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A Delphi Analysis on the Barriers of Battery Circularity in Indian Electric Vehicle Battery Infrastructure

Rudra Prakash Pradhan
Vinod Gupta School of Management
Indian Institute of Technology, Kharagpur, WB- 721302, India
rudrap@vgsom.iitkgp.ac.in

Ann Mary Varghese
Vinod Gupta School of Management
Indian Institute of Technology, Kharagpur, WB- 721302, India
annmaryvar008@gmail.com

Himanshu Chandra
Vinod Gupta School of Management
Indian Institute of Technology, Kharagpur, WB- 721302, India
himanshu2020chandra@kgpian.iitkgp.ac.in

Akanksha Jaiswal
Vinod Gupta School of Management
Indian Institute of Technology, Kharagpur, WB- 721302, India
akanksha.jaiswal2@gmail.com

P. Vanita
Vinod Gupta School of Management
Indian Institute of Technology, Kharagpur, WB- 721302, India
vanita.step@gmail.com

Abstract

This study aims to identify key resource-based and dynamic capability barriers that hinders the adoption of circularity principles in India's electric vehicle battery (EVB) infrastructure. A three-stage methodology was employed. First, an initial list of 58 barriers was compiled. In the second stage, frequency mapping was used to refine this list to 41 barriers. Finally, a survey using a five-point Likert scale was conducted. Based on responses from 23 experts and applying the Fuzzy Delphi technique, 17 relevant barriers were identified as influential in hindering battery circularity within the Indian context. The relevant barriers are discussed in details along with their significance to the Indian market. According to the experts, the most significant barrier in India is "Lack of infrastructure development for collecting EVBs". The study concludes by outlining relevant policy and managerial implications, along with its limitations and directions for future research.

Keywords
Circular Economy, Barriers, India, Delphi Method, and Electric Vehicle Battery Infrastructure.

1. Introduction
The increasing adoption of electric vehicles (EVs), largely powered by lithium-ion batteries (LIBs), is generating a growing volume of battery waste. These batteries pose environmental and safety risks at the end of their lifecycle due to hazardous and flammable components. Improper disposal can contaminate soil and groundwater, highlighting the urgent need for strategies to reuse, repurpose, or recycle LIBs (Sharma et al., 2023).

LIBs contain valuable materials such as lithium, cobalt, and graphite, but global recovery remains insufficient. Only about 3% of used batteries are collected and processed, with lithium rarely recovered in meaningful quantities (Ortego et al., 2020; Vikström et al., 2013). Recycling practices often prioritise metals like cobalt, copper, and aluminium, while other essential elements are overlooked due to technical and economic constraints (Ali et al., 2021; Richa et al., 2014). As demand for LIBs rises—driven by renewable energy and electric mobility—this gap in material recovery poses increasing challenges (Hua et al., 2020; Rajaeifar et al., 2022).

India, amid rapid EV market expansion, remains heavily reliant on imports for key battery materials like lithium and cobalt. This dependency introduces strategic risks related to supply stability and cost (Mayyas et al., 2019; Lander et al., 2021). Building a domestic circular value chain, including efficient recycling and second-life applications, is vital for environmental and economic sustainability (Bhuyan et al., 2022; Tripathy et al., 2022).

Initiatives such as the “National Mission on Transformative Mobility and Battery Storage” aim to strengthen local capabilities in battery manufacturing and recycling. However, the existing ecosystem remains weak. Extended Producer Responsibility (EPR) implementation is limited, and there is no comprehensive infrastructure for battery collection or processing (Deshwal et al., 2022). A lack of robust policy further impedes progress (Ellingsen et al., 2017). Globally, countries like China have mandated battery recovery and tracking systems for EV manufacturers (Deshwal et al., 2022). In contrast, India is still developing procedures and incentives for recycling (Bhuyan et al., 2022). Without prompt action, it risks being unprepared for the projected surge in battery waste.

By 2030, over one million EV batteries in India are expected to reach end-of-life (Environmental, 2019). Meeting this demand may require a 25-fold increase in recycling capacity (World Economic Forum, 2019). If addressed, India’s LIB recycling sector could grow into a $1 billion industry, recovering up to 23 GWh of capacity (Deshwal et al., 2022). This study identifies the key technological, policy, economic, social, and supply chain barriers limiting LIB reuse and recycling in India, aiming to inform future policy and industrial strategies.

