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Waste to Wattage: Enablers of Battery Circularity in India's Electric Vehicle Landscape

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Abstract

This study aims to identify key factors that facilitate the adoption of circularity principles in India's electric vehicle battery infrastructure. A three-stage methodology was employed. First, an initial list of enablers was compiled. In the second stage, frequency mapping was used to refine this list to 25 variables. Finally, a survey using a five-point Likert scale was conducted. Based on responses from 23 experts and applying the Fuzzy Delphi technique, nine relevant enablers were identified as influential in driving battery circularity within the Indian context. The relevant enablers are discussed in details along with their significance to the Indian market. According to the experts, the most significant enabler in India is "Development of an efficient infrastructure for collection and recycling of batteries". The study concludes by outlining relevant policy and managerial implications, along with its limitations and directions for future research.

Keywords
Circular Economy, Enabling Factors, India, Delphi Method, and Electric Vehicle Battery Infrastructure

1. Introduction
Electric vehicle batteries (EVBs), particularly lithium-ion batteries (LIBs), are expected to significantly contribute to electronic waste due to their hazardous components and risks of soil contamination (Sharma et al. 2023). Promoting reuse, repurposing, and recycling is essential to mitigate environmental and economic concerns (Wrålsen et al. 2021). LIBs typically retain 75–80% of their capacity after vehicle use (Barman et al. 2023; Li et al. 2018; Yıldızbaşı et al. 2022), making them suitable for second-life applications like energy storage and EV charging (Al-Alawi et al. 2022; Gu et al. 2021). This can delay recycling by up to a decade, reducing pressure on raw material demand.

LIBs have become the preferred battery type over alternatives like nickel-metal hydride (NiMH) due to superior efficiency and lower self-discharge (Egbue and Long 2012b; Sullivan and Gaines 2012). Their importance in grid storage and electric mobility supports climate goals (Hua et al. 2020; Rajaeifar et al. 2022). LIBs are projected to comprise 77% of the EV battery market by 2030 (Melin et al. 2021), with over one million reaching end-of-life (EoL) by then (Environmental 2019). This trend presents significant opportunities for reuse and recycling.

India is well-positioned to develop circular economy (CE) practices for EVBs and is collaborating globally on its electric mobility agenda (Bhuyan et al. 2022; Tripathy et al. 2022). However, growing LIB demand accelerates depletion of lithium reserves, highlighting the need for closed-loop supply chains (Li et al. 2018). Currently, only about 3% of spent LIBs are collected globally, with minimal lithium recovery (Ortego et al. 2020; Vikström et al.

2013). Recycling technologies mainly recover cobalt, copper, and aluminium, while lithium, manganese, and graphite are often neglected (Ali et al. 2021; Richa et al. 2014).

Recycling is essential to prevent raw material scarcity and price volatility (Egbue and Long 2012a; Mayyas et al. 2019; Rajaeifar et al. 2022). Efficient recovery could meet over half the global demand for key materials by 2040 (Richter 2022). Localised recycling reduces transport costs and supports greener recovery, aided by design improvements for disassembly (Fujita et al. 2021; Mossali et al. 2020). About 15–16% of batteries are unfit for reuse and must be recycled immediately (Canals Casals et al. 2017; Kampker et al. 2021; Standridge and Hasan 2015).

Originally dominant in electronics, LIB demand is now shifting to EVs. This growth raises challenges for EoL management, as improper disposal poses environmental risks (Gahlaut and Dwivedi 2024; Thompson et al. 2021). Meeting the 2030 goal of recycling 54% of EVBs will require a 25-fold increase in global capacity (World Economic Forum 2019). India's dependence on imported lithium and cobalt underscores the urgency of building domestic recycling systems. The EV battery market could grow to $300 billion by 2030 (Kala and Mishra 2021). India introduced an Extended Producer Responsibility (EPR) policy in 2019, but a comprehensive framework is still lacking (Deshwal et al. 2022; Ellingsen et al. 2017). Efforts like the "National Mission on Transformative Mobility and Battery Storage" aim to establish large-scale recycling infrastructure by 2024. The country's LIB recycling market could reach $1 billion by 2030, with a projected demand of 132 GWh (Deshwal et al. 2022). To support this growth, India must overcome infrastructure gaps and attract international investment (Gahlaut and Dwivedi 2024). Due to its socio-economic, technological and geographic circumstances, there are many challenges for India to bring about circularity in the EVB ecosystem. This is where emphasizing on the enablers to bring about circularity is important as efforts can be focused on strengthening them.

1.1 Objectives
Integrating circularity into the EVB infrastructure is a crucial element in advancing the Battery-as-a-Service (BaaS) business model (Koide et al. 2022; Singh and Ramani 2022). Despite its importance, there is limited research examining the factors that enable circularity in the Indian EVB infrastructure, particularly from the perspective of firms. This study seeks to identify the key resource-based and dynamic capability factors that support the adoption of circular practices in the Indian EVB sector. The specific objectives of the study are:

1. To identify factors that enable 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 influencing circularity within India's EV battery infrastructure.

2. Literature Review
Technology and Infrastructure
The technological and infrastructural base is fundamental to enabling CE practices in the EVB sector. A critical enabler is integrating EoL considerations in battery design, particularly "design for disassembly," which facilitates component recovery and reuse (Sopha et al. 2022; Albertsen et al. 2021). Modular battery architecture further supports CE goals by allowing easy repair, replacement, and upgrade of modules without discarding the entire unit (Alamerew and Brissaud 2020; Mathur et al., 2019).

