Journal of Information Technology Management
ISSN-OnLine: 2980-7972
University of Tehran

Sustainability Challenges of Lithium-Ion Battery Supply Chain: Evidence from the Indian Electric Vehicle Sector

Md Mostain Belal

Ph.D., Department of Business and Creative Industries, University of the West of Scotland. E-mail: mdmostain.belal@uws.ac.uk

Sayan Roy

MBA, Business School, University of the West of Scotland. E-mail: B00648270@studentmail.uws.ac.uk

Sreejith Balasubramanian*

*Corresponding author, Ph.D., Associate Professor, Middlesex University Dubai. E-mail: s.balasubramanian@mdx.ac.ae

Siti Norida Wahab

Ph.D., Faculty of Business and Management, Universiti Teknologi MARA, 42300 Puncak Alam, Selangor, Malaysia. E-mail: sitinorida23@uitm.edu.my

Journal of Information Technology Management, 2025, Vol. 17, Issue 1, pp. 178-197
Published by the University of Tehran, College of Management
doi: https://doi.org/10.22059/jitm.2025.99931
Article Type: Research Paper

Received: June 17, 2024
Received in revised form: August 28, 2024
Accepted: December 19, 2024
Published online: January 01, 2025

Abstract

This study critically examines the sustainability challenges within the lithium-ion battery (LIB) supply chain in India's electric vehicle (EV) sector, an area of growing importance due to the rapid expansion of EV adoption. While LIBs are essential for EVs due to their high energy density and reliability, their production and disposal pose significant environmental, social, and economic sustainability challenges. These include resource depletion, environmental degradation, ethical concerns in raw material sourcing, and inefficient recycling processes. This study adopts a qualitative case study approach, focusing on three leading Indian automotive companies, to explore these challenges in depth. Data were collected through semi-structured interviews with key stakeholders involved in various stages of the LIB supply chain, including production, waste management, and recycling. Key findings reveal that the primary environmental challenge is the lack of advanced green technologies for recycling and disposal, leading to high water and energy consumption, as well as hazardous waste emissions. Social challenges include unsafe labor practices, particularly in raw material extraction, and a shortage of skilled labor in battery recycling operations. On the economic front, the reliance on imported raw materials, coupled with high production and recycling costs, undermines the sector's sustainability and profitability. The research contributes to the literature by providing a comprehensive understanding of the environmental, social, and economic dimensions of sustainability in the LIB supply chain. It also offers practical insights for stakeholders and policymakers aiming to foster a greener and more sustainable EV sector in India.

Keywords: Electric vehicles, Environmental impact, Lithium-ion batteries, Recycling, Sustainability

Introduction

The global transportation industry is integral to economic and social development, yet it remains a leading cause of environmental pollution and the depletion of fossil resources. Amid concerns about the rapid depletion of petroleum resources, volatile oil prices, and geopolitical instability in oil-producing nations, electric vehicles (EVs) have emerged as a promising alternative, seen by many as the future of the automotive industry. This shift is catalyzing significant growth in the global lithium-ion battery (LIB) market, which was valued at USD 41.97 billion in 2021 and is projected to expand at a compound annual growth rate (CAGR) of 18.1% from 2022 to 2030. In India, the LIB market is expected to rise from 2.3 GWh in 2020-21 to 104 GWh by 2030, with electric vehicles accounting for approximately 90% of this demand according to a study conducted by JMK Research and the Institute for Energy Economics and Financial Analysis (IEEFA).

The increasing demand for lithium-ion batteries has been further accelerated by a substantial reduction in battery costs and improvements in battery safety, particularly with lithium-ion technology, which is less prone to fire or explosion when properly managed (Hua et al., 2020; Mossali et al., 2020). This trend is reshaping the automotive supply chain, influencing logistics, production systems, supplier networks, and various connected industries (Yang, Huang, & Lin, 2022). However, with the growing adoption of electric vehicles (EVs), the surge in spent lithium-ion batteries (LIBs) presents a significant threat to environmental sustainability and human health. LIBs contain hazardous materials that, if not properly managed, can lead to serious environmental contamination through pathways such as leaching and emissions of harmful gases (HF, CO, HCN), metal nano-oxides, and degradation byproducts (Mrozik et al., 2021). These pollutants can severely impact soil, water, and air quality, posing immediate risks to human and wildlife health, especially during incidents like EV fires.

In India, over 50,000 tons of lithium-ion battery waste is generated annually. This waste is projected to increase as the country expands its lithium-ion recycling capacity from 1,000 tons to 11,000 tons per year, requiring significant investment. Unfortunately, according to the Ministry of Mines, China and Hong Kong, India still imports nearly all the raw materials required for LIBs, with China and Hong Kong accounting for over 70% of its supply. The Indian EV industry’s dependence on imports poses a significant barrier to its growth, further exacerbated by the lack of technological expertise in recycling and waste management. Recycling techniques remain inefficient and environmentally damaging, generating high levels of carbon emissions, hazardous chemicals, and solid waste (Rajaeifar et al., 2022).

The opaque nature of the LIB supply chain also raises ethical concerns, including human rights violations, child labor, and forced labor in mining regions (Earley et al., 2011). Governments and civil organizations are taking steps to address these issues, but the challenges remain significant. In addition to ethical concerns, LIB manufacturing processes require significant amounts of water, often in areas where water is already scarce, leading to further social and environmental conflicts (Rajaeifar et al., 2022).

Despite these challenges, LIBs are the preferred energy source for EVs due to their high energy density, reliability, and extended life cycle. However, the recycling and disposal of spent batteries, coupled with a lack of sufficient charging infrastructure, are among the primary hurdles hindering the sector's sustainability (Kumar et al., 2022). The environmental, economic, and social challenges related to LIBs in India are further compounded by the absence of adequate recycling technologies and infrastructure. Moreover, improper disposal of used batteries exacerbates environmental pollution, and India ranks poorly on the Environmental Pollution Index (EPI), standing 178th out of 180 countries in 2018 (PS Market Research, 2018).

Given the rapid growth in EV adoption and the pressing environmental concerns, it is critical to address the end-of-life (EOL) management of LIBs. Reuse, recycling, and disposal are the three primary options for managing decommissioned batteries. Recycling presents an opportunity to recover valuable materials and reintegrate them into the supply chain, although the process is currently inefficient and costly. Reuse, where feasible, offers a more sustainable alternative by prolonging the battery’s life cycle, thereby reducing the need for new raw materials and minimizing waste generation (Dawson, 2020).