1.1 Objectives
The specific objectives of the study are:
1. To identify factors that challenge the circular economy in battery infrastructure through a review of academic literature.
2. To shortlist these factors based on their frequency of occurrence.
3. To determine the key factors challenging circularity within India's EV battery infrastructure.

2. Literature Review
Technology and Infrastructure
One of the key hurdles in battery recycling is the underdevelopment of core technologies and supporting infrastructure. Current practices suffer from a lack of mature recycling technology, which limits efficient processing at the end-of-life (EoL) stage (Ahuja et al., 2020; Sun et al., 2015; Yun et al., 2018). This results in low recycling efficiency (Sopha et al., 2022; Azadnia et al., 2021; Albertsen et al., 2021; Kurdve et al., 2019) and poor-quality recycled materials, reducing their reuse in new batteries (Sopha et al., 2022; Martins et al., 2021; Vu et al., 2020; Gu et al., 2018).

Simultaneously, infrastructure for collecting EVBs is lacking. The absence of organized systems hinders systematic retrieval from consumers (Sopha et al., 2022; Azadnia et al., 2021; Wrålsen et al., 2021). Even when batteries are collected, dismantling remains difficult due to a lack of standardised procedures (Ahuja et al., 2020; Meng et al., 2022), and the diversity of battery types complicates sorting (Azadnia et al., 2021; Neumann et al., 2022).
Efficient collection channels for waste batteries are also missing, preventing entry into the recycling stream (Ahuja et al., 2020; Islam et al., 2022). The limited number of formal recyclers further restricts capacity (Ahuja et al., 2020; Sun et al., 2015). Additionally, the industry lacks a mature battery recycling business model (Ahuja et al., 2020; Reinhardt et al., 2019) and standards (Sopha et al., 2022; Ahuja et al., 2020; Martins et al., 2021; Vu et al., 2020; Zeng et al.,

2015). Without commercial viability or clear technical guidelines, stakeholder involvement remains low. Harmonized production standards are also lacking, complicating recovery efforts (Sopha et al., 2022; Albertsen et al., 2021; Kurdve et al., 2019). A shortage of analytical tools for circular economy (CE) limits effective monitoring and planning (Azadnia et al., 2021; Ritzén & Sandström, 2017; Tura et al., 2019). Likewise, the absence of a developed recovery marketplace reduces visibility for recycled materials (Sopha et al., 2022; Azadnia et al., 2021; Martins et al., 2021; LaMonaca & Ryan, 2022). High costs of handling, transport, and recovery discourage commercial engagement (Sopha et al., 2022; Vu et al., 2020; Slattery et al., 2021; Malinauskaite et al., 2021; Kurdve et al., 2019; Wrålsen et al., 2021), especially given the low economic value of EoL EVBs (Sopha et al., 2022; Doose et al., 2021; Albertsen et al., 2021). Safety concerns during recovery, storage, and transport—like fire, explosions, and toxic fumes—remain significant (Azadnia et al., 2021; Rajaeifar et al., 2022; Ormazabal et al., 2018; Meng et al., 2022; Demartini et al., 2023; Kampker et al., 2016), further compounded by a lack of trained personnel (Azadnia et al., 2021; Rajaeifar et al., 2022).

Market and Economic Barriers

Despite growing emphasis on circular economy (CE) strategies for electric vehicle (EV) batteries, several market and economic challenges hinder widespread implementation. A key issue is the poor return rate of EV batteries, which disrupts the consistent flow of end-of-life (EoL) batteries into recycling or reuse systems (Sopha et al., 2022; Azadnia et al., 2021; Albertsen et al., 2021; Kurdve et al., 2019). Investment in circular battery systems remains risky due to uncertainties in technology, policy, and return on investment (Sopha et al., 2022; Ahuja et al., 2020; Alamerew & Brissaud, 2020). This is compounded by a lack of incentives, such as subsidies or regulatory support, to encourage industry participation in CE initiatives (Sopha et al., 2022; Ahuja et al., 2020; Bobba et al., 2020). Economically viable reverse logistics models are lacking, making battery transport from consumers to processing centres financially unsustainable without support infrastructure (Azadnia et al., 2021; Rajaeifar et al., 2022). In addition, the absence of transparent price mechanisms for battery recycling causes financial uncertainty (Ahuja et al., 2020; Xu et al., 2022; Feng et al., 2024). Firms in emerging economies face poor financial capability to adopt CE practices (Sopha et al., 2022; Azadnia et al., 2021; Martins et al., 2021; Kurdve et al., 2019; She et al., 2017), and many lack clarity on achieving economies of scale (Ahuja et al., 2020; Azadnia et al., 2021). Price volatility for new and used batteries, along with cheaper virgin materials, undermines recycled alternatives (Azadnia et al., 2021; Rajaeifar et al., 2022; Geng & Doberstein, 2008). Furthermore, low EoL battery volumes extend the amortisation period for CE infrastructure investment (Azadnia et al., 2021; Kampker et al., 2016).

