The ReCiPe method has been used (15 out of the 31 case studies) as the most common characterization tool. The Dutch National Institute for Public Health and the Environment (RIVM), CML, PRé Consultants, Radboud Universiteit Nijmegen, and CE Delft developed the ReCiPe approach for impact assessment in LCA which is described by Fig. 5.

By converting emissions and resource extraction into scores for the environmental impact, life cycle impact assessment (LCIA) aids in the interpretation of LCA studies [55]. This is done by means of characterization factors. Characterization factors indicate the environmental impact per unit of stressor.

In ReCiPe indicators are determined at 2 levels. They are:

Midpoint level- It features 18 midpoint indicators, which are challenging to interpret but have low uncertainty. Characterization factors at the midpoint level are found before the cause-effect chain, somewhere along the impact pathway. Midpoint indicators concentrate on single environmental issues, such as the global warming potential or acidification.

Endpoint level – It has 3 endpoint indicators which are easy to understand but more uncertain. Endpoint is a measure of the damage – at the end of the cause-effect chain – caused by a stressor. Endpoint indicators show the environmental impact on three higher aggregation levels, being the 1) effect on human health, 2) ecosystem quality, and 3) resource availability.

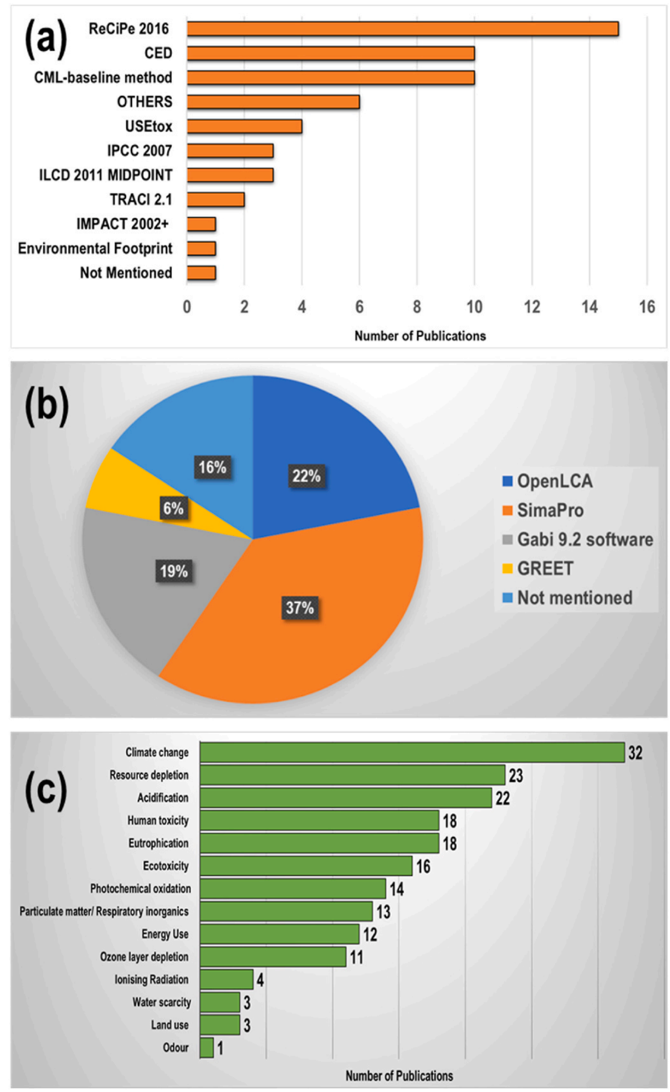

Fig. 4. (a) Impact category tools implemented in the case studies (b)Software utilized in the case studies (c)Impact categories analyses in the case studies.

In the reviewed works, it was observed that all studies included in the analysis integrated the calculation of Global Warming Potential (GWP). Following GWP, the next impact category examined was resource depletion, succeeded by acidification, human toxicity, and eutrophication, as seen in Fig. 4 (c).

The GWP is significantly influenced by the battery production site [42]. Coating and drying, formation, and drying rooms account for over 76 % (31.87 kWh/kWh of battery cell capacity) of total energy consumption resulting in 74 % of all greenhouse gas emissions [56]. In another study, it was found that the cathode and the electricity needed for material transformation and battery assembly were identified as the main contributors to the GWP. These factors were responsible for 44.5 % and 17.0 % of the overall impact in this category, respectively [47]. Li-ion batteries exhibit higher impacts on ozone layer depletion and global warming, primarily due to supply chains in China and reliance on electricity from coal-fired plants [50]. The nickel cobalt aluminum (NCA) LIB demonstrates a notable improvement over lead-acid batteries, with a reduction of approximately 45 % in impact for both climate change and fossil resource use, and a 52 % decrease in respiratory inorganics. Similarly, the nickel manganese cobalt (NMC) LIB exhibits a significant enhancement, being approximately 67 % better than lead-acid in terms of acidification potential. Additionally, the lithium iron phosphate battery (LFP) emerges as the best performer in the