Despite the benefits of LIBs for EVs, the lack of green manufacturing and recycling technologies in India presents significant sustainability challenges. The current literature on EV supply chains predominantly focuses on the technological benefits of LIBs, with limited emphasis on the environmental, economic, and social challenges associated with their production and disposal. Additionally, empirical evidence regarding the sustainability of LIB supply chains in India remains scarce, particularly concerning the micro-level experiences of practitioners in managing these challenges (Singh et al., 2020).

This study, therefore, aims to fill this gap by exploring the key challenges facing companies in developing sustainable EV battery supply chains in India. Specifically, it seeks to understand the environmental, economic, and social barriers to promoting sustainability in this sector. The research will focus on answering the following question: What are the key challenges that the EV sector in India is facing in promoting a sustainable LIB supply chain? By addressing this question, the study will provide insights into the sustainability challenges confronting the EV battery supply chain, particularly in the context of India's waste management, toxic emissions, and the high cost of recycling.

In summary, this research will contribute to a deeper understanding of the environmental, economic, and social dimensions of sustainability in the LIB supply chain, offering valuable insights for stakeholders aiming to build a greener and more efficient EV industry in India.

Literature Review

The transition to electric vehicles (EVs) has been hailed as a key strategy for mitigating environmental degradation, yet the lithium-ion battery (LIB) supply chain poses numerous sustainability challenges across environmental, social, and economic dimensions. The extraction of raw materials, the high energy consumption in production, and the inefficiencies in recycling all pose significant barriers to achieving a sustainable LIB supply chain as shown in Figure 1.

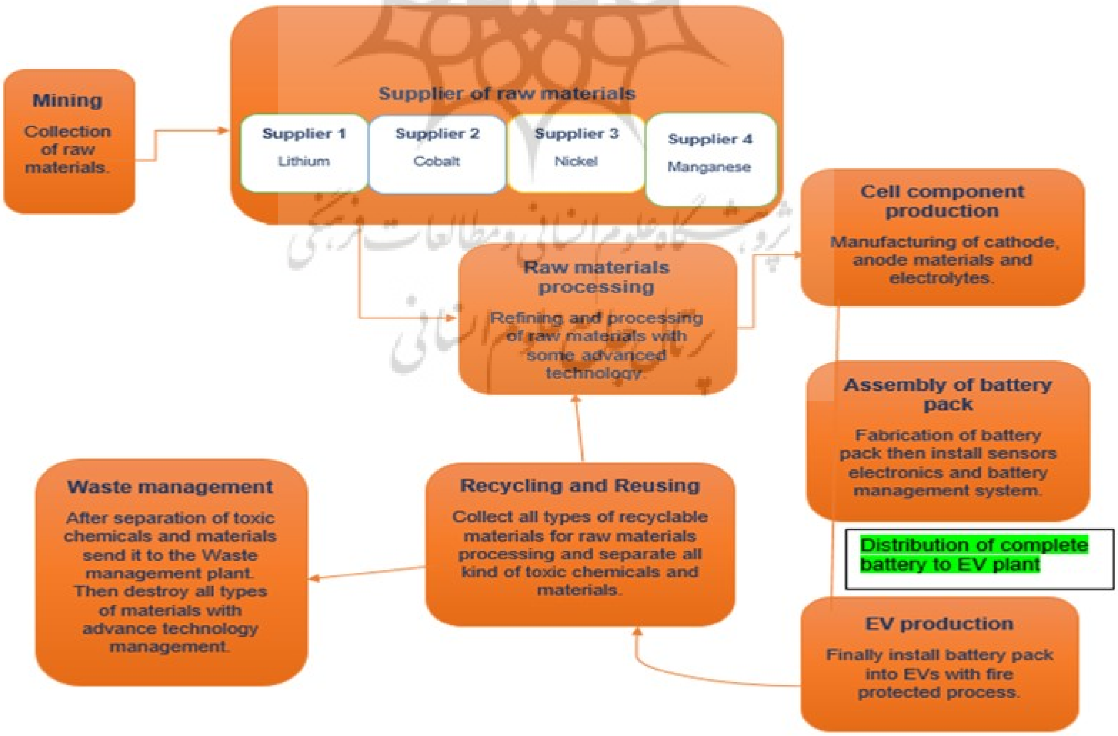

Figure 1. Supply Chain Diagram of Lithium-ion Battery (Source: Researchers)

This section provides a critical review of the literature concerning the environmental, social, and economic challenges facing the LIB supply chain, including raw material extraction, production, disassembly, recycling, and reuse. The relevant studies and their key findings are summarized in Table 1 and further discussed in the following sections.

Table 1. Summary of Literature Review

Author	Country/ Method	Key Purpose	Environmental Challenges	Social Challenges	Economic Challenges
Romare & Dahllof (2017)	Global	Assess life-cycle energy consumption and GHG emissions from LIBs.	150-200 kg CO_2 eq/kWh emitted; 350-650 MJ/kWh energy consumed in LIB manufacturing.	None	High costs for refining waste management and developing recycling technology.
Schüler, Dolega, & Degreif (2018)	Global (focused on Europe)	Examine lithium and cobalt sourcing challenges for electric mobility.	Sulphuric mineral pollution from recycling and high water usage in evaporation technology.	Child labor in Artisanal and Small-Scale Mining (ASM).	Inefficient resource recovery during evaporation (loss of lithium); high costs.
Mayyas et al. (2018)	NA/Expert Review	Identify short-term challenges in LIB recycling regulations.	Lack of environmental regulations for collecting and sorting LIBs; low recycling volumes.	None	High uncertainty around full costs of LIB recycling due to lack of regulations and low support.
Egbue, Long, & Kim (2022)	Global	Identify lithium availability and sustainability issues for Plug-in EVs (PEVs).	Recycling can reduce environmental impact (e.g., global warming, carbon footprint).	Unethical labor practices.	Future lithium supply uncertainty increases LIB prices.
Fence Wang, Introtor, Salopek, & Yuan (2022)	Global	Sustainable analysis tool design for next-gen silicon-based LIBs in EVs.	Toxic emissions during SiNW and SiNT battery production.	Hydrofluoric acid emissions pose health risks.	High energy costs due to lack of advanced, cost-efficient tech.
Kumar, Gupta, Paul, Join, & Haque (2022)	Global	Assess the environmental impacts of LIB production and recycling.	High electricity use and toxic waste production during battery manufacturing and recycling.	None	Low collection efficiency; high recycling costs.
Mohammad Ali Rajaeifar, Ghadimi, Raugei, Wu, & Heidrich (2022)	Global	Analyze environmental, economic, and social impacts of EV battery lifecycle.	Water consumption for lithium extraction affects agriculture and drinking water sources.	Child labor in small-scale mines in Russia, Australia, and Cuba.	Unethical political issues affecting raw material prices.
Chew, Tan, Sakundarini, Chin, Garg, & Singh	Global	Develop eco-design of LIBs to simplify recycling and disassembly.	Ineffective eco-design; produces toxic emissions during	None	High disassembly costs.