Policy and Regulatory Barriers

One of the primary barriers to circular economy (CE) adoption in the electric vehicle (EV) battery sector is the lack of comprehensive and clearly defined government policies. Existing frameworks often lack the specificity required for large-scale implementation, leading to stakeholder uncertainty (Sopha et al., 2022; Ahuja et al., 2020; Azadnia et al., 2021; Moore et al., 2020; Malinauskaite et al., 2021; Albertsen et al., 2021; Kumar et al., 2021; Garrido-Hidalgo et al., 2020; Alamerew & Brissaud, 2020). Weak regulatory enforcement and low societal pressure have also failed to push industries toward CE practices, particularly due to the absence of mandates on battery reuse and recycling (Ahuja et al., 2020; Yu et al., 2022; Ciez & Whitacre, 2019). In some cases, outdated laws unintentionally hinder CE innovation (Azadnia et al., 2021; Kirchherr et al., 2018). Uncertainty over producer responsibility for second-life batteries limits accountability (Azadnia et al., 2021; Olsson et al., 2018). Additionally, the lack of incentives, such as subsidies or tax breaks, and the underuse of tools like disposal charges weaken economic motivation (Ahuja et al., 2020; Sun et al., 2015; Azadnia et al., 2021; Tura et al., 2019; Ivanova, 2020). Fragmented waste management policies further create inefficiencies and hamper CE integration (Sopha et al., 2022; Martins et al., 2021; Moore et al., 2020; Debrah et al., 2022).

Awareness and Social Barriers

One of the key barriers to circular economy (CE) implementation in the electric vehicle (EV) battery sector is the lack of customer awareness. Many consumers are unfamiliar with circularity and the benefits of recovered or second-life batteries, limiting participation (Azadnia et al., 2021; Sopha et al., 2022; Albertsen et al., 2021; Kurdve et al., 2019). Additionally, concerns over performance, safety, and reliability create uncertainty around adopting second-life batteries (Sopha et al., 2022). Limited public education and outreach further restrict societal awareness and engagement in CE practices (Sopha et al., 2022; Galvao et al., 2018). Moreover, inadequate top management support and weak corporate social responsibility (CSR) dilute organisational commitment to CE adoption (Azadnia et al., 2021; Martins et al., 2021; Tripathy et al., 2022; Albertsen et al., 2021; Beaudet et al., 2020).

3. Methods

This study employed a systematic review approach to examine the application of circular economy (CE) principles in the electric vehicle battery (EVB) sector. A comprehensive literature search was conducted using the Scopus database, known for its extensive coverage of peer-reviewed scientific publications.

To enhance the accuracy and relevance of results, keywords were refined based on an initial review of related articles. The search employed predefined combinations such as: "battery AND circular AND economy," "battery AND circular AND economy AND electric AND vehicle," "battery AND circularity AND EV," among others, to capture literature focused on circularity in EV battery systems.

The review targeted peer-reviewed journal articles published between 2017 and 2025. A systematic three-stage process guided the selection. The initial search returned 1,412 articles. A qualitative filtering followed, based on three criteria: (1) publication in reputable journals, excluding research notes, books, theses, reviews, and non-peer-reviewed content; (2) availability of full-text, English-language articles within the management domain; and (3) a clear focus on both EV and circularity concepts.

Many initial results were concentrated in computer science, engineering, and energy domains. Therefore, a detailed screening was applied to retain only studies explicitly relevant to circularity in EVs. This refinement yielded 83 high-quality articles, which were reviewed and analysed in depth for discussion.

We initially identified 31 enablers of Battery Circularity in the EV sector from the literature review; however, based on their frequency of occurrence, we shortlisted 25 enablers for further analysis.

Fuzzy Delphi Method

This study employed the Fuzzy Delphi Method (FDM) to obtain expert consensus on the components used in module development design. FDM was selected due to its advantages in efficiently collecting expert opinions and facilitating iterative input, as supported by Mohd Jamil et al. (2017). Compared to the traditional Delphi method, the fuzzy variant offers faster, more cost-effective data collection and allows experts to express their views in linguistic terms (Mohd Jamil et al., 2013).