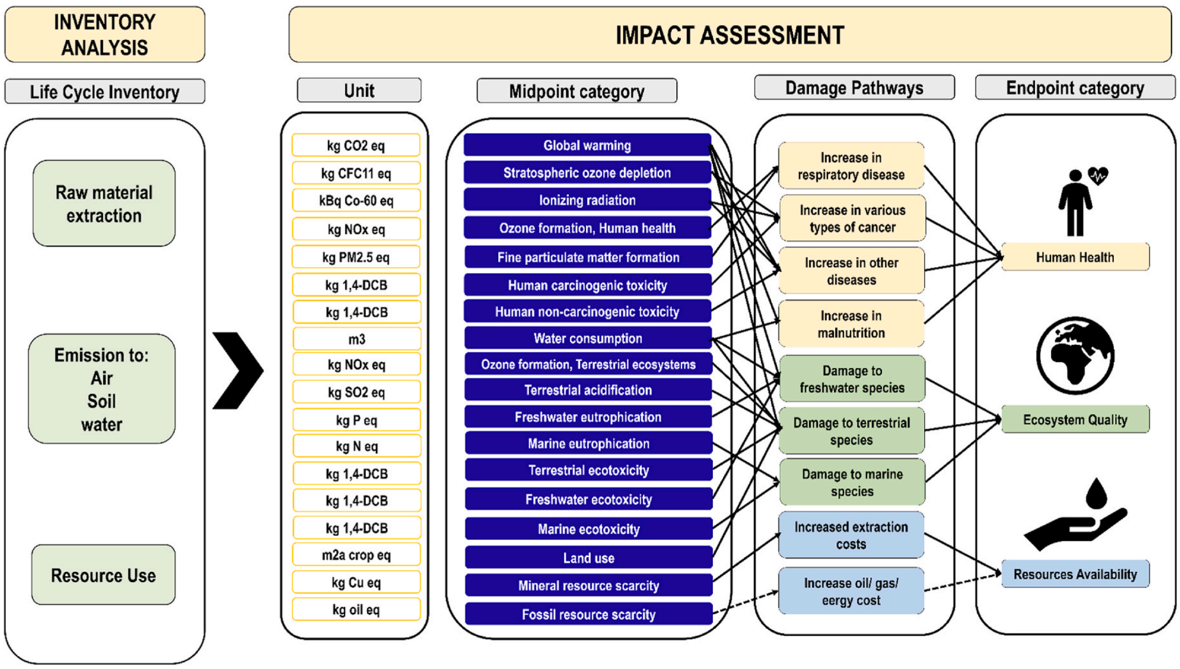

Fig. 5. Relationship between ReCiPe midpoint-endpoint indicators based on [55].

minerals and metals resource use category, boasting a 94 % reduction compared to lead-acid batteries. Consequently, LIBs prove to be superior to lead-acid batteries across various cradle-to-grave impact categories [57]. In another research three types of batteries (LFP, NMC532, and NMC622) were subjected to modeling using primary data, revealing GWP impacts per 1 kWh of cell capacity: 61.9 kg CO_2 eq kWh^{-1} for LFP cells, 78.4 kg CO_2 eq kWh^{-1} for NMC532 cells, and 80.4 kg CO_2 eq kWh^{-1} for NMC622 cells. Incorporating End-of-Life (EoL) considerations in the analyses can significantly reduce the performance gap between LFP and NMC batteries, with these two types benefitting the most from material recovery processes such as pyrometallurgical or hydrometallurgical methods [52].

In the case of Li-S batteries, the active material in the battery (anode, cathode, electrolyte) contributes over 70 % to all assessed impact categories (except resource depletion), and electronics in module packaging represent the largest contribution to resource depletion [43]. Also, compared to conventional NCM-Graphite LIB, Li-S batteries are found to have a relatively less environmental impact, exhibiting 9%–90 % lower impacts in most categories [29]. Lithium metal batteries (LMBs) exhibit lower climate impact, lower abiotic depletion potential, and lower toxicity compared to similarly designed LIBs (NMC- and LFP-based). This is because the higher energy density in LMBs results in lower battery weight and electricity consumption in vehicles [58]. Life cycle assessment (LCA) of lithium-oxygen $Li-O_2$ battery showed that the system had a lower environmental impact compared to the conventional NMC-G battery, with a 9.5 % decrease in GHG emissions to 149 g CO_2 eq km^{-1} [44]. Another study [46] also underscored the potential environmental benefits of lithium-air cells over time, including 4–9 times less climate impact compared to today's lithium-ion cells, and the potential avoidance of 10–30 % of production-related environmental impact through recycling.

In summary, the studies emphasised the importance of considering GWP alongside other environmental impact categories in assessing battery production and use. The results also showed that emerging batteries like Li-S, LMBs and $Li-O_2$ showed promising environmental benefits over current LIBs.

Interpretation of the results: Lastly, the final stage of the LCA study is interpretation of data. During the interpretation phase of LCA, the results of the environmental impact assessment are meticulously scrutinized to draw conclusions and provide recommendations. This process involves identifying significant environmental hotspots, understanding the implications of various life cycle stages and decisions, and assessing the overall environmental performance of the product or process under study. Moreover, uncertainties, limitations, and opportunities for improvement in the LCA results are taken into consideration to guide decision-making toward more sustainable behaviours and policies. Additionally, integrating the findings from impact assessments and inventory assessments allows for a comprehensive overview of batteries, aiding in the understanding of potential environmental issues and ensuring the environmental sustainability of Li-based battery production.

Through the review conducted, the main contributing factors to environmental impact have been identified:

Energy consumption factor: Cells, specifically the energy consumed during manufacturing, cathode paste production, and cell container fabrication, constitute the primary contributors to environmental impacts within the prototype battery's life cycle [58,59]. Vacuum drying, coating processes, and other drying procedures emerge as the predominant contributors to energy consumption [53]. Energy demand during the use phase remains a critical aspect. Electricity usage data originating from the use phase, especially if it is primary, significantly influences the determination of the overall environmental impact [57].

The direct energy prerequisites for cell manufacturing, encompassing activities such as maintaining a clean dry room and cleaning and conditioning processes, along with the impacts of battery assembly procedures, can be subject to significant uncertainty in battery LCAs due to the absence of primary data. Challenges persist in aligning direct energy prerequisites across different studies owing to factors such as assumed production facility locations, annual production capacities, and yield factors. These uncertainties make it difficult to accurately compare or integrate the energy requirements outlined in different studies [51].

Energy mix factor: Future research should prioritize improving production processes and integrating innovative technologies to decrease energy consumption and GHG emissions. Transitioning from natural gas to electricity for heat generation may decrease emissions, but its feasibility depends on the electricity emissions factor. Challenges include additional investments and higher energy costs associated with electricity. Alternative technologies like laser-based drying and dry coating show potential for reducing energy consumption, but further research is required [56].

Shifting the manufacturing electricity mix to renewables has the potential to reduce impact by up to 53 % for freshwater eutrophication [59]. Increasing the proportion of renewable energy sources in the electricity mix during the use phase could aid in mitigating environmental impacts [57].

Novel material factor: The third-generation prototype battery showcases a high-voltage cathode (NMC622), high-capacity anode (silicon alloy with no significant environmental impact on any category), and a stable and safe electrolyte, offering environmental advantages compared to a graphite-based battery [59]. The lithium-ion battery pack with NMC cathode and lithium metal anode (NMC-Li) is recognized as the most environmentally friendly new LIB based on 1 kWh storage capacity, with a cycle life approaching or surpassing lithium-ion battery pack with NMC cathode and graphite anode (NMC-C). Lithium metal anode (Li-A) exhibits promise for future development owing to its high specific capacity, lightweight, and environmental benefits. Due to these advantages, Li-A is anticipated to be widely adopted as an anode material in future traction batteries [60].

Battery type factor: The overall environmental performance of LFP batteries exceeds that of NMC batteries due to lower environmental and resource impacts. Significant environmental impacts of NMC batteries are attributed to rare metal materials like nickel and cobalt in cathodes, which are higher than those in LFP batteries. However, NMC batteries exhibit a better energy-saving effect during the use phase, saving about 30 % of electricity compared to LFP batteries, particularly in regions with coal-fired power generation like China [54].