(2022)			disassembly.		
Gebhardt, Beck, Kopyto, & Spieske (2022)	Global	Explore sustainability practices in the LIB supply chain.	High GHG emissions during recycling and manufacturing.	None	Low prioritization of economic sustainability.
Alessia et al. (2021)	NA/Literature Review	Review sustainability challenges of LIBs.	Low substitution rate for key raw materials.	None	High production costs.
Kumar et al. (2021)	India/Survey	Identify key challenges in LIB recycling and infrastructure.	Safety risks in LIBs during recycling and disposal.	None	High EV battery production costs.
Rajaeifar et al. (2022)	NA/Literature Review	Highlight major challenges across the lifecycle of EV LIBs.	Ineffective recycling and disposal of LIBs.	None	High costs due to inefficient recycling processes.
Niri et al. (2024)	NA/Literature Review	Assess energy consumption and mining challenges for LIBs.	High energy consumption in manufacturing; long mining lead times (20-25 years).	Human rights violations, child labor, and life-threatening work conditions.	Complex economic challenges due to long mining timelines and corrupt practices.

Raw Material Extraction

The extraction of raw materials for LIBs, such as lithium, nickel, cobalt, graphite, and manganese, is essential but fraught with environmental and ethical concerns. Lithium is primarily sourced from hard rock and brine, with major production centers in Chile, Bolivia, and Argentina, while cobalt mining, mostly in the Democratic Republic of Congo (DRC), raises significant human rights concerns (Schüler et al., 2018). Graphite, mostly mined in China, and manganese, sourced from South Africa, Australia, and Gabon, further complicate the supply chain due to high environmental costs, particularly water contamination from mining processes (International Energy Agency, 2022).

Raw Material Processing

Processing raw materials into battery-grade chemicals is energy-intensive and environmentally hazardous. Techniques such as pyrometallurgy and hydrometallurgy, which involve heat or chemical treatments, emit significant pollutants, including CO_2, exacerbating climate change (Forte et al., 2020). Hydrometallurgical processes, while more efficient at recovering valuable metals like lithium and cobalt, generate large amounts of liquid waste that are costly to manage, undermining the circular economy (Chen et al., 2019). Thus, material processing remains a critical bottleneck in ensuring the environmental sustainability of LIB production.

Cell Component Production and Inventory Management

The production of key lithium-ion battery (LIB) components, including anodes, cathodes, separators, and electrolytes, is highly specialized and requires precision engineering. Highpurity chemicals must be converted into active battery ingredients, a process fraught with technical challenges (International Energy Agency, 2022). Despite advances, the energy consumption involved in producing LIB cells contributes significantly to global emissions, raising questions about the long-term environmental feasibility of LIB production (Romare & Dahllof, 2017).

Battery Pack Assembly

Battery assembly involves energy-intensive processes that require advanced automation in controlled environments. Assembling LIB cells into modules and packs accounts for two-thirds of the production cost and emissions (Zhang et al., 2020). While industry trends suggest in-house module and pack assembly to reduce costs, the reliance on external suppliers for battery cells complicates efforts to streamline the supply chain and reduce environmental impact.

Supply to EV Production Plants

Integrating LIBs into EVs presents additional challenges in terms of logistics and infrastructure. Established automakers can retrofit existing production lines, but EV-specific plants are needed to support long-term growth (International Energy Agency, 2022). This raises economic challenges, as substantial capital investments are required to retool facilities, while the industry's reliance on imported components increases costs and limits scalability in markets like India (Rajaeifar et al., 2022).

Sustainability Impacts of LIB Production and Recycling

LIB production and recycling have notable environmental, social, and economic ramifications. The environmental impacts, particularly the water contamination from lithium and cobalt mining, are well-documented. For instance, lithium mining pollutes local ecosystems, and only a small percentage of lithium-ion waste is recycled globally, with much ending up in landfills, further harming the environment (Zhang et al., 2020; Putzer, 2022). The recycling process itself, while necessary, remains inefficient, with hydrometallurgical methods producing toxic wastes and pyrometallurgical methods consuming vast amounts of energy (Forte et al., 2020). The high cost of recycling technologies and limited infrastructure further impede the circular economy.

Environmental Sustainability Challenges

The environmental consequences of LIB production are vast, including landscape degradation, carbon emissions, and water pollution. Mining for lithium and cobalt has severe ecological repercussions, including the poisoning of water basins and the release of toxic gases (Wang et al., 2022). The ineffective recycling of LIBs exacerbates these issues, as only a small percentage of batteries are recycled properly, and the majority contribute to environmental degradation through landfilling (Rajaeifar et al., 2022). Emerging recycling technologies like direct recycling and bioleaching offer some promise but are not yet scalable (Liu et al., 2019).

Social Sustainability Challenges

The social challenges within the LIB supply chain are equally concerning. Cobalt mining, particularly in the DRC, is notorious for child labor and poor working conditions, with artisanal and small-scale miners (ASM) accounting for 20% of global production (Schüler et al., 2018). Workers face significant health risks, including lung damage from inhaling mining dust, while unsafe mining practices increase the risk of accidents. Despite global awareness, ethical labor practices remain a persistent issue in the cobalt supply chain (McKie, 2021). Efforts to improve working conditions in ASM sectors are still inadequate, and the health impacts of exposure to toxic chemicals, such as hydrofluoric acid used in LIB production, continue to pose significant risks (Wang et al., 2022).

Economic Sustainability Challenges

The economic challenges of LIB sustainability primarily stem from the high costs of raw materials, recycling technologies, and regulatory barriers. Hydrometallurgical recycling, while environmentally superior to pyrometallurgical methods, remains cost-prohibitive due to expensive waste management and the low efficiency of material recovery (Harper et al., 2019). The recycling of lithium, cobalt, and nickel is also limited by the lack of sufficient end-of-life batteries, leading to an unstable circular economy (Rajaeifar et al., 2022). Additionally, the high cost of manufacturing and the geopolitical instability surrounding raw material supply chains further undermine the economic sustainability of LIB production (Kumar et al., 2021).