Advanced diagnostic and tracking systems play a complementary role by enabling precise evaluation of battery health and usage, thereby supporting second-life applications and efficient recycling (Azadnia et al., 2021; Albertsen et al., 2021). The digitalisation of information, through IoT, RFID, and blockchain, enhances transparency and traceability throughout the battery lifecycle (Blömeke et al. 2020; Garrido-Hidalgo et al. 2020), reinforcing infrastructure for collection, sorting, and recycling (Beaudet et al., 2020).

Eco-design principles further promote circularity by ensuring materials and structures support reuse and reduce environmental impact. Secondary markets and incentive mechanisms for second-life batteries are also gaining traction (Sopha et al. 2022; Azadnia et al. 2021), while advancements in high-efficiency, low-emission recycling technologies remain essential for resource recovery (Gu et al., 2018).

Supply-Chain Operations and Management

Effective supply-chain operations are critical for advancing CE principles in the EVB systems. A key enabler is **standardised information sharing**, which supports seamless communication and coordination across the supply chain. Common platforms and protocols for data exchange promote traceability and transparency, crucial for battery recovery and reuse (Sopha et al. 2022; Albertsen et al. 2021).

Early and integrated collaboration among stakeholders, including manufacturers, recyclers, logistics providers, and policymakers, has also been identified as a successful driving factor. Such cooperation enables the development of systems and products designed with reuse, remanufacturing, and recycling in mind (Quinteros-Condoretty et al. 2025). Adopting **innovative business models** like servitization, battery leasing, and BaaS further facilitates CE by shifting ownership and lifecycle responsibility to producers. These models enhance end-of-life management through greater control and accountability (Alamerew and Brissaud 2020; Quinteros-Condoretty et al. 2025).

Finally, **top management commitment** is vital for CE success. Strategic leadership drives investment in reverse logistics, technology, and cross-sector partnerships necessary for systemic transition (Beaudet et al. 2020).

Economics

Economic considerations play a pivotal role in fostering circularity within the EVB value chain. Among the most frequently cited enablers are **financial incentives targeted at recycling stakeholders**. These include mechanisms such as tax rebates, direct subsidies, financial aid programs, and deposit-refund schemes, all of which are designed to reduce operational costs and enhance the economic viability of recycling and reuse practices (Azadnia et al. 2021; Ali et al. 2021).

Another essential enabler is the **clear articulation of legal environmental responsibilities**. Defining the accountability of producers, recyclers, and other stakeholders within environmental regulations ensures a shared obligation for sustainable EoL battery management. This legal clarity not only drives compliance but also strengthens long-term investment in circular practices (Sopha et al. 2022).

Furthermore, the **adoption of cost-effective and digital tracking systems** is gaining traction as a valuable economic enabler. These technologies support efficient monitoring and traceability across the battery lifecycle, enabling better resource allocation, reducing material losses, and improving regulatory reporting (Beaudet et al. 2020).

Policy and Regulation

Robust policy frameworks and regulatory instruments are crucial for driving the CE in the EVB sector. A key enabler is the **eco-design directive**, which promotes design for disassembly, recyclability, and material recovery at the EoL (Albertsen et al., 2021). Standardised requirements for EVB components improve interoperability, enhance recycling, and encourage use of secondary materials. Similarly, **EoL process standardisation** streamlines battery handling and aligns operations across jurisdictions. Certification schemes support transparency and encourage adherence to CE principles, while material taxes incentivise the use of recycled or alternative inputs. Regulatory frameworks that mandate data transparency and sharing improve traceability and coordination, and international regulatory consistency is key for harmonising global battery practices (Sopha et al. 2022; Albertsen et al. 2021). Clearly defined legal responsibilities reinforce accountability, while government incentives and strong enforcement ensure long-term CE adoption (Albertsen et al. 2021).

Social Category

Social factors play a pivotal role in enabling CE practices for EVBs by fostering awareness, stakeholder engagement, and shared responsibility across the supply chain. Broad social commitment is key to advancing sustainable battery practices, requiring collaboration among consumers, manufacturers, policymakers, and community organisations (Quinteros-Condoretty et al. 2025). One of the most influential enablers is enhancing consumer awareness. Educational programs, public campaigns, and training initiatives improve understanding of battery reuse, recycling, and second-life applications. These efforts foster responsible disposal and greater acceptance of refurbished batteries (Albertsen et al. 2021). Effective communication and strong corporate social responsibility (CSR) are equally important. Businesses that align strategies with CE goals and actively showcase their CSR initiatives can build trust and encourage widespread participation throughout the EVB lifecycle (Sopha et al., 2022).

3. Methods

This systematic research examined CE ideas in the EVB landscape. Scopus, noted for its vast peer-reviewed scientific publication coverage, was used to search the literature. To find literature on circularity in EV battery systems, the search used predefined combinations such "battery AND circular AND economy," "battery AND circular AND economy AND electric AND vehicle," and "battery AND circularity AND EV." The review focused on 2017–2025 peer-reviewed journals. The selection followed a three-step process. Initial search yielded 1,412 items. A qualitative filtering was performed 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 management articles; and (3) a clear focus on EV and circularity concepts. Early results focused on computer science, engineering, and energy. Thus, only circularity-related EV studies were selected after a thorough review. It produced 83 high-quality articles that were thoroughly examined and discussed. From the literature study, we discovered 31 EV battery circularity enablers, but we selected 25 for further investigation based on frequency.

Fuzzy Delphi Method

This study utilised the Fuzzy Delphi Method (FDM) to achieve expert consensus on the elements utilised in module development design. FDM was chosen for its efficacy in gathering expert viewpoints and enabling iterative feedback, as corroborated by Mohd Jamil et al. (2017). In contrast to the conventional Delphi approach, the fuzzy form facilitates expedited and more economical data collection, enabling experts to articulate their opinions in language terms (Mohd Jamil et al., 2013).