Li-S batteries are regarded as a sustainable energy storage alternative due to the absence of toxic metals like nickel, cobalt, and manganese. The introduction of sulfur in cathode composition improves the environmental profile of Li-S batteries compared to Li-ion batteries. Li-S batteries show potential for use in electric vehicles, offering higher specific energies than Li-ion and reducing raw material requirements. Li-S batteries exhibit up to a 31 % reduction in GHG emissions compared to Li-ion batteries. The production phase, including material extraction and component manufacture, contributes up to 70–90 % to impact categories like abiotic resource depletion (ADP) and natural resource scarcity [40].

Battery recycling factor: The impact reduction potential of recycling varies; considering recycled materials as avoided primary material could lead to a decrease in impacts by 25 %–46 % [59]. Recycling of cobalt, nickel, and copper significantly reduces overall battery impacts by avoiding the use of virgin raw materials [52].

In general, there are significant uncertainties involved while evaluating these studies for several reasons like insufficient data, wrong assumptions or insufficient information. So, the uncertainties in the LCA study need to be thoroughly identified and analyzed. In addition, sensitivity analysis, like the uncertainty analysis, can also be implemented at several LCA stages to investigate the energy and resource-related environmental impacts of any product [61].

3.2.2. End of life (EOL) and recycling

In the battery EOL stage, batteries no longer operate at sufficient capacity due to the ageing that happens as the electrolyte undergoes decomposition over time at a given temperature. The ageing is affected by the degradation rate of the battery and battery capacity. The proposed EOL option for batteries could be recycling, reusing or remanufacturing [62].

Reusing of battery is when the EV battery after reaching its useful life can be removed and be used as an energy storage system. This provides greater stability thus increasing the integration rate of renewable energy and reliability to the grid [63,64]. Another way to mitigate the environmental impacts of the EOL stage of battery is remanufacturing which reinstates the product like new condition along with a warranty to the buyer. This is environmentally friendly and a well-known practice in auto-industry as 80 % of the components are remanufactured [65].

Proper recycling is another potential strategy to alleviate environmental pollution by increasing the opportunity for secondary supply, lessens the manufacturing cost for LIBs as the price fluctuations of critical raw materials is mitigated. This is in principle with the sustainable development strategy of resources and energy. The three major technical means of recycling available include [63,66].

- The pyrometallurgical process (In this stage, the component metal oxides from lithium-ion batteries are reduced in a high-temperature furnace to form an alloy. The primary procedures are roasting and calcination)
- The hydrometallurgical process (This involves the dissolution of metallic components from lithium-ion batteries using mineral acids, followed by metal separation through processes like solvent extraction and precipitation)
- Direct recycling method (This method intends to minimize the number of processing steps required for the re-synthesis of cathode materials by recovering cathode materials with still-useable morphology, and has a comparatively low impact on the environment) [67].

3.3. Life cycle costing (LCC) of Li- based batteries

Battery LCC involves evaluating the total cost of owning and operating a battery system over its entire lifetime, including the costs associated with production, installation, maintenance, and disposal. The total of a battery's initial investment cost (CAPEX), operating cost (OPEX), and disposal cost (End-of-life Expenditures, EOLEX) is the battery's life cycle cost. The CAPEX, which includes all expenses related to design, engineering, procurement, and construction, is the cost of purchasing and installing the battery. Over the course of the product's lifecycle, all expenses such as those related to energy use, maintenance, and repair are included in the OPEX. The EOLEX is the price of disposing of a product after the end of its useful life. It includes costs for transportation, disposal, and remediation of the environment [68].

By considering the total life cycle cost of a product, LCC can help organizations make more informed decisions about product selection, procurement, and use. For example, a product with a lower initial cost may have a higher life cycle cost if it has higher operating and disposal costs. Therefore, LCC can be an opportunity for organizations to reduce costs and improve corporate sustainability by choosing products with lower life cycle costs.

An important feature of some of the LCA studies is the LCC comparison of different battery chemistries and technologies, such as lead-acid and lithium-ion batteries, in stationary energy storage applications. Variations in performance characteristics, lifetimes, safety considerations, and recycling/disposal costs between these different battery chemistries, can impact the total cost of ownership [69–71].

LCC can be divided into conventional LCC (actual cash flows) and environmental LCC (with assumed adoption of additional external costs and benefits) [72]. Cathode materials make up a significant portion of the raw materials needed for, and the expense associated with, lithium-ion batteries (LIBs). The high cost of cathodes results from the use of essential elements like lithium and cobalt. Still, it's important to evaluate the supply, demand, and broader impacts of all the elements used in cathodes to accurately forecast the effects of swift electric vehicle (EV) adoption [73].

In addition, LCC can be conducted from different perspectives, including that of the customer, the manufacturer, or a larger entity (from the perspective of public perception or society as a whole). When conducting LCC, different scopes can also be considered, including conventional LCC, environmental LCC, and societal LCC.

3.3.1. LCC framework

The findings of the LCC analysis are presented in Table S2 of the supplementary information. A summarized overview is provided below:

Goal and scope: The goal and scope of LCC studies differ in the battery system level, ie. battery cells, battery packs, battery energy storage systems (BESS) or battery electric vehicles. The evaluation of the costs of the battery system is most often viewed from the point of view of the price of battery production [10,74–79] or the operation of the user in relation to the consumption of the electric car [75,80]. In the cost expression, the functional unit is expressed in the currency of the given country per kWh of the battery or the given system level (cell/BESS/-electric vehicle) [76–79,81–83]. Most studies are focused on the system boundary Cradle-to-grave [10,74,80,82–84] or Cradle-to-usage [76–79]. In one study, the system boundary is Cradle-to-gate [81].

Life Cycle Inventory: Data sources and their quality are essential for the evaluation of LCC of battery systems. The mentioned studies draw data mainly from secondary sources in the form of open access or restricted databases [74,80–82,84] or review of articles [77–79], data from the market [10,76,83,85], or data from simulation analyses [75], and expert analysis [78]. Global organizations from which the data was obtained include the European Landscape Contractors Association, the World Bank's and Eurostat's and the United Nations' Comtrade database.