Research Gaps in LIB Supply Chain Sustainability

Despite significant research into LIB technologies, several gaps remain in understanding the sustainability challenges in the LIB supply chain. Most studies focus on the technological aspects of LIB production, with limited exploration of the environmental, social, and economic impacts. The recycling and reuse of LIBs, while essential for reducing the environmental footprint, are not well-researched, particularly regarding the scalability of emerging recycling technologies (Rajaeifar et al., 2022). Additionally, there is a lack of empirical evidence on the social impacts of LIB production, particularly concerning ethical labor practices in raw material sourcing. The economic viability of large-scale recycling initiatives also needs further exploration, especially given the high costs associated with waste management and the low efficiency of current recycling methods (Liu et al., 2019).

Methodology

This study adopted a qualitative case study approach to explore the sustainability challenges of lithium-ion battery (LIB) supply chains in the Indian automotive sector. Case studies are particularly useful when the research phenomenon is relatively new and requires in-depth understanding within its context (Yin, 2012). In this research, a multiple case study design was used, where each department within the selected case companies served as the unit of analysis. This allowed for a more granular understanding of the challenges faced at different levels of the LIB supply chain.

Data Collection

Semi-structured interviews were chosen as the primary method of data collection, enabling flexibility for participants to discuss their experiences while maintaining a structured focus on key areas (Yonjoo Cho, 2020). Semi-structured interviews are known to provide rich qualitative data, allowing respondents to share their perspectives in their own words, thus facilitating better contextualization and interpretation of the issues under investigation. Key areas targeted during the semi-structured interviews included:

Understanding EV technical terms and manufacturing processes: To gain insights into the complexities of LIBs used in electric vehicles, including the production challenges.

Battery supplier networks and inbound logistics: To explore the supply chain dynamics and the role of battery suppliers in managing the inbound flow of materials.

Waste management and battery recycling systems: Focused on how automotive companies handle battery disposal and recycling, addressing sustainability from an environmental perspective.

Future advancements in the EV industry: This included topics like battery power innovations, smart charging systems, and raw material inventory planning.

Cost-reduction methods in electric automobile manufacturing: How companies are lowering production costs to meet growing demand and what impact this has on the battery supply chain.

The interviews provided a comprehensive view of the LIB supply chain challenges and offered insights into environmental, social, and economic factors influencing the sustainability of the industry.

Sampling Approach

The study employed purposive sampling, specifically the extreme/deviant sampling technique (Gray, 2004), to ensure that the selected participants represented a wide spectrum of experiences and perspectives. This sampling approach is useful for identifying key factors that influence the most prominent challenges in sustainability.

The sampling was done to gather in-depth data on the environmental, social, and economic challenges faced in the LIB supply chain in India and to ensure that the participants had sufficient expertise to provide critical insights into these issues, which are essential for the future growth of the automotive sector.

Eight individuals from India's top three automakers (companies represented as A, B, and C) were selected for the interviews as shown in Table 2. These individuals were chosen because of their deep involvement in the LIB supply chain, with an average of over seven years of experience handling sustainability challenges related to EV production and battery recycling. Their experience spanned environmental management, supply chain logistics, and corporate sustainability initiatives, providing a diverse perspective on the issues at hand.

Table 2. Demographic Details of Participants

Company	Annual revenue (Billion INR)	Participants	Duration
A	732.80	Project Manager	30 minutes
C	470.40	Warehouse Manager	42 minutes
A	732.80	Operation Manager	48 minutes
B	445. 00	Sales Manager	30 minutes
B	445.00	Supply Chain Manager	45 minutes
C	470.40	Logistic Coordinator	45 minutes
A	732.80	Production Manager	30 minutes
B	445.00	Sustainability Associate	42 minutes

Data Collection Procedure

Interviews were conducted via phone and Zoom, a video conferencing platform, given the convenience and accessibility of these methods during the data collection period. Each interview lasted between 30 and 48 minutes, and all interviews were recorded and transcribed with participants' consent to ensure accuracy. Semi-structured interviews were used because they allow for open-ended responses while keeping the conversation focused on the research objectives (Cho, 2020).

Data Analysis

An inductive approach was applied to analyze the data, where the themes emerged from the participants' responses rather than being predefined. This method of analysis is commonly used in qualitative research to ensure that findings are grounded in the data itself (Braun & Clarke, 2006). Thematic analysis was used to identify patterns and themes across the interviews. Key themes were identified around: Environmental sustainability, particularly the challenges related to the disposal and recycling of LIBs; Social sustainability, focusing on labor practices in the supply chain and the ethical issues surrounding raw material extraction; Economic sustainability, dealing with the high costs of production, raw material shortages, and the inefficiency of recycling processes.

To ensure the reliability of the data, the findings were validated through triangulation by cross-checking responses with secondary data sources and follow-up discussions with additional industry experts. This process helped to confirm the initial findings and provided a more robust understanding of the sustainability challenges in the LIB supply chain (Yin, 2012).

Ethical Considerations

Ethical guidelines were followed throughout the research process. All participants were informed of the study's purpose and gave their consent for the interviews. Data confidentiality was maintained, and participants were assured that their identities would remain anonymous.

Results

This study investigated the environmental, social, and economic challenges faced by three leading Indian automakers in managing the sustainability of the lithium-ion battery (LIB) supply chain. The results were derived from thematic analysis, combining insights from semi-structured interviews and relevant literature. This section integrates the findings and discusses the implications for sustainability in the electric vehicle (EV) battery supply chain.

Environmental Sustainability Challenges

The interviews and analysis revealed significant environmental obstacles for the Indian automakers, largely stemming from the lack of sustainable technologies and inefficient waste management systems. The production of LIBs requires substantial resources, with one case revealing that each battery pack consumes around 12,000 liters of water and 100 kWh of electricity for every six battery packs (interview data). This excessive use of water and energy is largely attributed to the absence of advanced green manufacturing technologies, as pointed out by Company A’s operations manager.

Additionally, the toxic emissions generated during LIB production, especially from the use of chemicals, contribute to severe environmental degradation. The supply chain manager of Company B mentioned that the company struggles with high chemical emissions due to outdated technology, which cannot reduce or filter out harmful by-products. Furthermore, Company C’s logistics coordinator raised concerns about the mining waste generated during the LIB recycling process, which includes hazardous chemicals and radioactive by-products such as uranium. These wastes, if not managed properly, pose a serious threat to the environment, as they can leach into the soil and water (Wang et al., 2022).