The conventional Delphi method relies on linguistic expressions to capture expert judgments. However, such expressions can vary in meaning between individuals. For instance, the term "high" may be interpreted differently by two experts, potentially introducing bias if represented by a single fixed value. This limitation highlights the challenge of quantifying human cognition using crisp values.

Fuzzy logic, by contrast, aligns better with human reasoning, allowing for imprecision and subjectivity. In this context, fuzzy sets—specifically fuzzy numbers—are used to express expert opinions more accurately.
A fuzzy number is a special type of fuzzy set that satisfies three conditions: Normalisation, Convexity, and Bounded support set.
The triangular fuzzy number (TFN), represented as F = (l, m, u), is commonly used in FDM. Here, l, m, and n refer to the lower limit (minimum possible value), most likely value, and upper limit (maximum possible value), respectively. The TFN's membership function reflects the degree of confidence associated with each value, offering a more nuanced representation of expert judgment than conventional methods.
The membership function (μ) is represented below:

$$\mu_f(x) = \begin{cases} \frac{x-l}{m-l} l < x < m \\ \frac{u-x}{u-m} m < x < u \\ 0 \text{ otherwise} \end{cases} \quad \text{Eq. 1}$$

TFNs are commonly used when precise data is unavailable, but approximate boundaries (l, u) and a most probable estimate (m) can be identified. These values are typically derived based on expert judgment or incomplete information (Figure 1).

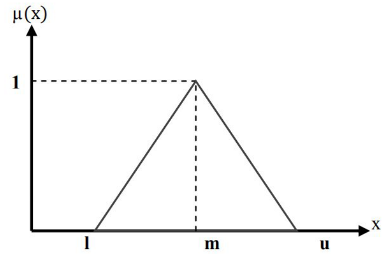

Figure 1. Triangular Fuzzy Number

Graphically, the TFN forms a triangle with its peak at (m, 1), and the base spanning from l to u, as shown in Fig. 1. This intuitive representation makes TFNs especially useful in expert-based evaluations, such as those used in the Fuzzy Delphi Method. These values are typically derived based on expert judgment or incomplete information. Triangular fuzzy numbers offer high computational efficiency because of their straightforward mathematical operations. Operations involving two fuzzy numbers, F1 and F2, can be performed easily as follows:

$$F_1 = (l_1, m_1, u_1)$$ Eq.2
$$F_2 = (l_2, m_2, u_2)$$
$$F_1 \oplus F_2 = (l_1 \oplus l_2, m_1 \oplus m_2, u_1 \oplus u_2)$$
$$F_1 \oplus F_2 = (l_1 \oplus l_2, m_1 \oplus m_2, u_1 \oplus u_2)$$

4. Data Collection

Data for this study were collected through a structured survey administered both online and offline to ensure broad participation. The online version was distributed via Google Forms, while in-person surveys were conducted to enhance inclusivity. Respondents included experts from academia, policymaking, and industry.

Following the guidelines of Adler and Ziglio (1996) and Jones and Twiss (1978), who recommend a minimum of 10 experts for Fuzzy Delphi studies to ensure consistency, a total of 23 experts were selected through purposive sampling (Chua, 2010). These individuals possessed domain expertise in circular economy, electric vehicles (EVs), technology, and problem-based learning. Selection criteria included: (i) at least a bachelor's degree, and (ii) a minimum of [insert number] years of relevant experience, consistent with Berliner (2004), who defines expertise as more than five years in a specific field, and Gambatese et al. (2008), who emphasize academic qualifications.

The survey instrument was structured in two parts. The first section gathered demographic data to ensure respondent diversity. The second section identified key enablers of circular economy adoption in battery infrastructure, using a 5-point Likert scale ranging from 1 ("Extremely Irrelevant") to 5 ("Extremely Relevant"). This scale allowed for nuanced expert input and contributed to the depth and validity of the analysis.

5. Results and Discussion

This study found barriers influencing the adoption of battery circularity in electric vehicle battery infrastructure using a literature review. The preliminary factors found in the literature review were subsequently validated by academicians in a focus group discussion. Consequently, 41 barriers pertinent to the purpose of this study were chosen for additional analysis. The Fuzzy-Delphi Method (FDM) is employed to determine the barriers influencing the adoption of battery circularity within the Indian electric vehicle battery infrastructure. The responses gathered from industrial, academic, and policy professionals were analysed utilising FDM.