Life Cycle Impact Assessment: The impact category within the LCC is always in the area of costs from different perspectives. Studies mainly mention conventional LCC (variable and fixed costs) but environmental costs are also evaluated, which are expressed mainly in the sum of GHG emissions (EUR/ton CO_2 eq) [74]. CAPEX (capital expenditures) are costs associated with the acquisition of new physical assets and OPEX (operation and maintenance expenditures) are costs associated with battery operation [74,75,83]. The Commodity -LCC indicator expresses the sum of the market prices of the raw materials used excluding costs such as labor and depreciation [81]. In studies, the LCC framework appears to evaluate different phases - acquisition, development, production, use, maintenance phases and liquidation [10,76,77]. The LCC analysis of EVs varies by model, size of batteries, and region, with specific studies showing that the BYD e6 BEV had a higher LCC of US$ 2.63 million compared to US$ 1.80 million for the BALK EV 200 BEV in China, while in Singapore, the Mitsubishi EV brand recorded the highest LCC among others. Studies also indicated that EVs are not cost-competitive when compared to conventional and hydrogen EVs, despite incentives like exemptions from purchase and driving restrictions in China influencing the LCC outcomes [10,76,77].The findings [75,80]. indicate that due to elevated initial purchase prices, hybrid and battery electric vehicles incur the highest expenses, whereas vehicles powered by internal combustion engines are the least costly. Yet, when it comes to operational costs, electric vehicles are around 37 % cheaper than diesel vehicles and 60 % more affordable than those running on petrol.

For battery energy storage systems (BESS), the mentioned parameter is LCOE (levelized cost of energy) which is defined as the total lifetime cost of an investment divided by the cumulated generated energy by this investment [86]. The cost model for battery cells represents the costs of material and scrap, labor, land, energy, machinery and installation, overhead, buildings, and maintenance [79].

Interpretation of the results: The LCC analysis indicates that Battery Electric Vehicles (BEV) and Internal Combustion Engine Vehicles (ICEV) powered by diesel are the most economical choices, showing total consumer life cycle costs that are about 5 % and 15 % lower than those for petrol-powered ICEVs and Hybrid Electric Vehicles (HEV), respectively [75,80]. Mela et al. [81] emphasizes that market prices are not always adequate to stimulate the sustainable use of resources. The high cost of the battery is the reason for the higher cost of producing battery electric vehicles than conventional combustion engine vehicles [76,77]. This is related to the statement of Maik et al. [78] that the prerequisite for the use of lithium-ion batteries is their decreasing price and high cycle stability. In a study of battery prices across different countries, applying economies of scale to reduce the battery price is effective in order to use all resources in the manufacturing plant [79]. The LCC of electricity storage in batteries is mainly driven by the cost of the battery system itself. Conversely, the GHGs from the electricity needed for charging significantly affect the additional life cycle emissions through losses from round-trip inefficiencies. Thus, the LCE of batteries can be significantly decreased by increasing the renewable energy proportion in an electricity system, which also indirectly lowers emissions associated with the electricity used in production [74]. Another influence on the price of the battery is its lifespan, which is estimated to be 8 years [10].

Optimum battery costs are achieved by adding thermal energy storage to a relatively large battery instead of partial battery replacement. Extensive sensitivity analyses were conducted [75] to ensure the accuracy of the findings and the selected parameters, which revealed that the LCC is significantly influenced by economic factors such as fuel cost, fuel price increase, and the discount rate. Incorporating PV with a diesel generator cuts LCC by 9–10 %, and adding batteries reduces it further by 14–17 %. Combining battery and thermal energy storage offers 51–77 % fuel cost savings, surpassing battery-only savings of 39–48 %, but raises investment costs by 27–50 %. Cars with LFP batteries tend to use more energy and emit more during use than those with Li-NMC batteries, which adversely affects their overall greenhouse gas emissions. However, when considering different environmental impact metrics, electric vehicles equipped with LFP batteries are on par with or outperform those with Li-NMC batteries, a benefit linked to the lesser emissions from LFP battery materials and the predominant influence of vehicle manufacturing on these metrics. Li-NMC batteries offer greater cost-effectiveness, benefiting both consumers and society in terms of external expenses [85]. Optimum economic impact on the environment can be ensured by reducing the cost of batteries and photovoltaics [84].

3.4. Social life cycle assessment (S-LCA) of Li-based batteries

S-LCA builds the social counterpart to LCA, sharing many of its key methodological characteristics. However, assessments are based on the status quo of the social environment including related factors such as economics, politics and social dynamics which are by nature subject to continuous changes. The results are provided in the form of social hotspots of the entire life cycle of a product covering several social indicators (e.g., workplace accidents, child labour, etc.) related to the different used cell materials (e.g. mining raw materials) and main stakeholders (workers, value chain actors, etc.). Special attention is usually given to supplier countries for raw materials used for cell manufacturing [87–90].

To address more vividly the overview and methods of S-LCA for Li-based batteries, it is necessary to mention that to do the assessment of the social aspects is the least addressed pillar among the three dimensions of sustainability, namely environment, economy, and social aspects. In addition, S-LCA has also been created as a tool to evaluate the positive or negative social and socioeconomic impacts throughout the product line, such as Li-batteries [91–94]. Although there exist several tools focused on assessing social impacts, S-LCA differs from the others by its object on products and services, and its scope concerns the entire life cycle. The advantages of adopting a life cycle perspective include informing multi-stakeholders, i.e., retailers, common people, and end consumers about the positive and negative social impacts of the Li-batteries they sell or buy, or they use in order to prevent the changing of negative social impacts from one life cycle stage to another, or from one social issue to another [95–97].

In this review study, the importance of S-LCA for Li-based batteries has been considered to explore the supervision of the groups (manufacturers) making products as well as to create awareness among the retailers, common people, and end user, i.e., consumers. Additionally, the purpose of doing S-LCA for Li-batteries is also to assess and follow the social/geopolitical norms of the countries wherein the product is manufactured, used, and disposed of. However,the purpose of S-LCA is to create an awareness of social responsibility as well as to assess impacts on human and social capital. As, most of the time these two sectors always remain out of the track during the manufacturing phase. By leaving these capitals out of the design process, engineers may miss various human and social impacts that may cause different negative impacts in the society by the use and disposal of Li-batteries. An S-LCA for Li-based batteries could be the key to designing truly sustainable Li-battery products and manufacturing processes.

For example.

- Poor working conditions, i.e., lack of information on health & safety measures of the Li-batteries production units' workers, i.e., socially responsible human resources management (SRHRM)
- Unfair manufacturing practices of the Li-batteries manufacturing companies or research & development unit due to lack of knowledge, education, and cultural differences, i.e., business ethics
- Human rights violations of the Li-batteries manufacturer due to lack of proper leadership or Government's initiation of civilization, i.e., corporate social responsibility

To illustrate the significance of Social-LCA in relation to Li-based batteries, Fig. 6 above shows how the joint collaboration of S-LCA for Li-based batteries helps raise social consciousness. This in turn impacts areas relating to human capital and social capital by promoting social responsibility and corporate social responsibility for the betterment of society. This thematic model demonstrates that both sectors have the ability to raise awareness through the promptness and learning abilities of manufacturers. The S-LCA method takes into account various stakeholder groups and impact categories to evaluate the potential social effects, whether positive or negative, on human well-being caused by the use or production of Li-based batteries throughout their life cycle.