The storage of LIB waste also poses significant environmental challenges. Many warehouses are not designed with adequate fire safety measures, which is concerning given the flammability of lithium. Company A's project manager noted that some LIB storage facilities lack green design features, such as solar energy systems, which could reduce the energy consumption required to maintain a cold storage environment. As a result, high electricity consumption exacerbates the company’s environmental footprint. This issue is particularly troubling because the limited stock of lithium in India poses a major risk for future supply, which is expected to rise as EV adoption increases (Kumar et al., 2022). The key environmental challenges faced by case companies are provided in Table 3.

Table 3. Key Environmental Challenges

Key Challenges	Case 1 (A Company)	Case 2 (B Company)	Case 3 (C Company)
Lack of sustainable technology	High water and electricity consumption in production	High toxic emissions during production	Hazardous mining waste from recycling
Lack of green-designed warehouses	Waste flammability and inadequate fire-safety measures	High electricity use for cooling without solar energy sources	Flammable and toxic waste storage
Limited lithium stock for future demand	Scarcity of lithium poses challenges for future demand	Lithium shortages may lead to environmental deforestation risks	Supply limitations for India's growing EV market
Lack of non-renewable raw material sources	Non-renewable components in LIB manufacturing	Non-renewable raw materials hinder green energy potential	Raw materials combined with non-renewable chemicals

These challenges highlight the pressing need for investment in sustainable technologies within the LIB supply chain. The development of green production processes and eco-friendly recycling techniques could mitigate environmental risks. Furthermore, the use of renewable energy sources such as solar power could significantly reduce the industry's reliance on electricity generated from non-renewable sources (Kumar et al., 2022; Miao et al., 2021). As noted in the literature, without systemic changes to adopt green manufacturing technologies, the LIB supply chain will continue to produce harmful emissions and contribute to resource depletion (Wang et al., 2022).

Social Sustainability Challenges

The social challenges identified in the study primarily concern worker health and safety and labor practices in LIB production and recycling facilities. The manufacturing process for LIBs involves the release of hazardous fumes that can have severe health implications for workers. Company A's project manager pointed out that many employees are exposed to these fumes during production, which increases the risk of respiratory illnesses. Although some companies, like Company B, have set up health check-up camps to monitor the well-being of their workers, this is more of a reactive measure. Proactive approaches, such as installing air filtration systems, are still lacking in most facilities (Rajaeifar et al., 2022).

Another key issue is the lack of skilled labor in the EV industry, which has led some companies to resort to forced labor practices to meet production targets. Company A's operations manager admitted to hiring workers from other industries to bridge this labor gap, despite the potential ethical concerns. On the other hand, Company B has managed to address this issue by offering higher wages to incentivize workers to join, particularly in its battery recycling facilities. However, the harsh working conditions, including extreme temperatures exceeding 40°C during recycling, deter many workers, adding to the labor shortage (Wang et al., 2022). The key social sustainability challenges facing the case companies are shown in Table 4.

Table 4. Key Social Challenges

Key Challenges	Case 1 (A Company)	Case 2 (B Company)	Case 3 (C Company)
Worker health and safety issues	Harmful fumes during production	Free monthly health check-up camps for workers	High temperatures during recycling processes
Forced labor practices	Forced labor due to lack of skilled workers	High wages offered to convince workers to join	No forced labor practices reported

The lack of investment in human capital is evident in the absence of structured training programs to upskill workers in handling LIB production and recycling tasks. These challenges underscore the importance of addressing social sustainability through improved labor conditions and employee welfare. As indicated in the literature, companies that neglect the well-being of their workforce risk long-term social and economic consequences (Rajaeifar et al., 2022).

Economic Sustainability Challenges

Economic sustainability in the LIB supply chain faces significant hurdles due to high energy consumption and the inefficiency of recycling processes. The project manager at Company A highlighted the high energy costs associated with LIB manufacturing and recycling, which stem from the underdeveloped state of technology in India. The lack of research and development (R&D) infrastructure compounds this issue, as automakers are forced to outsource R&D activities to other countries at exorbitant costs (Wang et al., 2022).

Furthermore, the recycling process for LIBs is both time-consuming and expensive. Company B's supply chain manager noted that the poor life cycle of recycled batteries reduces their cost-effectiveness, as they require more energy to recycle than to manufacture new batteries. Company C’s logistics coordinator confirmed that the quantity of waste generated during recycling far exceeds that produced during manufacturing, adding to the overall costs. The outsourcing of raw materials such as lithium, cobalt, and nickel from other countries, coupled with unethical tax policies, further increases the financial burden on these companies (Kumar et al., 2022). The key economic challenges identified from the case studies are summarized in Table 5.

Table 5. Key Economic Challenges

Key Challenges	Case 1 (A Company)	Case 2 (B Company)	Case 3 (C Company)
High energy consumption in manufacturing and recycling	Underdeveloped technology increases costs	Recycling is not cost-efficient due to poor battery life	Waste storage issues lead to higher energy costs
High cost of research and development	Lack of local R&D facilities forces outsourcing	High R&D component costs	High cost due to lack of automation in research machines
Recycling costs higher than manufacturing	Recycling consumes more energy than production	Outdated recycling technology; hydrometallurgical recycling used	Higher recycling waste quantities than manufacturing waste
High outsourcing costs for raw materials	Unethical tax policies inflate raw material costs	Suppliers charge high prices due to raw material demand	High transportation costs due to unethical tax policies

These findings underscore the need for greater investment in R&D to develop more cost-effective technologies that can improve the energy efficiency of the recycling process. According to the literature, the development of hydrometallurgical recycling methods has been shown to be more cost-efficient than traditional recycling processes, yet Indian companies have been slow to adopt this technology (Gupta et al., 2022). Additionally, automation in the LIB production process could reduce the labor costs associated with skilled foreign workers, further improving economic sustainability.

Conclusion

The results highlight the systemic challenges that hinder the sustainability of the LIB supply chain in India. Environmental degradation, driven by the inefficient use of resources and harmful emissions, remains a critical issue that can only be addressed through the adoption of green technologies. The social challenges, particularly worker health and safety, are exacerbated by the lack of skilled labor and poor working conditions, leading to unethical labor practices. On the economic front, high production and recycling costs present substantial barriers to achieving a circular economy.