The traditional Delphi approach utilizes verbal expressions to obtain expert evaluations. Nevertheless, such phrases may differ in interpretation among persons. The term "high" may be subject to varying interpretations by two experts, thereby adding bias if represented by a singular fixed value. This constraint underscores the difficulty of defining human cognition with precise values.

Fuzzy logic, in contrast, corresponds more closely with human reasoning, accommodating imprecision and subjectivity. In this context, fuzzy sets, particularly fuzzy numbers, are employed to articulate expert viewpoints with greater precision.

A fuzzy number is a specific category of fuzzy set that meets three criteria: 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:

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

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. 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:

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

4. Data Collection

The data for this study were gathered via a structured survey conducted both online and offline to facilitate extensive participation. The digital version was disseminated through Google Forms, whereas face-to-face surveys were administered to improve inclusivity. Participants were specialists from academia, policy formulation, and industry.
In accordance with the recommendations of Adler and Ziglio (1996) and Jones and Twiss (1978), which stipulate a minimum of 10 experts for Fuzzy Delphi investigations to maintain consistency, a total of 23 experts were chosen using purposive sampling (Chua 2010). These individuals held specialized knowledge in CE, EVBs, technology, and problem-based learning. Selection criteria encompassed: (i) a minimum of a bachelor's degree, and (ii) at least 10 years of pertinent experience, aligning with Berliner (2004), who characterizes expertise as exceeding five years in a particular domain, and Gambatese et al. (2008), who underscore the importance of academic credentials.

the highest level of education consulted experts in our sample consisted of 52.2% PhD and 47.8% Post-doc.
The survey instrument consisted of two sections. The initial component collected demographic information to guarantee responder variety. The second segment highlighted critical facilitators for the adoption of a circular economy in battery infrastructure, utilising a 5-point Likert scale from 1 ("Extremely Irrelevant") to 5 ("Extremely Relevant"). This scale facilitated nuanced expert input and enhanced the depth and validity of the analysis.

5. Results and Discussion

This study identified enablers for battery circularity in EVB infrastructure through a literature review. The initial set of factors identified through the literature review was then subsequently validated by academicians during a focus group discussion. Therefore, 25 enablers relevant to the objective of this study were selected for further analysis. The FDM is used for the purpose of identifying the enablers relevant for battery circularity in the Indian EV battery infrastructure. The responses obtained from the industry, academic and policy experts were analysed using FDM. Based on the Fuzzy Scale (see Table 1) used in this study, the value of 0.5 and above is considered relevant. All the enablers having the threshold value (α) of 0.55 and above are considered relevant. Therefore, based on the analysis, nine enablers were found to be relevant for battery circularity in EVB infrastructure (see Table 2). The following section discusses the relevant enablers and their significance to India.

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

Table 2. Fuzzy Delphi Method

	Enablers	Fuzzy Weights			Defuzzification	Decision
		p	Q	r		
E1	EoL design for EVBs (design for disassembly)	0.1	0.638124	0.9	0.54604148	Reject
E2	Proper status checking, diagnosing, and tracking	0.1	0.671827	0.9	0.557275826	Accept
E3	Information digitalization	0.1	0.584398	0.9	0.528132693	Reject
E4	Development of an efficient infrastructure for collection and recycling of batteries	0.3	0.818584	0.9	0.672861334	Accept
E5	Recovery marketplace development and incentivization of secondary battery reuse	0.3	0.800889	0.9	0.666963062	Accept

E6	Improved recycling technologies for higher material recovery and efficiency	0.3	0.777796	0.9	0.659265297	Accept
E7	Information sharing and standards of information interfaces)	0.1	0.58419	0.9	0.528063282	Reject
E8	Extensive collaboration, cooperation, and alignment of supply-chain stakeholders	0.3	0.80386	0.9	0.667953329	Accept
E9	Innovative business model such as servitization, leasing platform	0.1	0.571562	0.9	0.523853927	Reject
E10	Strong top management commitment and decision-making	0.1	0.671349	0.9	0.557116265	Accept
E11	Economic incentives for recyclers	0.1	0.656837	0.9	0.55227889	Accept
E12	Legal environmental responsibilities	0.1	0.525007	0.9	0.508335634	Reject
E13	Implementation of digital and cost-effective tracking systems	0.1	0.595314	0.9	0.53177147	Reject
E14	Eco-design directive	0.1	0.592799	0.9	0.53093297	Reject
E15	EVB standards including compounds	0.1	0.61299	0.9	0.537663235	Reject
E16	Standardization of EoL process	0.1	0.577841	0.9	0.525947106	Reject
E17	Certification	0.1	0.628633	0.9	0.542877684	Reject
E18	Material tax on critical elements	0.1	0.573783	0.9	0.524594214	Reject
E19	Policy and legislation on information sharing	0.1	0.532744	0.9	0.510914601	Reject
E20	Regulation consistency in the global market]	0.1	0.666871	0.9	0.55562365	Accept
E21	Government subsidies and incentives for CE infrastructure	0.3	0.766639	0.9	0.655546259	Accept
E22	Well-defined and enforced government policies supporting CE adoption]	0.1	0.649581	0.9	0.5498604	Reject
E23	Social commitment	0.1	0.55303	0.9	0.517676549	Reject
E24	High customer awareness through training and engagement campaigns	0.1	0.640376	0.9	0.546791892	Reject
E25	Improved communication and active corporate social responsibility (CSR)	0.1	0.473739	0.9	0.491246202	Reject

The enablers are ranked based on the relevance (see Table 3). The most relevant enabler, according to the experts, is "*Development of an efficient infrastructure for collection and recycling of batteries*". Developing efficient infrastructure for battery collection and recycling is crucial for sustainable EV growth. Efficient battery collection and recycling infrastructure involves standardised collection systems, producer responsibility frameworks, and advanced recycling technologies. It ensures safe handling, maximises material recovery, and minimises environmental harm. Such systems support a circular economy by reintegrating recovered materials into new batteries, promoting sustainability across the electric vehicle lifecycle.