Table 1. Fuzzy Scale

Linguistic variable	**Rating**	**p**	**q**	**r**
Extremely irrelevant	1	0.1	0.1	0.3
Irrelevant	2	0.1	0.3	0.5
Normal	3	0.3	0.5	0.7
Relevant	4	0.5	0.7	0.9
Extremely relevant	5	0.7	0.9	0.9

According to the Fuzzy Scale (refer to Table 1) employed in this study, a value of 0.5 or higher is deemed meaningful or relevant. All barriers with a threshold value (α) of 0.55 or higher are deemed relevant. Consequently, based on the responses received from the experts, the analysis identified 17 barriers pertinent to battery circularity in the Indian electric vehicle battery infrastructure (see Table 2). The following section discusses the relevant barriers and their significance to India.

Table 2. Fuzzy Delphi Method

	Barriers	**Fuzzy Weights**			**Defuzzification**	**Decision**
		p	**q**	**r**		
B1	Lack of mature battery recycling technology	0.3	0.750067	0.9	0.650022276	Accept
B2	Lack of infrastructure development for collecting EVBs	0.3	0.760983	0.9	0.653660922	Accept
B3	Inconvenient dismantling of batteries	0.1	0.629081	0.9	0.543027093	Reject
B4	Low efficiency of recycling	0.3	0.720523	0.9	0.640174286	Accept
B5	Low-quality of recycled material	0.1	0.647759	0.9	0.549253045	Reject
B6	Lack of efficient collection channels for waste batteries	0.3	0.728439	0.9	0.642812991	Accept
B7	Insufficient number of formal battery recyclers	0.1	0.62444	0.9	0.54148004	Reject
B8	Lack of mature battery recycling business model	0.1	0.64993	0.9	0.549976751	Reject
B9	Lack of mature battery recycling standards	0.1	0.647759	0.9	0.549253045	Reject
B10	Lack of harmonized technical standards for the battery production industry	0.1	0.617546	0.9	0.53918192	Reject
B11	Shortage of analytical tools for evaluating the potential for CE	0.1	0.565651	0.9	0.521883765	Reject
B12	Lack of developed recovery marketplace	0.1	0.655109	0.9	0.551703083	Accept
B13	High cost of handling, transporting, and recovering process	0.3	0.758308	0.9	0.652769178	Accept
B14	Low economic value of EoL EVBs	0.3	0.731141	0.9	0.643713676	Accept

B15	Diverse range of battery sizes, shapes, capacities, designs, and chemical compositions complicates sorting	0.1	0.666633	0.9	0.555544444	Accept
B16	Safety concerns during the recovery process	0.3	0.710059	0.9	0.636686297	Accept
B17	Safety issues during storage and disassembly of batteries	0.1	0.621802	0.9	0.540600516	Reject
B18	Lack of safety precautions for transportation and management of used batteries	0.1	0.622023	0.9	0.540674396	Reject
B19	Risks related to potential explosions and release of electrolyte fumes	0.1	0.661835	0.9	0.553944931	Accept
B20	lack of trained personnel for proper handling of end-of-life batteries	0.1	0.679451	0.9	0.559816899	Accept
B23	Lack of incentives	0.3	0.723196	0.9	0.641065182	Accept
B25	Lack of transparent price mechanism for waste battery recycling	0.1	0.669583	0.9	0.556527737	Accept
B26	Poor financial capability for CE adoption	0.3	0.662423	0.9	0.620807658	Accept
B27	Lack of clear idea on economics of scales	0.1	0.586148	0.9	0.528715966	Reject
B28	Uncertainty in future market prices for new and used batteries	0.1	0.652109	0.9	0.550702883	Accept
B29	Cheaper prices for virgin materials	0.1	0.645365	0.9	0.548455077	Reject
B30	Amortization period for infrastructure investment in CE due to low volume of waste batteries	0.1	0.597736	0.9	0.532578546	Reject
B31	Poor government policy for CE adoption	0.1	0.633868	0.9	0.544622734	Reject
B32	Lack of regulatory pressure from government and society	0.1	0.617874	0.9	0.539291447	Reject
B33	Obstructive laws and regulations	0.1	0.555279	0.9	0.518426299	Reject
B34	Responsibility of producers for second-life batteries is unclear	0.1	0.606328	0.9	0.535442734	Reject
B35	Lack of more appropriate incentive policies	0.1	0.64298	0.9	0.547660059	Reject
B36	Lack of tax structure	0.1	0.542889	0.9	0.514296231	Reject
B37	Inefficient recycling and waste management policy	0.1	0.669345	0.9	0.556448209	Accept
B38	Inadequate use of instruments like disposal charges	0.1	0.606544	0.9	0.535514775	Reject
B39	Lack of customer awareness	0.1	0.61299	0.9	0.537663235	Reject
B40	Uncertainty in how customers perceive second-life batteries	0.1	0.613101	0.9	0.537700187	Reject
B41	Inadequate social/environmental awareness regarding CE and recovered batteries	0.1	0.67694	0.9	0.558979891	Accept