Investment in R&D, along with the development of local recycling infrastructure, could alleviate many of the economic and environmental pressures on the LIB supply chain. By embracing Industry 4.0 technologies and AI-driven recycling solutions, Indian automakers can reduce waste, lower energy consumption, and improve the efficiency of LIB recycling. Furthermore, addressing the social sustainability of the supply chain by implementing better labor practices and worker protection measures would enhance the industry's long-term viability (Miao et al., 2021; Rajaeifar et al., 2022).

Overall, the findings of this study indicate that achieving sustainability in the LIB supply chain requires holistic solutions that integrate environmental, social, and economic considerations. The adoption of green technologies, improvement of labor conditions, and investment in R&D are key steps in moving toward a more sustainable EV industry in India.

Implications of the Study

The implications of the study are manifold for driving sustainability in India. They are discussed in the following sections.

Theoretical Contributions

This research contributes to the literature by identifying the lack of sustainable technology, including cost-effective LIB recycling processes, carbon capture technologies, and green warehousing systems, as a critical challenge in the LIB supply chain. These technological shortcomings result in high energy and water consumption, hazardous emissions, and waste management difficulties, all of which impede the automotive industry's progress toward establishing a circular economy.

The study's findings align with the resource-based view (RBV) theory, which emphasizes the importance of internal organizational strengths, specifically, developing rare and innovative resources like specialized LIB technology to achieve competitive advantage. In this context, technological advancements in LIB recycling and sustainable production processes can become key resources that provide a long-term competitive edge. The research also highlights the role of resource visibility and cross-functional resource usage, both essential RBV strategies that can enhance sustainability in the automotive sector. The study thus supports and extends the RBV framework, showing how the development of unique, sustainable technologies can contribute to competitive advantage and sustainability in the EV industry.

Managerial/Practical Contributions

This study offers several practical insights for industry managers and supply chain stakeholders in the EV and LIB sectors. The identified challenges provide a starting point for managers to evaluate how these factors, ranging from technological limitations to labor and resource issues affect their operations and to develop strategies to mitigate them. Key practical implications include:

Optimizing LIB Recycling Technologies: Managers should explore and invest in advanced LIB recycling technologies, such as the hydrometallurgical process, to improve resource efficiency, reduce waste, and lower energy and water usage. This shift could turn the negative trade-offs in LIB recycling into positive sustainability outcomes.

Redesigning Warehouses for Safety: Warehouse managers need to reconsider the layout and storage processes to minimize fire risks and exposure to toxic chemicals from stored LIB waste. This could involve retrofitting existing facilities to comply with green building standards and incorporating renewable energy sources such as solar power.

Training and Developing Skilled Labor: To reduce the reliance on expensive foreign operators and forced labor practices, companies should invest in training programs to develop skilled local manpower. This would not only lower operational costs but also improve labor practices and enhance the sustainability of the workforce.

Collaboration with Policymakers: Policymakers and industry leaders should work together to address forced labor practices in the LIB supply chain and unethical tax policies that inflate the cost of raw materials. By negotiating forward agreements with suppliers, companies can secure more transparent and ethical outsourcing arrangements, minimizing the impact of fluctuating demand on taxation.

Adopting Green Energy Solutions: As EV adoption grows, the industry must improve energy storage and production technologies to reduce overall energy consumption. This will promote the development of a circular economy and support environmental sustainability. Solid-state batteries could offer a promising alternative to LIBs, reducing hazardous emissions and waste while increasing battery life and recyclability.

Industry 4.0 and Smart Recycling: Embracing Industry 4.0 technologies, such as artificial intelligence (AI) and automation, can revolutionize the LIB recycling process. By separating harmful contaminants more effectively and reducing waste, companies can contribute to a greener EV supply chain.

Integrating EVs with Renewable Energy: The integration of EV charging systems with renewable energy sources can help reduce the environmental impact of grid-connected EV batteries. As the EV sector grows, the opportunity to combine renewable energy with battery charging will become increasingly important for sustainability.

Limitations and Recommendations for Future Research

While this study provides valuable insights into the sustainability challenges of the electric vehicle (EV) and lithium-ion battery (LIB) supply chains, it is important to acknowledge certain limitations. One of the main limitations is the sample size, which primarily focused on interviews with stakeholders in the automotive production and battery recycling sectors. Expanding the sample to include more waste management professionals and experts in production technology could provide a more comprehensive view of the challenges and opportunities, particularly concerning large-scale mining waste and the broader technical obstacles in LIB production.

Additionally, the study's focus was primarily on the Indian automotive sector, which may limit the generalizability of the findings to other countries with different regulatory, technological, and economic environments. Future research could address this limitation by conducting comparative studies across multiple countries to assess how regional policies and resources influence the sustainability of the LIB supply chain. To advance the field and address the gaps identified in this study, future research should focus on the following areas:

Sustainable Waste Management for Mining Waste: Large-scale mining activities generate significant environmental harm, and future research should prioritize developing sustainable waste management methods to reduce the volume of toxic waste generated from both mining and LIB recycling processes. A focus on reducing hazardous by-products from recycling could contribute significantly to the circular economy by mitigating the environmental impact of LIB production and disposal.

Value-Added Supply Chain for Rising Demand: With the expected increase in global demand for lithium, especially in India, research should explore how to create a value-added supply chain that can adapt to rising demand. Current lithium inventories are insufficient to meet the anticipated needs of the growing EV market, making it crucial to investigate alternative sources, such as solid-state batteries and improved mining practices, to diversify supply chains and enhance their resilience.

Recycling Value Chains and Recyclable Nature of Batteries: Future research should focus on improving the recycling value chain for LIBs. Given the environmental and economic challenges identified in this study, there is a pressing need to explore how recyclable battery materials and improved recycling technologies can contribute to the circular economy. This could include investigating urban mining scenarios, where materials from end-of-life batteries are recovered and reintegrated into the production cycle, thus reducing reliance on new lithium sources.

Low-Carbon Economy and Integrated Lithium Supply Systems: As lithium plays an increasingly critical role in a low-carbon economy, research should also explore integrated supply systems that combine both primary production (from natural lithium sources) and secondary products (from recycled batteries). This integration could decrease the environmental impact of lithium extraction and promote a more sustainable and reliable supply chain, crucial for green technologies and a low-carbon future.