The second most relevant enabler is "*Extensive collaboration, cooperation, and alignment of supply-chain stakeholders*", which refers to the integrated efforts of various entities, ranging from raw material suppliers to recyclers, to create a cohesive, efficient, and sustainable supply chain. This collaborative approach is essential for addressing the complexities of the EVB lifecycle, which includes sourcing critical materials, manufacturing, usage, and end-of-life management. By working together, stakeholders can ensure the responsible sourcing of materials, optimise manufacturing processes, and establish effective recycling systems. Therefore, in terms of Indian context, collaboration among supply-chain stakeholders is pivotal for advancing the Indian EV industry towards a more sustainable and circular economy, ensuring that environmental considerations are integrated throughout the battery lifecycle.

The enabler "*Recovery marketplace development and incentivization of secondary battery reuse*" is the third most relevant enabler according to Indian experts. It refers to establishing systems and policies that facilitate the collection, repurposing, and resale of used EVBs. This approach aims to extend battery life, reduce environmental impact, and create economic opportunities. A recovery marketplace enables the efficient return and redistribution of EoL batteries for second-life applications, such as stationary energy storage. Incentivization involves implementing policies like Extended Producer Responsibility (EPR), subsidies, and tax benefits to encourage manufacturers and consumers to participate in battery reuse programs. India's rapid adoption of EVs is projected to generate approximately 128 GWh of recyclable batteries by 2030. Currently, a significant portion of battery waste is exported, leading to the loss of valuable materials like cobalt, lithium, and nickel. Developing a domestic recovery and reuse ecosystem can enhance energy security, stimulate economic growth, support renewable energy goals and promote environmental sustainability (Lohum 2024). Additionally, initiatives like the Battery Waste Management Rules 2022 mandate that 90% of discarded materials be recycled by 2026, with 20% incorporated into new batteries by 2030. These regulations, along with government support for energy storage projects, position India to become a leader in sustainable battery management.

The fourth most relevant enabler is "*Improved recycling technologies for higher material recovery and efficiency*". It refers to advanced methods and processes designed to enhance the extraction of valuable materials from EoL EVBs. These technologies aim to maximise the recovery rates of critical minerals such as lithium, cobalt, and nickel, while minimising environmental impact and energy consumption. Focuses on preserving and reusing battery components without breaking them down entirely, leading to energy savings and reduced processing steps. By investing in and adopting improved recycling technologies, India can address the challenges posed by the increasing volume of end-of-life EV batteries, ensuring environmental sustainability and economic resilience.

Thus, the top four most relevant enablers focus on establishing recycling facilities and developing effective recycling technologies. India is one of the biggest producers of E-waste, with a 73% increase in annual E-waste generation in five years. Moreover, a large portion, more than half of E-waste in India, goes untreated. Therefore, there is a huge gap in effective E-waste management and recycling in India. By investing in recycling infrastructure, India can reduce the gap between E-waste generation and energy recovery.

The fifth most relevant enabler is "*Government subsidies and incentives for CE infrastructure*". It refers to financial and policy measures designed to promote the development of systems that support resource efficiency, waste reduction, and sustainable practices. Through subsidies, the government can aim to encourage industries and stakeholders to adopt CE principles by offsetting initial costs and providing economic benefits. To encourage the adoption of sustainable technologies, the government may provide capital subsidies for importing machines and technology to businesses investing in recycling and waste management infrastructure. This financial support from the government reduces the burden of initial investments and accelerates the transition to a circular economy. Adopting CE practices aligns India with international environmental standards, enhancing its global competitiveness. Therefore, by investing in and incentivising circular economy infrastructure, India can pave the way for a more sustainable and resilient future.

Table 3. Accepted Enablers

	Enablers	Defuzzification	Rank
E4	Development of an efficient infrastructure for collection and recycling of batteries	0.672861	1
E8	Extensive collaboration, cooperation, and alignment of supply-chain stakeholders (i.e., early integration in product development)	0.667953	2
E5	Recovery marketplace development and incentivization of secondary battery reuse	0.666963	3
E6	Improved recycling technologies for higher material recovery and efficiency	0.659265	4
E21	Government subsidies and incentives for CE infrastructure	0.655546	5
E2	Proper status checking, diagnosing, and tracking	0.557276	6
E10	Strong top management commitment and decision-making	0.557116	7
E20	Regulation consistency in the global market	0.555624	8
E11	Economic incentives for recyclers	0.552279	9

The next enabler, "*Proper status checking, diagnosing, and tracking*", is essential for real-time monitoring of battery parameters such as state of charge (SoC), state of health (SoH), temperature, and voltage. Diagnosing pertains to the identification of potential faults or degradation patterns, while tracking encompasses the documentation and analysis of battery usage history and performance data. It refers to the systematic processes involved in monitoring the health, performance, and lifecycle of EVBs throughout their use and EoL stages. These processes are crucial for ensuring safety, optimising performance, and facilitating effective recycling or repurposing of batteries. India's expanding EV market underscores the need for robust battery management systems. Implementing proper status checking, diagnosing, and tracking mechanisms is vital for the advancement of India's EV industry, ensuring batteries are used safely, efficiently, and sustainably throughout their lifecycle.