In summary, this study has not yet conducted an S- LCA for lithium-based batteries. Since S-LCA is the most recently developed out of the three life cycle approaches, it is still being debated and modified. Moreover, it is crucial to emphasize that the primary purpose of this analysis is to conduct a suggestive examination of S-LCA regarding Lithium (Li) based batteries. The aim is to understand how to assess the possible societal impacts of these batteries, both beneficial and detrimental, throughout their entire lifespan. This encompasses a variety of tasks such as extracting and purifying natural resources, manufacturing, distributing, using, maintaining, recycling, and disposing. The effects on society are seen as the outcomes that affect various individuals or groups involved in these actions.

Fig. 6 illustrates that manufacturers in both sectors have the capability to raise awareness effectively through their promptness and capacity for learning. The S-LCA approach considers different groups of people affected by the use or manufacturing of Li-based batteries and assesses the potential social consequences, both positive and negative, on human welfare across the entire lifespan of these batteries.

3.4.1. S-LCA framework

The findings of the S-LCA analysis are presented in Table S3 of the supplementary information. A summarized overview is provided below:

Goal and scope: The goal and scope of S-LCA studies vary across technologies and application sectors. There have been social risks associated with electric vehicle transportation technologies compared with conventional ones. The use of the functional unit is one of the most widely discussed aspects in the analyzed studies, especially regarding the linking of social indicators to the functional unit [98]. In some studies, the working hours necessary to produce a certain amount in tonnes of product is used [99], alternatively impacts per mile travelled or per product produced [100]. Mostly, the scope of the studies is focused on the cobalt supply chain for battery manufacturing [98, 100–103]. Although it is encouraging that NMC cathodes are shifting towards a lower cobalt content in new iterations of the technology, still small amount of cobalt is used in "low-cobalt" cathode chemistry, It is estimated that 6.6 kg of cobalt would still be needed for the production of a single 75 kWh EV battery pack, which raise concerns about the associated social and environmental impacts [104].

Life Cycle Inventory: In S-LCA, the theme of data source and quality

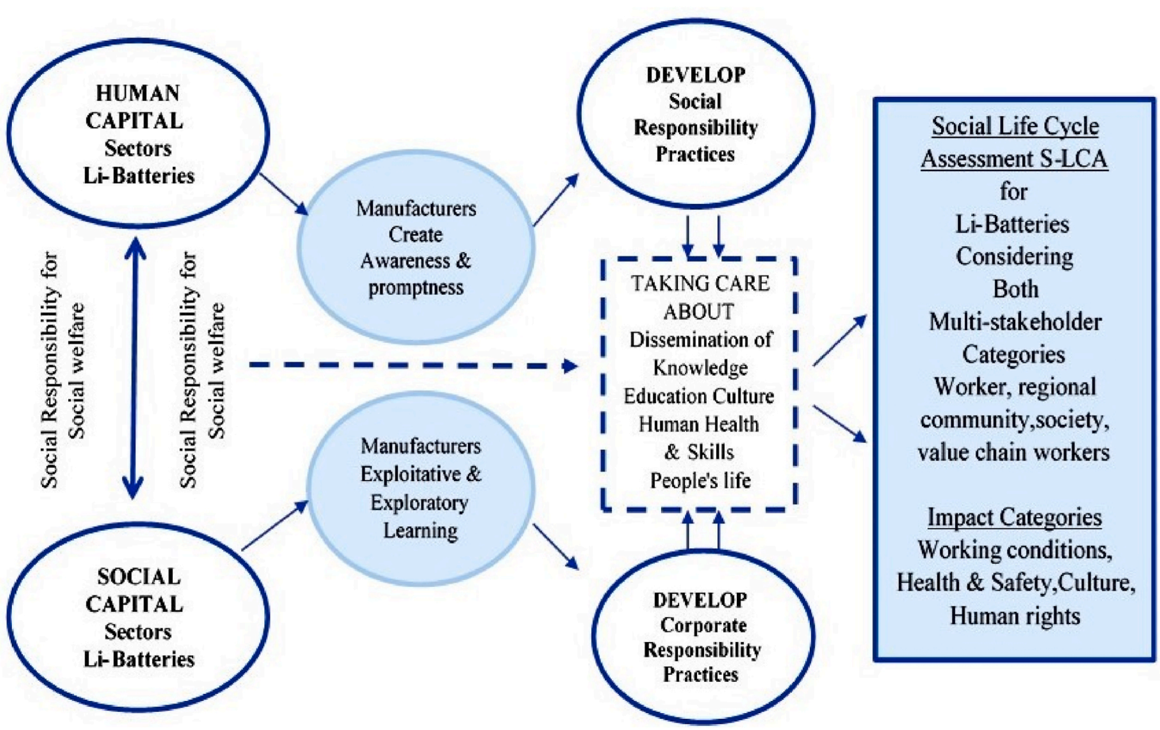

Fig. 6. Thematic Model of Social -LCA for Li-Batteries influencing human capital sectors and social capital sectors along with multi-stakeholder categories & impact categories (author's own interpretation).

holds significant importance, as a considerable amount of quantitative and qualitative information is required, and their availability and robustness are crucial for the study's outcomes. Furthermore, the utilization of generic data appears to be a more complicated issue in S-LCA than in E-LCA, as performances are more susceptible to local variability and rely heavily on companies' practices rather than the technological system [98]. The studies utilize a combination of secondary study resources and primary data. Although scenarios are common in LCA, where less environmental impacts are always better, social improvements are not always clearly defined [94]. In S-LCA, defining a referencing scenario with pre-defined targets or building a baseline scenario is therefore helpful [103].

Life Cycle Impact Assessment: Usually, all relevant energy, material, water, and electricity flows along the life cycle have to be considered to provide insights into potential environmental impacts and support e.g., sustainable material selection in development stages. S-LCA guidelines and its Methodological Sheets of Subcategories of Impact for a Social LCA build essential cornerstone guidance for the social life cycle impact assessment [96]. The S-LCA methodology can be used to identify social hotspots in the supply chain [103]. A way (methodology) of identification and prioritization of relevant impact subcategories is often mentioned as the user's stakeholder's category is the least represented stakeholders' category in S-LCA studies related to the battery sector. The indicators vary in the studies and examples include Working conditions, Community and Infrastructure, Legal System [98], or set of generic and specific indicators for each impact category or subcategory [99].