Technological Innovations for Green Energy Storage: Research and development in green energy storage technologies, particularly in solid-state batteries and other advanced energy storage systems, could provide alternatives to lithium-based technologies. This focus could reduce the pressure on lithium supply chains and introduce more sustainable battery options for the EV market

Acknowledgements

The authors would like to express their sincere gratitude to the participating companies and all individuals who generously contributed their time, expertise, and valuable insights to this research.

Conflict of interest

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

References

Ahbe, S., Weihofen, S., & Wellge, S. (2017). *The ecological scarcity method for the European Union*. Springer.

Ahuja, J., Dawson, L., & Lee, R. (2020). A circular economy for electric vehicle batteries: Driving the change. *Journal of Property, Planning and Environmental Law, 12*(3), 235–250. https://doi.org/10.xxxx/jpp.2020.0001

Arora, S., & Shen, W. (2020). Advances in rechargeable lithium-ion batteries and their systems for electric and hybrid electric vehicles. In *Rechargeable lithium-ion batteries: Trends and progress in electric vehicles* (pp. 99-126). [Publisher name].

Arshad, F., Lin, J., Manurkar, N., Fan, E., Ahmad, A., Tariq, M.-u.-N., Wu, F., Chen, R., & Li, L. (2022). Life cycle assessment of lithium-ion batteries: A critical review. *Resources, Conservation and Recycling, 180*, 106164. https://doi.org/10.xxxx/j.retrec.2022.106164

AZoCleantech. (2022). Environmental impacts of lithium-ion batteries. *AZoCleantech*. Retrieved May 29, 2022, from https://www.azocleantech.com/article.aspx?ArticleID=1520

Center for Climate and Energy Solutions. (n.d.). Plug-in electric vehicles: Literature review. *C2ES*. Retrieved August 26, 2022, from https://www.c2es.org/document/plug-in-electric-vehicles-literature-review/

Cusenza, M. A., Bobba, S., Ardente, F., Cellura, M., & Di Persio, F. (2019). Energy and environmental assessment of a traction lithium-ion battery pack for plug-in hybrid electric vehicles. *Journal of Cleaner Production, 215*, 634–649. https://doi.org/10.xxxx/jclepro.2019.106488

Dunn, J., Kendall, A., & Slattery, M. (2022). Electric vehicle lithium-ion battery recycled content standards for the US – targets, costs, and environmental impacts. *Resources, Conservation and Recycling, 185*, 106488. https://doi.org/10.xxxx/j.retrec.2022.106488

Earley, R., Kang, L., An, F., & Green-Weiskel, L. (2011). Electric vehicles in the context of sustainable development in China. *The Innovation Center for Energy and Transportation (iCET), Background Paper*, 9.

Engel, J. (n.d.). Development perspectives of lithium-ion recycling processes for electric vehicle batteries. [Publisher name].

Gebhardt, M., Beck, J., Kopyto, M., & Spieske, A. (2022). Determining requirements and challenges for a sustainable and circular electric vehicle battery supply chain: A mixed-methods approach. *Sustainable Production and Consumption, 33*, 203-217. https://doi.org/10.xxxx/j.spc.2022.03.012

Higgins, R., & Kruger, K. (1990). *High energy non-rechargeable batteries and their applications*. SAE Technical Paper Series.

Hua, Y., Liu, X., Zhou, S., Huang, Y., Ling, H., & Yang, S. (2021). Toward sustainable reuse of retired lithium-ion batteries from electric vehicles. *Resources, Conservation and Recycling, 168*, 105249. https://doi.org/10.1016/j.resconrec.2021.105249

Industry Week. (n.d.). EV has a problem: 90% of the battery supply chain does not exist. *Industry Week*. Retrieved August 26, 2022, from https://www.industryweek.com/supply-chain/article/21244607/ev-has-a-problem-90-of-the-battery-supply-chain-does-not-exist

Khalid, A. M., & Khuman, Y. S. C. (2022). Electric vehicles as a means to sustainable consumption: Improving adoption and perception in India. In J. Bhattacharyya, M. S. Balaji, Y. Jiang, J. Azer, & C. R. Hewege (Eds.), *Socially responsible consumption and marketing in practice* (pp. 20). Springer. https://doi.org/10.1007/978-981-16-64335_20

Klug, F. (2014). Logistics implications of electric car manufacturing. *International Journal of Services and Operations Management, 17*(3), 350. https://doi.org/10.1504/ijsom.2014.059573

Lambert, D. M. (2014). *Supply chain management: Processes, partnerships, performance*. Supply Chain Management Institute.

Mark, J. (1992). Environmental, health, and safety issues of sodium-sulfur batteries for electric and hybrid vehicles. In-vehicle safety (Vol. 4).

Miao, Y., Liu, L., Zhang, Y., Tan, Q., & Li, J. (2022). An overview of global power lithium-ion batteries and associated critical metal recycling. *Journal of Hazardous Materials, 425*, 127900. https://doi.org/10.1016/j.jhazmat.2021.127900

Mikolajczak, C., Kahn, M., White, K., & Long, R. T. (2012). *Lithium-ion batteries hazard and use assessment*. Springer Science & Business Media.

Mrozik, W., Rajaeifar, M. A., Heidrich, O., & Christensen, P. (2021). Environmental impacts, pollution sources, and pathways of spent lithium-ion batteries. *Energy & Environmental Science, 14*(12), 6099-6121. https://doi.org/10.1039/D1EE02294K

Naor, M., Coman, A., & Wiznizer, A. (2021). Vertically integrated supply chain of batteries, electric vehicles, and charging infrastructure: A review of three milestone projects from the theory of constraints perspective. *Sustainability, 13*(7), 3632. https://doi.org/10.3390/su13073632

Nature. (2022). Electric cars and batteries: How will the world produce enough? *Nature*. Retrieved September 11, 2022, from https://www.nature.com/articles/d41586-021-02222-1

Nicholson, P. (1978). Past and future development of the market for lithium in the world aluminium industry. In *Lithium needs and resources* (pp. 243–246).

Omar, N., Daowd, M., Van den Bossche, P., Hegazy, O., Smekens, J., Coosemans, T., & Van Mierlo, J. (2012). Rechargeable energy storage systems for plug-in hybrid electric vehicles—Assessment of electrical characteristics. *Energies, 5*(8), 2952–2988. https://doi.org/10.3390/en5082952

Ortego, A., Valero, A., Valero, A., & Restrepo, E. (2018). Vehicles and critical raw materials: A sustainability assessment using thermodynamic rarity. *Journal of Industrial Ecology, 22*(5), 1005-1015. https://doi.org/10.1111/jiec.12696

Pandey, D. A., Manocha, D. S., & Saini, D. P. (2020). A study on an automobile revolution and future of electric cars in India. *Social Science Research Network*. Retrieved August 15, 2020, from https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3568382

Passarini, F., & Ciacci, L. (2021). *Life cycle assessment (LCA) of environmental and energy systems*. MDPI.