"*Strong top management commitment and decision-making*" is essential in implementing circularity practices due to the proactive engagement and leadership of an organisation's senior executives in initiating, supporting, and sustaining CE initiatives. This encompasses setting clear sustainability goals, allocating necessary resources, integrating CE principles into core business strategies, and fostering a culture that values environmental responsibility and innovation. For India, where the EV market is rapidly expanding, strong leadership commitment ensures that sustainability is embedded in the growth trajectory. It enables companies to align with national environmental goals, comply with emerging regulations, and meet the increasing demand for eco-friendly transportation solutions.

Another relevant enabler, "*Regulation consistency in the global market*", ensures that products and processes meet uniform criteria, reducing barriers to international collaboration and promoting sustainable practices. It collectively holds policies, standards, and legal frameworks across countries to facilitate seamless trade, manufacturing, and recycling processes, particularly vital for industries like EVBs. Consistent regulations. Achieving regulation consistency in the global market is essential for India to align its regulations with international standards can enhance its participation in global EV supply chains, attracting foreign investment and technology transfer.

Furthermore, the last relevant enabler is "*Economic incentives for recyclers*", which encompasses financial mechanisms such as tax breaks, subsidies, economic support, and deposit-refund schemes designed to encourage the recycling industry. These incentives aim to make recycling operations more economically viable, promote environmental sustainability, and integrate informal recycling sectors into formal systems. Governments can offer tax reductions or direct subsidies to recycling enterprises, lowering operational costs and encouraging investment in recycling infrastructure. India's recycling industry is predominantly informal. Incentives can help integrate informal workers into formal systems, ensuring better working conditions and environmental compliance. Therefore, by adopting and scaling these economic incentives, India can strengthen its recycling infrastructure, promote environmental sustainability, and drive inclusive economic growth (Table 4).

Table 4. Enabler and management

ENABLER	MANAGERIAL IMPLICATIONS	POLICY IMPLICATIONS
Development of an efficient infrastructure for collection and recycling of batteries	- Develop logistics systems for battery return, collection, and reverse supply chains. - Partner with specialized recycling firms to manage EoL batteries. - Establish regional hubs near auto manufacturing clusters (e.g., Pune, Chennai, Gurugram). - Leverage existing dealership networks for battery collection and reverse logistics. - Integrate digital platforms for tracking battery flow and efficiency of collection systems.	- Launch national battery collection infrastructure schemes. - Mandate EPR in EV battery regulations. - Offer tax breaks and infrastructure grants to firms establishing collection and recycling nodes. - Strengthen implementation of EPR under the Battery Waste Management Rules, 2022. - Offer Viability Gap Funding (VGF) for recycling plants, especially in underserved states. - Create common recycling facilities in industrial zones via state-level policies.
Extensive collaboration, cooperation, and alignment of supply-chain stakeholders	- Facilitate early-stage collaboration with suppliers, recyclers, and OEMs. - Create platforms for real-time information sharing across the value chain. - Align internal processes with circular principles through integrated project teams.	- Create regulatory frameworks encouraging cross-sector partnerships. - Develop industry consortia or alliances for CE in EVs.

	- Build alliances with Indian OEMs, battery recyclers, and government labs (e.g., CSIR, BHEL). - Engage MSMEs and startups through joint pilots and supply agreements. - Use platforms like FICCI or SIAM to coordinate industry efforts and share knowledge.	- Provide funding for joint ventures and consortium-based initiatives in battery circularity. - Promote cluster-based policies encouraging regional circularity alliances. - Provide grants under Make in India and PLI schemes to multi-stakeholder projects. - Facilitate state-industry roundtables for aligning circular economy priorities.
Recovery marketplace development and incentivization of secondary battery reuse	- Design business models that enable resale, leasing, or repurposing of used batteries. - Assess the economic feasibility of second-life applications (e.g., grid storage). - Create internal marketplaces or platforms for tracking and monetizing recovered batteries. - Identify business opportunities in low-cost energy storage using second-life EV batteries (e.g., for telecom towers, solar storage). - Collaborate with renewable energy and rural electrification programs for battery reuse. - Build local resale or leasing platforms for recovered batteries.	- Establish clear standards and certifications for second-life batteries. - Provide fiscal incentives for companies enabling reuse and repurposing. - Regulate performance benchmarks for secondary use to build market trust. - Define safety and quality guidelines for second-life batteries under BIS/ISI certification. - Provide financial incentives under schemes like Startup India for secondary-use innovations. - Enable resale through GST-compliant secondary markets.
Improved recycling technologies for higher material recovery and efficiency	- Invest in or partner with technology providers developing next-gen recycling methods. - Set internal recovery targets and monitor yield rates. - Conduct life-cycle assessments to optimize material flows. - Collaborate with Indian research institutes (e.g., IITs, NITI Aayog-supported labs) to develop indigenous technologies. - Focus on low-cost, scalable recycling suitable for Indian conditions. - Incorporate AI and automation to improve throughput in material recovery units.	- Provide R&D grants and subsidies for advanced recycling tech. - Mandate minimum recovery rates for key materials (e.g., lithium, cobalt). - Build technology parks or innovation zones for battery recycling. - Offer innovation grants via Department of Science & Technology (DST) or Ministry of Heavy Industries. - Develop public-private pilot plants for lithium, cobalt, and nickel recovery. - Set phased recovery efficiency targets in alignment with global norms.
Government subsidies and incentives for CE infrastructure	- Align capital investment strategies with available subsidies. - Use government grants to offset high upfront infrastructure costs. - Prioritize CE-aligned projects in corporate sustainability agendas. - Align internal investment strategies with FAME-II and National Electric Mobility Mission Plan incentives. - Use government schemes to reduce capital expenditure on recycling and refurbishing infrastructure. - Explore co-investment models with state industrial development corporations.	- Expand subsidy programs for CE-aligned infrastructure. - Include circular economy targets in national EV and battery roadmaps. - Provide differentiated incentives based on impact, scale, and innovation. - Expand the scope of existing central subsidies to cover circular infrastructure. - Launch dedicated CE infrastructure financing schemes through SIDBI or IREDA. - Allow duty exemptions on imported CE equipment and recycling machinery.
Proper status checking, diagnosing, and tracking	- Integrate diagnostic tools and digital twins in battery lifecycle management. - Implement data-driven predictive maintenance and retirement strategies.	- Standardize diagnostic and tracking protocols across the industry. - Require traceability from manufacturing to end-of-life.