Interpretation of the results: The socioeconomic impacts on workers, the local community, and the society differ in the type of mining techniques and socio-economic status of countries, and thus the S-LCA needs to be tailored to local contexts [105]. An important sustainability dichotomy of low carbon policies is represented by the trade-off between the global benefits (e.g. reduced greenhouse gas emissions) and the negative impacts frequently borne by local communities, linked to energy justice [106,107]. Some results are interpreted in the form of a conceptual map, while others develop a specific matrix. The objective of the conceptual map is not to resolve unresolved methodological problems, but to encourage practitioners to address them critically, thereby aiding in the improvement of research in the S-LCA field [98]. By utilizing the matrix developed in the other case study [99], it became feasible to determine the stages of the product life cycle in which data is not accessible. The objective is to not only prevent the occurrence of severe risks but also to generate favourable outcomes for employees and nearby communities [101]. The overall social impacts along the battery life cycle encompass various dimensions that affect workers, local communities, and broader society, influenced by mining techniques and the socio-economic conditions of the countries involved. On one hand, the global benefits of battery use in low carbon policies, such as reduced greenhouse gas emissions, contrast with the local negative impacts, such as potential exploitation of workers, disruption to local communities, and environmental degradation, which raise concerns about energy justice.

3.5. Life-cycle sustainability assessment (LCSA) of Li-based batteries

LCSA enables the assessment of all previously mentioned dimensions as well as life phases (from extraction and processing of resources, production etc.) and to provide decision aid in the face of contradicting goals (e.g. cost vs. socially responsible material extraction). Such an LCSA requires a multi-criteria evaluation/analysis (MCA) to consolidate different category dimensions for one evaluation scale [108].

For the prospective assessment of energy technologies, it is necessary to operationalize sustainability concepts such as the Sustainable Development Goals (SDGs) and the Integrative Concept of Sustainable Development (ICoS), as well as its guiding principles and objectives [109]. The study [110] highlight that there are several different frameworks and tools available for conducting LCSA, each with its own set of metrics and indicators, while others highlight the lack of data and transparency in the battery supply chain [111].

While most LCSA frameworks consider the environmental and economic impacts associated with the production, use, and disposal of batteries, they may not account for the full social impacts of battery systems. For example, LCSA may not consider the impact of battery production on local communities or the social implications of battery disposal [112]. Fig. 7 describes the framework for battery LCSA.

3.5.1. LCSA framework

Goal and scope of LCSA: When performing an LCSA of Li-based batteries, the goal and scope specification is an important step. It helps to define the purpose, boundaries, and stakeholders of the assessment. Depending on the specific environment and assessment objectives, the goal of the LCSA of Li-based batteries may change. For instance, the goal may be to evaluate the environmental, social, and economic impacts of the batteries and identify opportunities for improvement. Alternatively, the goal may include comparing the sustainability performance of various Li-based battery types or rating the sustainability of the entire battery supply chain. The scope of the LCSA defines the boundaries of the assessment, including the system and processes to be analyzed, the functional unit, and the life cycle stages to be included.

Life Cycle Inventory: LCI for Li-based batteries entails gathering information on the resources including raw materials, energy, and water used in the manufacturing process, as well as the emissions and waste produced throughout each stage of the life cycle, which includes the extraction of raw materials, production, use, and disposal. By assessing the battery's social, economic, and environmental implications and highlighting areas for improvement, the LCSA of Li-based batteries expands on the LCI data. This can involve determining the environmental effects of the battery's complete life cycle as well as the social and economic effects of mining for raw materials, manufacturing, and recycling the battery. The relatively common structure of the LCSA inventory is as follows: E-LCA - Ecoinvent; LCC - market information; country-specific data and SHDB for S-LCA [114].

Life Cycle Impact Assessment: is an approach used to evaluate the environmental impact of a product or service throughout its entire life cycle, from the extraction of raw materials to its end-of-life disposal. In the case of LCSA of Li-based batteries, LCIA can be used to assess the environmental, social and economic impacts of the battery production process, use, and disposal. To integrate the three dimensions, a technique for order of preference by similarity to ideal solution (TOPSIS) is used for multicriteria decision-making [115] and a set of Sustainability Rating, Beta-analysis of Flexibility (Analytic Hierarchy Process, Multi-criteria Analysis), and Relative Sustainability Index in Ref. [116].

Interpretation of the results: In the coming decades, the demand for lithium, nickel and other critical raw materials is expected to rise significantly due to the market trends for plug-in electric vehicles and grid-scale energy storage systems [73,117]. The drawbacks of lithium mining may be reduced through innovative mining techniques, battery or component recycling, and new lithium-free battery technologies. Each of these technological developments has a different time frame for potential implementation, ambiguous technical costs, and varying environmental implications, all of which will include sustainability decisions [118]. Regarding non-technological aspects, a shift to electric vehicles and a greener electricity grid offers notable environmental benefits, as analyzed in a study that also explores a shift to shared mobility. A UK-conducted study highlights that while electrification reduces emissions and energy use, adopting shared mobility is essential to mitigate the increased demand for critical minerals in electric vehicle batteries and to avoid potential rises in resource depletion and toxicity impacts [119].

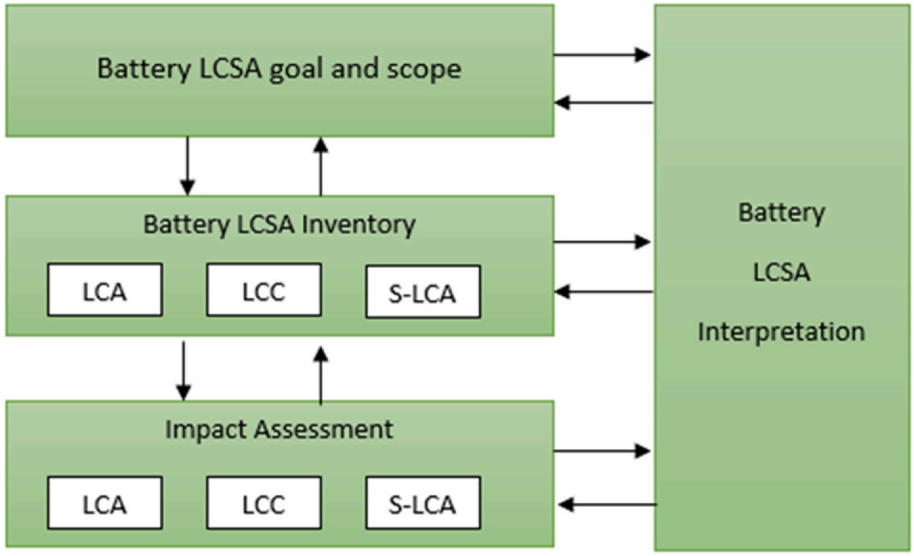

Fig. 7. Battery LCSA concept, (own adaption from) [113].