The barriers influencing the adoption of battery circularity in India, based on the responses received from the experts, are ranked based on their scores in Table 3. The most significant barrier, according to experts, is "*Lack of infrastructure development for collecting EVBs*". It refers to the absence of a comprehensive, organized system for the collection, transportation, and processing of end-of-life (EoL) EV batteries. This deficiency hampers the efficient recycling and repurposing of valuable materials contained within these batteries, posing environmental and economic challenges. In India, the EV batteries are largely handled by the informal sector. Workers in the informal sector often operate without adequate safety measures, exposing themselves and surrounding communities to toxic substances. The informal handling of battery waste not only poses health risks but also represents a missed opportunity for job creation and economic growth in the formal recycling sector. Therefore, by proactively developing the necessary infrastructure and regulatory mechanisms, India can effectively manage the growing volume of EVBs, safeguarding environmental and public health while fostering economic development (Table 3).

Table 3. Accepted Barriers

	Barriers	Defuzzification	Rank
B2	Lack of infrastructure development for collecting EVBs	0.653660922	1
B13	High cost of handling, transporting, and recovering process	0.652769178	2
B1	Lack of mature battery recycling technology	0.650022276	3
B14	Low economic value of EoL EVBs	0.643713676	4
B6	Lack of efficient collection channels for waste batteries	0.642812991	5
B23	Lack of incentives	0.641065182	6
B4	Low efficiency of recycling	0.640174286	7
B16	Safety concerns during the recovery process	0.636686297	8
B26	Poor financial capability for CE adoption	0.620807658	9
B20	Lack of trained personnel for proper handling of end-of-life batteries	0.559816899	10
B41	Inadequate social/environmental awareness regarding CE and recovered batteries	0.558979891	11
B25	Lack of transparent price mechanism for waste battery recycling	0.556527737	12
B37	Inefficient recycling and waste management policy	0.556448209	13
B15	Diverse range of battery sizes, shapes, capacities, designs, and chemical compositions complicates sorting	0.555544444	14
B19	Risks related to potential explosions and release of electrolyte fumes	0.553944931	15
B12	Lack of developed recovery marketplace	0.551703083	16
B28	Uncertainty in future market prices for new and used batteries	0.550702883	17

The second most influential barrier is "*High cost of handling, transporting, and recovering process*" which refers to the substantial expenses associated with the end-of-life (EoL) management of EV batteries. These costs encompass the safe collection, transportation, and processing required to reclaim valuable materials, posing significant challenges to the development of a sustainable battery recycling ecosystem, particularly in countries like India. EV batteries are classified as hazardous waste due to their chemical composition and potential for thermal runaway. The transportation of spent EVBs requires compliance with stringent safety regulations, specialised containers, and sometimes permits, all of which contribute to elevated costs. Additionally, India's vast geography and infrastructural limitations exacerbate these expenses. India's growing EV market underscores the urgency of establishing cost-effective recycling infrastructure. India currently lacks sufficient commercial-scale recycling facilities, leading to increased costs due to the need for long-distance transportation to existing centres. One way to mitigate the challenges of high cost of handling is to establish regional recycling centres equipped with advanced technologies, which can reduce transportation costs and improve material recovery rates.

The two most significant barriers signify the challenges in collecting and handling the used EV batteries. There is a need to develop infrastructure that facilitates the collection and handling of EV batteries. Rather than developing an entirely new infrastructure for the handling and collection of batteries, strategies specific to states or districts could be formed to collectively work with the informal sector to facilitate the collection and handling of.