	- Train technical teams to conduct diagnostics aligned with circularity goals. - Adopt affordable IoT-based battery health monitoring tailored for Indian usage conditions. - Partner with Indian telematics firms to deploy tracking solutions at scale. - Train field staff for diagnostics in remote regions.	- Fund pilot projects that implement blockchain or IoT-based tracking. - Mandate digital tracking of EV batteries through a national portal under CPCB. - Include diagnostic capability in the type approval process for EV batteries. - Standardize diagnostics through BIS technical standards.
Strong top management commitment and decision-making	- Embed circularity as a core strategic objective with board-level oversight. - Allocate budget and KPIs to CE performance metrics. - Lead by example through public commitments to circular goals. - Align CSR and ESG goals with circularity targets to meet SEBI's BRSR disclosure norms. - Integrate CE into board-level discussions and sustainability charters. - Identify CE champions within Indian leadership teams.	- Encourage corporate governance regulations to include CE responsibility. - Promote circularity leadership awards or recognition programs. - Integrate CE leadership into ESG reporting requirements. - Recognize companies with strong CE leadership through national awards (e.g., India Green Energy Awards). - Require CE-related disclosures in company sustainability reports. - Incentivize CE leadership via corporate tax deductions for green practices.
Regulation consistency in the global market	- Benchmark internal processes against global best practices. - Streamline export-import logistics by aligning with global standards. - Prepare for global regulatory shifts (e.g., EU Battery Directive updates). - Benchmark Indian processes against EU Battery Directive and adapt for compliance in exports. - Engage with export councils (e.g., EEPC, ACMA) to align standards. - Prepare products for harmonization with future cross-border CE regulations.	- Harmonize Indian CE policies with international frameworks (e.g., UNEP, Basel Convention). - Negotiate bilateral or regional agreements on battery circularity standards. - Create a compliance roadmap for global CE norms. - Align national battery rules with global frameworks like the UN ECE regulations. - Establish bilateral regulatory convergence initiatives (e.g., with EU, ASEAN). - Develop a CE export-readiness certification system for Indian manufacturers.
Economic incentives for recyclers	- Partner with third-party recyclers to leverage cost-sharing opportunities. - Explore profit-sharing or rebate models to encourage efficient recovery. - Reduce internal recycling costs through volume-based contracts. - Collaborate with state pollution control boards to access clearance faster and reduce regulatory friction. - Outsource to certified Indian recyclers to reduce internal costs. - Participate in take-back schemes with municipal or state agencies.	- Offer tax incentives, subsidies, and low-interest loans to formal recyclers. - Establish performance-based reward systems for high-yield recovery. - Create a licensing regime to prioritize high-efficiency recyclers. - Provide GST concessions and tax holidays for recyclers certified under Battery Waste Management Rules. - Establish incentive schemes under National Resource Efficiency Policy (NREP). - Offer performance-linked financial rewards for recyclers achieving high recovery rates.

6. Conclusion

This research has identified and prioritised battery circularity enablers in India's EVB infrastructure using systematic methods. After a thorough literature study and academic focus group validation, 25 enablers have been selected for further investigation. The FDM has been used to analyse expert answers from academia, business, and policy sectors to identify nine key enablers for circular economy (CE) application in EV batteries. Development of an efficient infrastructure for the collection and recycling of batteries is the top enabler, underlining the importance of physical systems and technology in battery circularity. This has been followed by substantial, Extensive collaboration, cooperation, and alignment of supply-chain stakeholders, emphasising the necessity for value-chain coordination. Recovery marketplace development and incentivization of secondary battery reuse, Improved recycling technologies for higher material recovery and efficiency, and Government subsidies and incentives for CE infrastructure are further drivers. These data show that battery circularity requires technical innovation, economic assistance, and institutional alignment.

This study contributes to the growing body of knowledge on circular economy practices in the EV sector, provides a priority framework for targeted interventions, and guides businesses seeking to transition to sustainable and circular operations. This research rates relevant enablers but does not examine their linkages. This study may be expanded using DEMATEL or Interpretive Structural Modelling (ISM) to identify causal links and generate strategic implementation approaches. The changing legal and technical context allows for ongoing appraisal of these enablers to meet India's clean energy and transportation ambitions.

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References

Adler, M. and Ziglio, E., Gazing into the Oracle: The Delphi Method and its Application to Social Policy and Public Health, Jessica Kingsley Publication, 1996.

Al-Alawi, M. K. Cugley, J. and Hassanin, H., Techno-economic feasibility of retired electric-vehicle batteries repurpose/reuse in second-life applications: A systematic review, Energy and Climate Change, vol. 3, 2022.

Alamerew, Y.A. and Brissaud, D., Modelling reverse supply chain through system dynamics for realizing the transition towards the circular economy: A case study on electric vehicle batteries, Journal of Cleaner Production, vol. 254, pp. 120025, 2020.

Albertsen, L. Richter, J.L. Peck, P. Dalhammar, C. and Plepys, A., Circular business models for electric vehicle lithium-ion batteries: An analysis of current practices of vehicle manufacturers and policies in the EU, Resources, conservation and recycling, vol. 172, pp.105658, 2021.