4. Challenges faced while conducting life cycle assessment for batteries

4.1. Challenges of E-LCA

It might be a challenge to compile accurate data that covers every phase of a product's life cycle. The scarcity of availability of primary data is an issue faced by many LCA practitioners. This results in a higher degree of uncertainty [120]. Hence, the reliability of the evaluation can be impacted by data gaps, inconsistencies, and uncertainties in the data sources. Also, the lack of quality data and unoptimized processes for the end of life and recycling phases of battery is a major challenge as recycling infrastructure for batteries is currently being developed [121]. Usage of secondary data can have issues like compromise of data quality as the databases are old and may not reflect the current scenario. Even the database from the previous studies also can be outdated [122] The selection of evaluation techniques and the weighting of various impacts can affect the study's overall findings and interpretation. A wide range of choices of functional unit, system boundaries, impact assessment methods, environmental impact categories, evaluation and comparative study is another challenge faced by LCA practitioners and thus a unified framework of LCA is required [121]. The regional and temporal dimensions for energy demand/resource scarcity as a result of market evolution have a significant impact on LCA which was usually not assumed in many studies [123].

4.2. Challenges of LCC

While LCC can provide valuable insights into the economic viability of battery systems, there are several challenges associated with this approach.

One of the primary challenges of battery LCC is the uncertainty around future costs. Predicting future prices for raw materials, energy, and labor can be difficult, particularly given the rapidly evolving nature of the battery industry. Additionally, there may be unexpected costs associated with battery maintenance or disposal that are difficult to predict [69].

Comparing LCC across various battery chemistries and technologies is another difficult task. The total cost of ownership can be affected by the performance characteristics, lifetimes, and safety constraints of different battery chemistries. Furthermore, the cost of recycling or disposing of batteries can differ based on the chemistry and composition of the battery [70].

Accurate data on the manufacturing and disposal procedures related to battery systems may be challenging to come by. Manufacturers may choose not to publish this information because it is frequently confidential for competitive reasons. Additionally, it may be challenging to assess LCC across different geographies due to variations in data collection and reporting standards between various regions [71].

And lastly, there can be difficulties in taking into consideration battery system externalities such as social costs or environmental effects. Although these externalities are frequently challenging to quantify and monetize, they can significantly affect the overall cost of ownership [72].

Overall, battery LCC is a valuable tool for evaluating the economic viability of battery systems. However, there are several challenges associated with this approach, including uncertainty around future costs, difficulties in comparing LCC across different battery chemistries, challenges in obtaining accurate data, and accounting for externalities.

4.3. Challenges of S-LCA

According to Kloepffer [124], the assessment of S-LCA is still in the growth stage compared to the assessments of E-LCA and LCC. LCSA necessitates the consideration of social aspects as well to promote the improvement of social conditions throughout the lifecycle of the battery after environmental and economic ones.

Therefore, from the socioeconomic and global business perspective point of view, one of the major challenges of S-LCA contests for battery life cycle assessment needs to focus on how to create high-quality, high-added value segments, and niche markets in battery research and businesses that can flourish the social impacts among people and create social awareness.

Relating to the issue of challenges S-LCA this review focuses on the following areas [125] such as.

- Lack of socioeconomic impact of battery research and its key enabling corporate social responsibility strategies, e.g., indicators adopted for social corporate responsibility.
- Lack of diagnostic study about the social impact of batteries that can create high-quality and high-added value business segments and niche markets through "Socially Responsible Human Resources Management (SRHRM) e.g., for health and safety, and fairness concerns".
- Lack of adequate ideas about battery life cycle assessment and implementation of social innovation ecosystems.

- Lack of integration of social innovation in the local economies and strengthening the capacity for enhancing research on battery technologies.
- Lack of social awareness among the scientific community to develop a different set of social indicators of batteries for assessing the social-related impact of specific countries' supply chains and classify the benefits for achieving sustainable development.
- Lack of proper methodology for measuring the social impacts of battery manufacturing companies, which has become an active area of research in recent years.

Finally, it is significant to highlight that while addressing the challenges of social life cycle assessment of battery research, the idea of social initiatives and the importance of socially responsible human resources presence. S-LCA is responsible for supporting human dignity and well-being, which represents the value of a decent, healthy, and happy life. The significant role of S-LCA has been viewed with the perception of growing the relation of battery technologies' social and environmental impacts from different stakeholders (e.g., local workers, community people, and Government) perspective.

Additional information about types of battery, applications, E-LCA, LCC, S-LCA and LCSA has been mentioned in the Supplementary file from S1.1-S1.7.

4.4. Challenges of LCSA

Battery LCSA entails a thorough analysis of the effects of the manufacture, use, and disposal of battery systems on the environment, society, and the economy. Although LCSA is a crucial tool for assessing the sustainability of battery systems, this method has a number of drawbacks.

The absence of standardized measures and procedures for measuring sustainability is one of the primary challenges with battery LCSA. For conducting LCSA, a variety of frameworks and tools are available, each with its own set of measurements and indicators. As a result, it may be challenging to evaluate findings from various studies and to create consistent sustainable standards for battery systems [108,110].

The battery supply chain's lack of data and transparency is another issue. Comprehensive data of battery manufacture, usage, and disposal, as well as the social and environmental effects of the battery supply chain, is necessary to evaluate the sustainability of battery systems. However, this information is frequently confidential, and manufacturers might not provide it for competitive reasons. Additionally, it could be challenging to compare outcomes across different geographies because regions may have different standards for collecting data and reporting [111].

The complete lifecycle impacts of battery systems may be difficult to account for. While the majority of LCSA frameworks take into consideration the economic and environmental costs associated with the production, use, and disposal of batteries, they may not account for the full social impacts of battery systems. For instance, LCSA might not consider how battery manufacture affects the surrounding community or how disposing of batteries socially will affect them [112].

Finally, there can be difficulties in ensuring that LCSA is integrated into battery system decision-making procedures. Despite the fact that LCSA can offer insightful information on the sustainability of battery systems, decision-making processes may not take it into account because of conflicting priorities or a lack of awareness. In addition, it may be challenging to incorporate LCSA into decision-making processes due to the complexity of LCSA and the absence of established procedures and measurements.