The third most significant barrier is "*lack of mature battery recycling technology*", which signifies the underdevelopment or absence of advanced, efficient, and scalable processes for recycling electric vehicle (EV) batteries, particularly the most used lithium-ion batteries. This deficiency encompasses limited technological capabilities, inadequate infrastructure, and insufficient regulatory frameworks, leading to suboptimal recovery of valuable materials and environmental concerns. In the global landscape, mature battery recycling technology involves sophisticated methods like hydrometallurgical and pyrometallurgical processes, which enable the efficient extraction of critical materials such as lithium, cobalt, and nickel from spent batteries. These technologies are characterized by high recovery rates, environmental compliance, and economic viability. Improper disposal of batteries can lead to soil and water contamination due to hazardous substances. Moreover, India relies heavily on imports for critical battery materials. Efficient recycling can mitigate this dependency.

The fourth most relevant barrier is "*Low Economic Value of End-of-Life Electric Vehicle Batteries (EoL EVBs)*", which signifies the limited financial returns obtained from recycling spent EV batteries, primarily due to declining prices of recovered materials and the adoption of battery chemistries with lower concentrations of valuable metals. This economic challenge hinders the development of a sustainable battery recycling industry, particularly in countries like India. The profitability of recycling EoL EVBs is closely tied to the market value of extracted materials such as cobalt, nickel, and lithium. However, fluctuations in global commodity prices can render recycling economically unviable. For instance, cobalt, once a high-value material, has experienced price volatility, impacting the returns from recycling processes. The processes involved in recycling, including collection, transportation, and material recovery, are capital-intensive. In many cases, the costs associated with these processes exceed the value of the recovered materials, leading to economic losses. In developing countries like India, where EV adoption is still emerging, the volume of EoL EVBs is insufficient to achieve economies of scale in recycling operations. This limitation further diminishes the financial viability of recycling initiatives. Thus, to make address these economic challenges, the government could provide subsidies, tax breaks, and other financial incentives to make recycling more economically attractive. The economic challenges could also be mitigated with an efficient channel for waste batteries. Therefore, this brings us to our next barrier.

The fifth most significant barrier is "*lack of efficient collection channels for waste batteries*". It refers to the absence or inadequacy of systematic, accessible, and regulated mechanisms for gathering end-of-life (EoL) batteries from consumers and businesses. This deficiency hampers the safe disposal, recycling, and resource recovery processes, leading to environmental hazards and loss of valuable materials. A significant portion of battery waste is handled by unregulated informal sectors, which often employ unsafe and environmentally detrimental methods. Many consumers are unaware of proper disposal methods for used batteries, leading to improper disposal practices. The lack of efficient collection channels hinders the development of a robust recycling industry, affecting job creation and economic growth. There is a scarcity of designated collection points, especially in rural and semi-urban areas, making it inconvenient for consumers to dispose of batteries responsibly.

The next most significant barrier is "*lack of incentives*". It signifies that the context of battery recycling refers to the insufficient financial, regulatory, or policy-driven motivations for stakeholders, such as manufacturers, recyclers, and consumers, to actively participate in the collection, processing, and reuse of end-of-life (EoL) batteries. This deficiency hampers the development of a sustainable circular economy for batteries, particularly in emerging markets like India. While regulations like the Battery Waste Management Rules, 2022, exist, their enforcement and the provision of tangible incentives for compliance remain weak. Without direct benefits or awareness campaigns, consumers lack motivation to return used batteries for recycling. Improper disposal of batteries leads to soil and water contamination, posing health hazards. Inefficient recycling exacerbates reliance on imported raw materials, affecting energy security. The informal sector dominates battery recycling, often employing unsafe methods, and the absence of incentives deters formal sector participation. By fostering a conducive environment through incentives and supportive policies, India can enhance battery recycling rates, mitigate environmental risks, and move towards a sustainable circular economy

6. Conclusion

This study explores the critical barriers hindering the adoption of circular economy (CE) practices in India's electric vehicle (EV) battery infrastructure, with a particular focus on lithium-ion batteries (LIBs). With the rapid growth of the Indian EV market, the improper disposal and inadequate recycling of EV batteries have emerged as major environmental, economic, and safety concerns. Motivated by the urgent need for sustainable battery waste management, the research employs a Delphi methodology supplemented by the Fuzzy Delphi Method (FDM) to systematically identify and validate key obstacles. A total of 41 barriers were initially identified through literature review and expert discussions, out of which 17 were confirmed as highly relevant based on expert feedback from academia, industry, and policy domains. These barriers were then ranked to highlight the most pressing issues affecting circularity in EV battery management.