Ali, H. Khan, H. A. and Pecht, M. G., Circular economy of Li Batteries: Technologies and trends, Journal of Energy Storage, vol. 40, 2021.

Azadnia, A.H. Onofrei, G. and Ghadimi, P., Electric vehicles lithium-ion batteries reverse logistics implementation barriers analysis: A TISM-MICMAC approach, Resources, Conservation and Recycling, vol. 174, pp. 105751, 2021.

Barman, P. Dutta, L. and Azzopardi, B., Electric Vehicle Battery Supply Chain and Critical Materials: A Brief Survey of State of the Art, Energies, vol. 16, no. 8, 2023.

Berliner, D. C., Describing The Behaviuor and Documenting The Accomplishments of Expert Teachers, Bulletin of Science, Technology & Society, vol. 24, no. 3, pp. 200-212, 2004.

Beaudet, A. Larouche, F. Amouzegar, K. Bouchard, P. and Zaghib, K., Key challenges and opportunities for recycling electric vehicle battery materials, Sustainability, vol. 12, no. 14, pp. 5837, 2020.

Bhuyan, A. Tripathy, A. Padhy, R. K. and Gautam, A., Evaluating the lithium-ion battery recycling industry in an emerging economy: A multi-stakeholder and multi-criteria decision-making approach, Journal of Cleaner Production, vol. 331, pp. 130007, 2022.

Blömeke, S. Mennenga, M. Herrmann, C. Kintscher, L. Bikker, G. Lawrenz, S. Sharma, P. Rausch, A. Nippraschk, M. Goldmann, D. and Poschmann, H., Recycling 4.0: An integrated approach towards an advanced circular economy, Proceedings of the 7th International Conference on ICT for Sustainability, pp. 66-76, 2020.

Canals Casals, L. Amante García, B. and Cremades, L. V., Electric vehicle battery reuse: Preparing for a second life, Journal of Industrial Engineering and Management, vol. 10, no. 2, pp. 266–285, 2017.

Chua, Y. P., Mastering Research Methods, McGraw-Hill Education, 2010.

Deshwal, D. Sangwan, P. and Dahiya, N., Economic Analysis of Lithium Ion Battery Recycling in India, Wireless Personal Communications, vol. 124, no. 4, pp. 3263–3286, 2022.

Egbue, O. and Long, S., Barriers to widespread adoption of electric vehicles: An analysis of consumer attitudes and perceptions, Energy Policy, vol. 48, pp. 717–729, 2012a.

Egbue, O. and Long, S., Critical issues in the supply chain of lithium for electric vehicle batteries, EMJ - Engineering Management Journal, vol. 24, no. 3, pp. 52–62, 2012b.

Ellingsen, L. A.-W. Hung, C. R. and Strømman, A. H., Identifying key assumptions and differences in life cycle assessment studies of lithium-ion traction batteries with focus on greenhouse gas emissions, Transportation Research Part D: Transport and Environment, vol. 55, pp. 82–90, 2017.

Environmental, K., Research study on reuse and recycling of batteries employed in electric vehicles: The technical, environmental, economic, energy and cost implications of reusing and recycling EV batteries, Energy Api, 2019.

Fujita, T. Chen, H. Wang, K.-T. He, C.-L. Wang, Y.-B. Dodbiba, G. and Wei, Y.-Z., Reduction, reuse and recycle of spent Li-ion batteries for automobiles: A review, International Journal of Minerals, Metallurgy and Materials, vol. 28, no. 2, pp. 179–192, 2021.

Gambatese, J. A. Behm, M. and Rajendran, S., Design's Role in Construction Accident Causality and Prevention: Perspectives from an Expert Panel, Safety Science, vol. 46, pp. 675-691, 2008.

Gahlaut, T. and Dwivedi, G., Policy recommendations to enhance circular economy of LIBs in an emerging economy, Environment Systems and Decisions, vol. 44, no. 2, pp. 398–411, 2024.

Garrido-Hidalgo, C. Ramirez, F.J. Olivares, T. and Roda-Sanchez, L., The adoption of internet of things in a circular supply chain framework for the recovery of WEEE: The case of lithium-ion electric vehicle battery packs, Waste Management, vol. 103, pp.32-44, 2020.

Gu, X. Zhou, L. Huang, H. Shi, X. and Ieromonachou, P., Electric vehicle battery secondary use under government subsidy: A closed-loop supply chain perspective, International Journal of Production Economics, vol. 234, 2021.

Hua, Y. Zhou, S. Huang, Y. Liu, X. Ling, H. Zhou, X. Zhang, C. and Yang, S., Sustainable value chain of retired lithium-ion batteries for electric vehicles, Journal of Power Sources, vol. 478, 2020.

Jones, H. and Twiss, B.L, Forecasting Technology for Planning Decisions, Macmillan, 1978.

Kala, S. and Mishra, A., Battery recycling opportunity and challenges in India, Materials Today: Proceedings, vol. 46, pp. 1543–1556, 2021.

Kampker, A. Wessel, S. Fiedler, F. and Maltoni, F., Battery pack remanufacturing process up to cell level with sorting and repurposing of battery cells, Journal of Remanufacturing, vol. 11, no. 1, 2021.

Koide, R. Murakami, S. and Nansai, K., Prioritising low-risk and high-potential circular economy strategies for decarbonisation: A meta-analysis on consumer-oriented product-service systems, Renewable and Sustainable Energy Reviews, vol. 155, 2022.

Lander, L. Cleaver, T. Rajaeifar, M. A. Nguyen-Tien, V. Elliott, R. J. R. Heidrich, O. Kendrick, E. Edge, J. S. and Offer, G., Financial viability of electric vehicle lithium-ion battery recycling, IScience, vol. 24, no. 7, 2021.