Potential sources of error in this analysis could stem from the variability and uncertainty in data quality across environmental, economic, and social assessments, as well as from the assumptions made to fill data gaps or to project future trends in battery technology and market dynamics. Assumptions regarding the lifecycle impacts of batteries, particularly in emerging and rapidly evolving markets, can lead to discrepancies in the outcomes of the LCSA. Such inaccuracies could mislead policymakers and stakeholders, potentially leading to suboptimal decisions that may not align with the intended climate change mitigation and sustainability targets. To improve the robustness of the analysis, it's crucial to refine data collection processes, enhance the transparency of assumptions, and incorporate adaptive frameworks that can be updated as new information emerges. This approach will ensure that policy and scientific recommendations remain aligned with the evolving understanding of lithium-based battery impacts and their role in transitioning to a sustainable energy future.

5. Conclusion

This study on lithium-based LCA batteries is a thorough evaluation of how lithium-ion batteries affect the economy, society, and environment—the three cornerstones of sustainability. The goal of the study is to provide an in-depth comprehension of the whole life cycle of these batteries, starting with the extraction of the raw materials and ending with the disposal.

The review first studies various Li-based batteries along with their potential applications. The analysis of E-LCA studies indicates that only 45 % employ a blend of primary and secondary data, with the remainder relying solely on secondary sources. Among these studies, only 35 % provide openly accessible inventory data, while 38 % lack such transparency. Also, the E-LCA gives an understanding of the negative environmental impacts of the production of batteries. Notably, battery production sites significantly influence the Global Warming Potential (GWP), with coating, drying, formation, and drying rooms constituting over 76 % of total energy consumption and 74 % of greenhouse gas emissions. Key contributors to GWP include cathode production and electricity usage during material transformation and battery assembly, accounting for 44.5 % and 17.0 % of the overall impact, respectively. Hence, these batteries must be produced using a lot of energy consumption and resource use, which can result in greenhouse gas emissions, depletion of rare metals, land and water pollution. Case studies also incorporated the understanding of the detailed LCA framework and analyses that were required to generate LCA results.

The economic impact of these batteries depends on a number of variables, including the cost of raw materials, production techniques, and governmental regulations. Different LCC types have been studied and a detailed LCC methodology of various Li-based batteries has been provided.

In addition, the evaluation considers how Li-based batteries may affect societal issues like labor standards, health and safety, and human rights. According to the study, the sociological risk factors are addressed, and a methodology to assess the positive or negative social and socioeconomic impacts of the battery has been studied.

The future perspective of conducting LCA of batteries will likely involve addressing and overcoming several ongoing challenges. These challenges are expected to evolve as technology advances as the understanding of sustainability deepens. The potential future perspectives on the challenges faced while conducting LCA of batteries is summarized below.

1. Data Availability and Quality: To ensure accurate assessments of battery sustainability, future LCA studies must secure trustworthy and thorough data.
2. Incorporating Emerging Battery Technologies: It will be critical to modify LCA approaches to take new battery technology's unique characteristics into consideration.
3. Temporal and Regional Considerations: An evolving challenge in battery LCAs is addressing how the environmental effect of batteries varies by geography and develops over time.

4. Integration with SDGs: Aligning LCA techniques with the United Nations' SDGs will necessitate the refinement of methodologies to include social and economic factors.
5. Interdisciplinary Collaboration: A comprehensive understanding of battery sustainability requires effective collaboration among professionals from several domains.
6. Technological Transparency: Transparency in LCA methodology and reporting is critical for increasing trust and reliability in assessment outcomes.
7. Externalities and Social Impacts: Quantifying and addressing externalities and social impacts beyond the typical scope of assessments is a key focus for future battery LCAs.
8. LCSA Standardization: LCSA methodology standardization will provide consistency and allow for meaningful comparisons of LCA outcomes.
9. Policy Integration: To effectively promote sustainable practices in the battery business, it will be crucial to incorporate LCA findings into the decision-making procedures and laws.

The key findings of this study underscore the critical interplay of environmental, economic, and social factors in the sustainability of lithium-based batteries, as evaluated through a comprehensive LCSA framework. In essence, an in-depth assessment of the sustainability of battery life cycles serves as an essential compass that directs us toward a cleaner and more sustainable energy landscape. The studies have explored every aspect of each battery's life cycle, from material extraction through end-of-life management, to reveal the intricate network of environmental, social, and economic effects that are woven throughout. By combining this information, there is the capacity to minimize the drawbacks and maximize the positive aspects of batteries. The lessons learnt through LCSA highlight what lies ahead as society moves forward into a future where these energy storage solutions serve as the foundation for advancement.

Overall, the analysis points to the complexity and diversity of Li-based batteries' effects on the environment, the economy, and society. Although these batteries may help create a future that is more sustainable, their impact must be carefully considered and managed throughout their life cycle. Policymakers, businesses, and consumers are better able to make decisions that minimize their environmental footprint, take ethical issues into account, and make the best use of available resources now that they are aware of these issues. Implementing this all-encompassing strategy not only paves the path for the development of ecologically responsible and efficient battery technologies but also represents a diligent step toward a sustainable energy paradigm.

In conclusion, the limitation of this study is acknowledged, such as the potential constraints in the comprehensiveness of the review, the challenges in methodological consistency across different sustainability assessments, and the dynamic nature of technological advancements and policy landscapes affecting the generalizability of the findings. These limitations underline the necessity for ongoing research to broaden the scope of review analysis, refine the integration of interdisciplinary methodologies, and continuously update the framework to reflect emerging technologies and shifting regulatory contexts. Future studies should aim to address these gaps, enhancing the robustness and applicability of the LCSA framework in guiding the sustainable development of lithium-based batteries and other energy storage technologies.

Author Contributions

Conceptualization, DP (Debashri Paul), VP, NS (Nabanita Saha), PS; Visualization., DP (Debashri Paul), TJ, NS (Nibedita Saha), LH; Methodology, MM, MC, AI, MV, DP (Drahomíra Pavelková;); Writing – original draft, DP (Debashri Paul), VP, NS (Nabanita Saha), NS (Nibedita Saha), TJ, MM, LH, MC, AI, MV, DP (Drahomíra Pavelková;), PS; Writing – review & editing, DP (Debashri Paul), TJ, VP, DP (Drahomíra Pavelková;); Project administration, VP, NS (Nabanita Saha), PS; Funding acquisition, VP, PS.

Declaration of competing interest

None.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2024.114860.

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