The key findings of the study reveal that the most significant barrier is the lack of infrastructure for collecting end-of-life EV batteries (EVBs), followed closely by the high costs associated with handling, transporting, and recovering batteries. Other major impediments include the lack of mature battery recycling technologies, the low economic value of spent EV batteries, and the absence of efficient waste collection channels. Additional barriers encompass safety concerns, inadequate financial capacity for CE adoption, lack of trained personnel, weak policy incentives, and low societal awareness regarding circular practices. These findings underscore systemic gaps across technological, economic, regulatory, and social dimensions, particularly the dominance of the informal sector in battery waste handling, which leads to unsafe practices and missed economic opportunities.

The implications of the study span academic, policy, and managerial spheres. Academically, the work offers a validated and prioritized framework of CE barriers that can be used in further theoretical modeling and empirical testing. For policymakers, the study highlights the urgent need for clear, enforceable regulations, financial incentives, and coordinated infrastructure development to support battery recycling and repurposing. Managerially, the findings emphasize the importance for industry leaders to invest in capacity building, technological innovation, and public-private collaborations to foster sustainable battery lifecycle management. In the absence of strong institutional support and viable business models, achieving large-scale circularity remains a challenge.

While the study offers important insights, it also acknowledges its limitations. It focuses solely on identifying and ranking barriers without examining the interrelationships among them. Additionally, the findings are based on expert opinion rather than empirical data from field implementation. Future research should address these limitations by applying structural analysis methods such as DEMATEL or Interpretive Structural Modeling (ISM) to explore the causal relationships between barriers. Further studies could also include life cycle assessments, techno-economic feasibility analysis, and cross-country comparisons to enrich the understanding of CE adoption in EV battery infrastructure. Such future directions would help develop more actionable and scalable strategies for enhancing battery circularity in India and other emerging economies

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Biographies

Rudra Prakash Pradhan is a Professor at the Vinod Gupta School of Management, Indian Institute of Technology Kharagpur. He holds a Ph.D. from Indian Institute of Technology Kharagpur and has been a faculty member at this school since 2007. Prof. Pradhan's research interests encompass infrastructure and project finance, business analytics, financial economics, and transport economics. His scholarly contributions include numerous publications in national and international refereed journals, addressing topics such as innovation, economic growth, and the nexus between finance and infrastructure. He has actively participated in organizing various national and international conferences, serving as a convenor and contributing to the academic discourse in his fields of expertise. Notably, Prof. Pradhan is the Principal Investigator for the project titled "Sustainable Development of Electric Vehicle Battery Infrastructure in India: Challenges, Circular Economy Integration, and Policy Measures", funded by the Indian Council of Social Science Research (ICSSR). His academic impact is further reflected in his inclusion in the top 2% of scientists worldwide, as per a study by Stanford University, highlighting his significant contributions to research and scholarship.

Ann Mary Varghese is a PhD candidate at the Vinod Gupta School of Management, Indian Institute of Technology Kharagpur. She holds a Bachelor's, Master's, and MPhil in Economics, and has approximately two years of professional experience with multinational consulting firms. Her research focuses on sustainable transportation, climate finance, and policy, with a particular interest in fostering academia–industry collaboration, especially within the context of low- and middle-income countries.

Himanshu Chandra is a PhD scholar at the Indian Institute of Technology Kharagpur. He is a sustainability enthusiast, and his research is primarily focused on circular economy practices in developing countries.

Akanksha Jaiswal is a Senior Research Fellow at the Rajendra Mishra School of Engineering Entrepreneurship, Indian Institute of Technology Kharagpur. She holds a B.Tech in Electronics and Communication Engineering and an MBA in Operations Management, with academic and research exposure that includes an international research internship. Her research interests lie in the domains of quality in operations, supply chains, lean and six-sigma concepts, and theories in manufacturing. Recently, she has focused her research work on IoT, emerging technologies, Industry 4.0, and Maturity Models.

P. Vanita served as a Field Investigator for the project titled "Sustainable Development of Electric Vehicle Battery Infrastructure in India: Challenges, Circular Economy Integration, and Policy Measures", funded by the Indian Council of Social Science Research (ICSSR). She holds a Bachelor's and Master's degree in Computer Applications. Her prior experience includes biomedical research at the Department of Electronics and Electrical Communication Engineering, Indian Institute of Technology Kharagpur. She has also worked as a Full Stack Software Developer at GahanAI Pvt. Ltd., Bangalore, India, contributing to innovative technology solutions across diverse domains.