Peter, V. den B., Joeri, V. M., Jean-Marc, T., Julien, M., Gaston, M., & Frédéric, V. (2007). Evolutions in hydrogen and fuel cell standardization: The HarmonHy experience. *World Electric Vehicle Journal, 1*(1), 148–154.

Picatoste, A., Justel, D., & Mendoza, J. M. F. (2022). Exploring the applicability of circular design criteria for electric vehicle batteries. *Procedia CIRP, 109*, 107-112. https://doi.org/10.1016/j.procir.2022.01.016

Placke, T., Heckmann, A., Schmuch, R., Meister, P., Beltrop, K., & Winter, M. (2018). Perspective on performance, cost, and technical challenges for practical dual-ion batteries. *Joule, 2*(12), 2528-2550. https://doi.org/10.1016/j.joule.2018.10.019

Rajaeifar, M. A., Ghadimi, P., Raugei, M., Wu, Y., & Heidrich, O. (2022). Challenges and recent developments in supply and value chains of electric vehicle batteries: A sustainability perspective. *Resources, Conservation and Recycling, 180*, 106144. https://doi.org/10.1016/j.resconrec.2022.106144

Rosen, M. A. (2022). The circular economy and energy. In *CSR, sustainability, ethics & governance* (pp. 133-149).

Roy, J. J., Rarotra, S., Krikstolaityte, V., Zhuoran, K. W., Cindy, Y. D., Tan, X. Y., Carboni, M., Meyer, D., Yan, Q., & Srinivasan, M. (2021). Green recycling methods to treat lithium-ion batteries E-waste: A circular approach to sustainability. *Advanced Materials, 34*(25), 2103346. https://doi.org/10.1002/adma.202103346

Saw, L. H., Ye, Y., & Tay, A. A. (2016). Integration issues of lithium-ion battery into electric vehicles battery pack. *Journal of Cleaner Production, 115*, 1032–1045. https://doi.org/10.1016/j.jclepro.2015.12.107

Schröder, M., Iwasaki, F., & Kobayashi, H. (2021). Current situation of electric vehicles in ASEAN. *Promotion of Electromobility in ASEAN: States, Carmakers, and International Production Networks*. ERIA Research Project Report FY2021 (03), 1-32.

Spieske, A., Gebhardt, M., Kopyto, M., & Birkel, H. (2022). Improving resilience of the healthcare supply chain in a pandemic: Evidence from Europe during the COVID-19 crisis. *Journal of Purchasing and Supply Management*, 100748. https://doi.org/10.1016/j.pursup.2022.100748

Stampatori, D., Raimondi, P. P., & Noussan, M. (2020). Li-ion batteries: A review of a key technology for transport decarbonization. *Energies, 13*(10), 2638. https://doi.org/10.3390/en13102638

Swain, B. (2017). Recovery and recycling of lithium: A review. *Separation and Purification Technology, 172*, 388-403. https://doi.org/10.1016/j.seppur.2016.08.014

Tian, G., Yuan, G., Aleksandrov, A., Zhang, T., Li, Z., Fathollahi-Fard, A. M., & Ivanov, M. (2022). Recycling of spent lithium-ion batteries: A comprehensive review for identification of main challenges and future research trends. *Sustainable Energy Technologies and Assessments, 53*, 102447. https://doi.org/10.1016/j.seta.2022.102447

U.S. International Trade Commission. (n.d.). The supply chain for electric vehicle batteries. *USITC*. Retrieved August 26, 2022, from https://www.usitc.gov/staff_publications/jice/supply_chain_electric_vehicle_batteries

Van den Bossche, P., Vergels, F., Van Mierlo, J., Matheys, J., & Van Autenboer, W. (2006). SUBAT: An assessment of sustainable battery technology. *Journal of Power Sources, 162*(2), 913–919. https://doi.org/10.1016/j.jpowsour.2006.06.097

Vanhaverbeke, L., Schreurs, D., De Clerck, Q., Messagie, M., & Van Mierlo, J. (2017). Total cost of ownership of electric vehicles incorporating vehicle to grid technology. *Twelfth International Conference on Ecological Vehicles and Renewable Energies (EVER)*.

Vimmerstedt, L., Ring, S., & Hammel, C. (1995). Current status of environmental, health, and safety issues of lithium-ion electric vehicle batteries.

Yang, Z., Huang, H., & Lin, F. (2022). Sustainable electric vehicle batteries for a sustainable world: Perspectives on battery cathodes, environment, supply chain, manufacturing, life cycle, and policy. *Advanced Energy Materials, 12*(7), 2200383. https://doi.org/10.1002/aenm.202200383

Zackrisson, M., Avellán, L., & Orlenius, J. (2010). Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles—Critical issues. *Journal of Cleaner Production, 18*(15), 1519–1529. https://doi.org/10.1016/j.jclepro.2010.04.017

Zhang, Q., Dou, Y., He, Q., Deng, S., Huang, Q., Huang, S., & Yang, Y. (2022). Emerging carbonyl polymers as sustainable electrode materials for lithium-free metal-ion batteries. *Energy & Environmental Materials*. https://doi.org/10.1002/eem2.1244

Zhang, Y., Rysiecki, L., Gong, Y., & Shi, Q. (2020). A SWOT analysis of the UK EV battery supply chain. *Sustainability, 12*(23), 9807. https://doi.org/10.3390/su12239807

Zou, H., Gratz, E., Apelian, D., & Wang, Y. (2013). A novel method to recycle mixed cathode materials for lithium-ion batteries. *Green Chemistry, 15*(5), 1183. https://doi.org/10.1039/c3gc00023a

Bibliographic information of this paper for citing:

Belal, Md Mostain; Roy, Sayan; Balasubramanian, Sreejith & Wahab, Siti Norida (2025). Sustainability Challenges of Lithium-Ion Battery Supply Chain: Evidence from the Indian Electric Vehicle Sector. *Journal of Information Technology Management*, 17 (1), 178-197. https://doi.org/ 10.22059/jitm.2025.99931