Lohum, India Accelerates Clean Energy Transition with Second-Life Lithium Battery Solutions. LOHUM - Safeguarding Earth's Tomorrow, Today, Available: https://lohum.com/media/news/energy-revolution-india-needs, Accessed on May 30, 2025, 2024.

Li, L. Dababneh, F. and Zhao, J., Cost-effective supply chain for electric vehicle battery remanufacturing, Applied Energy, vol. 226, pp. 277–286, 2018.

Mathur, N. Deng, S. Singh, S. Yih, Y. and Sutherland, J.W., Evaluating the environmental benefits of implementing Industrial Symbiosis to used electric vehicle batteries, Procedia CIRP, vol. 80, pp.661-666, 2019.

Mayyas, A. Steward, D. and Mann, M., The case for recycling: Overview and challenges in the material supply chain for automotive li-ion batteries, Sustainable Materials and Technologies, vol. 19, 2019.

Melin, H. E. Rajaeifar, M. A. Ku, A. Y. Kendall, A. Harper, G. and Heidrich, O., Global implications of the EU battery regulation, Science, vol. 373, no. 6553, pp. 384–387, 2021.

Mohd Jamil, M. R. Siraj, S. Hussin, H. Mat Noh, N. and Sapar, A. A., Pengenalan Asas Kaedah Fuzzy Delphi dalam Penyelidikan Rekabentuk dan Pembangunan, Bangi: Minda Intelek, 2017.

Mohd. Jamil, M. R. Hussin, Z. Mat Noh, N. R. Sapar, A. A. and Alias, N., Applicationof Fuzzy Delphi Method in Educational Research, Design and Developmental Research, 2013.

Mossali, E. Picone, N. Gentilini, L. Rodrìguez, O. Pérez, J. M. and Colledani, M., Lithium-ion batteries towards circular economy: A literature review of opportunities and issues of recycling treatments, Journal of Environmental Management, vol. 264, 2020.

Ortego, A. Calvo, G. Valero, A. Iglesias-Émbil, M. Valero, A. and Villacampa, M., Assessment of strategic raw materials in the automobile sector, Resources, Conservation and Recycling, vol. 161, 2020.

Quinteros-Condoretty, A.R. Laukkanen, M. Kainiemi, L. Pinto, S.M. Lourenço, E.J. Oliveira, L. Albareda, L. and Barbiellini, B., Conceptual model for extending electric vehicle battery lifetime, Resources, Conservation and Recycling, vol. 212, pp. 107943, 2025.

Rajaeifar, M. A. Ghadimi, P. Raugei, M. Wu, Y. and Heidrich, O., Challenges and recent developments in supply and value chains of electric vehicle batteries: A sustainability perspective, Resources, Conservation and Recycling, vol. 180, 2022.

Richa, K. Babbitt, C. W. Gaustad, G. and Wang, X., A future perspective on lithium-ion battery waste flows from electric vehicles, Resources, Conservation and Recycling, vol. 83, pp. 63–76, 2014.

Richter, J. L., A circular economy approach is needed for electric vehicles, Nature Electronics, vol. 5, no. 1, pp. 5–7, 2022.

Sopha, B.M. Purnamasari, D.M. and Ma'mun, S., Barriers and enablers of circular economy implementation for electric-vehicle batteries: from systematic literature review to conceptual framework, Sustainability, vol. 14, no. 10, pp. 6359, 2022.

Sharma, P. Kaur, J. and Katnoria, J. K. Assessment of spatial variations in pollution load of agricultural soil samples of Ludhiana district, Punjab, Environmental Monitoring and Assessment, vol. 195, no. 1, 2023.

Singh, N. K. and Ramani, V. Battery swapping business model: The case of lithion power, Cases on Circular Economy in Practice, 2022.

Standridge, C. R. and Hasan, M. M., Post-vehicle-application lithium–ion battery remanufacturing, repurposing and recycling capacity: Modeling and analysis, Journal of Industrial Engineering and Management, vol. 8, no. 3, pp. 823–839, 2015.

Sullivan, J. L. and Gaines, L., Status of life cycle inventories for batteries, Energy Conversion and Management, vol. 58, pp. 134–148, 2012.

Thompson, D. Hyde, C. Hartley, J. M. Abbott, A. P. Anderson, P. A. and Harper, G. D. J., To shred or not to shred: A comparative techno-economic assessment of lithium ion battery hydrometallurgical recycling retaining value and improving circularity in LIB supply chains. Resources, Conservation and Recycling, vol. 175, 2021.

Tripathy, A. Bhuyan, A. Padhy, R. and Corazza, L., Technological, Organizational, and Environmental Factors Affecting the Adoption of Electric Vehicle Battery Recycling, IEEE Transactions on Engineering Management, 2022.

Vikström, H. Davidsson, S. and Höök, M., Lithium availability and future production outlooks, Applied Energy, vol. 110, pp. 252–266, 2013.

World Economic Forum, A vision for a sustainable battery value chain in 2030 unlocking the full potential to power sustainable development and climate change mitigation, Available: https://www3.weforum.org/docs/WEF_A_Vision_for_a_Sustainable_Battery_Value_Chain_in_2030_Report.pdf, Accessed on May 30, 2025, 2019.

Wrålsen, B. Prieto-Sandoval, V. Mejia-Villa, A. O'Born, R. Hellström, M. and Faessler, B., Circular business models for lithium-ion batteries - Stakeholders, barriers, and drivers, Journal of Cleaner Production, vol. 317, 2021.

Yıldızbaşı, A. Öztürk, C. Yılmaz, İ. and Arıöz, Y., Key Challenges of Lithium-Ion Battery Recycling Process in Circular Economy Environment: Pythagorean Fuzzy AHP Approach, pp. 561–568, 2022.

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