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Closing the Willingness–Infrastructure Gap in End-of-Life EV Battery Management: Stakeholder Evidence and Policy Pathways for Urban Nepal

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Abstract

The rapid electrification of Nepal's transport sector has raised critical concerns about the sustainable management of end-of-life lithium-ion batteries (LIBs). While government incentives have accelerated electric vehicle (EV) adoption, institutional and technological readiness for battery recycling remains insufficient. This study provides a comprehensive, data-driven assessment of EV battery recycling in Nepal, integrating primary survey data (n = 120), stakeholder analysis, and policy evaluation. Quantitative results show moderate awareness but high stakeholder willingness to participate in recycling systems, particularly under Extended Producer Responsibility (EPR) frameworks, while qualitative findings highlight gaps in infrastructure, governance, and technical capacity. To address these challenges, the study proposes a hybrid circular economy model that combines local battery dismantling with regional processing, supported by regulatory reforms and public–private partnerships. The findings contribute to sustainability transition theory in developing economies and offer practical policy recommendations aligned with global best practices.

Keywords: *Electric Vehicles, Lithium-ion Batteries, Recycling, Circular Economy, Nepal, EPR*

1 Introduction

The global transition to electric mobility is a key strategy for addressing climate change and promoting sustainable energy. Nepal, with its abundant hydropower resources, has rapidly adopted electric vehicles (EVs), evidenced by a 188.91% increase in EV imports in the fiscal year 2023/24. This reflects a strong shift in both consumer preference and national policy toward cleaner transportation.

Despite this progress, the sustainability of Nepal's EV transition is critically undermined by the absence of structured systems for managing end-of-life lithium-ion batteries (LIBs). These batteries contain valuable yet hazardous materials such as lithium, cobalt, and nickel, which require specialized recycling processes to prevent environmental contamination and resource loss (Harper et al., 2019) Without appropriate intervention, Nepal risks replicating the environmental challenges associated with unmanaged electronic waste.

This study addresses this critical gap by providing a comprehensive evaluation of EV battery recycling strategies in Nepal, integrating empirical data with global best practices to develop a context-specific framework.

2 Literature Review

2.1 Global Transition to Electric Mobility and Emerging Battery Waste Challenges

The shift toward electric mobility has accelerated over the past decade, driven by global goals for decarbonization, energy security, and improved urban air quality. As reported by the International Energy Agency (IEA, 2023), annual global EV sales have surpassed 10 million units, signaling a major transformation in transportation systems. However, while this transition supports greenhouse gas reduction, it also creates a significant sustainability challenge: the effective management of end-of-life lithium-ion batteries (LIBs).

Lithium-ion batteries, the core energy storage systems in EVs, offer high energy density, efficiency, and a lifespan of about 8–10 years, after which they may be reused or discarded (Gaines, 2018).However, the rapid growth in battery retirements presents serious environmental and economic risks if not managed through proper recycling systems (Harper et al., 2019)

2.2 Environmental and Economic Imperatives of Battery Recycling

Lithium-ion batteries contain critical raw materials such as lithium, cobalt, nickel, and manganese, which are both valuable and environmentally hazardous. Improper disposal can lead to soil contamination, groundwater pollution, and fire hazards due to the reactive nature of battery components.

From an economic perspective, recycling offers significant benefits by recovering high-value materials and reducing dependence on primary mining. As noted in the proposal, recycling can stabilize material supply chains and reduce production costs of EV batteries, thereby improving affordability and accessibility of EV technologies. Furthermore, recycling contributes to resource security, particularly for countries like Nepal that rely entirely on imported battery materials.

The concept of a circular economy is central to this discourse, emphasizing resource efficiency, waste minimization, and material reuse (UNEP, 2022). In the context of EV batteries, circularity involves closing the loop through collection, recycling, and reintegration of recovered materials into production systems.

2.3 Technological Approaches to Lithium-Ion Battery Recycling

Battery recycling technologies have evolved significantly, with four primary approaches identified in the literature:

2.3.1 Pyrometallurgical Recycling

Pyrometallurgical processes involve high-temperature smelting to recover valuable metals such as cobalt and nickel. This method is technologically mature and widely used in industrial applications. However, it is energy-intensive and results in the loss of lighter elements such as lithium and aluminum, reducing overall material recovery efficiency(Gaines, 2018).

2.3.2 Hydrometallurgical Recycling

Hydrometallurgical methods utilize chemical leaching processes to extract metals with higher recovery rates. This approach is more efficient in recovering lithium and other critical materials but requires complex chemical management and generates secondary waste streams.

2.3.3 Mechanical Separation

Mechanical recycling involves dismantling battery packs and separating components through physical processes. While this method is essential as a pre-treatment stage, it cannot independently achieve full material recovery and is typically integrated with other techniques.

2.3.4 Direct Recycling

Direct recycling focuses on preserving cathode materials without breaking them down into elemental form. This method offers significant energy savings and maintains material integrity; however, it remains in the experimental stage and faces scalability challenges (Harper et al., 2019).

A critical insight from the literature is that no single recycling method is universally optimal. Instead, hybrid approaches combining multiple technologies are often required to achieve economic and environmental efficiency.

2.4 Policy Frameworks and Governance Mechanisms

Effective battery recycling systems are strongly influenced by policy frameworks and governance structures. Among these, Extended Producer Responsibility (EPR) has emerged as a dominant model in developed economies. EPR shifts the responsibility for waste management from consumers and governments to producers, incentivizing sustainable product design and lifecycle management (Global Waste Management Outlook 2024).

Countries such as China, Japan, and South Korea have successfully implemented EPR policies, supported by regulatory enforcement and industrial infrastructure. These systems have resulted in higher collection rates, improved recycling efficiency, and reduced environmental risks.

2.5 Battery Recycling in Developing Economies: Structural constraints

The implementation of battery recycling systems in developing countries is constrained by several structural factors:

- Technological limitations: Advanced recycling technologies require significant capital investment and technical expertise.
- Economic barriers: High initial costs and uncertain return on investment discourage private sector participation.
- Institutional fragmentation: Lack of coordination among government agencies hinders policy implementation.
- Informal sector dominance: Recycling activities are often carried out by informal actors with limited environmental safeguards.

Studies from India and China demonstrate that government intervention, public–private partnerships, and regional collaboration are essential for overcoming these barriers.

2.6 Nepal Context: Informal Systems and Emerging Risks

Table 1: Literature Review Synthesis on EV battery Recycling

Author(s) & Year	Study Context	Focus Area	Key Findings	Limitations	Relevance To Nepal
(Global EV Outlook 2023	Global	EV adoption & battery waste	EV sales >10 million annually; future surge in battery waste	Global focus, lacks local context	Highlights urgency for Nepal
Harper et al. (2019)	Global	Battery recycling technologies	Identifies hydrometallurgical, pyrometallurgical, and direct recycling methods	Focus on developed economies	Provides technological baseline
(World Bank. (2020).	Developing countries	Infrastructure gaps	Weak infrastructure limits EV ecosystem sustainability	Broad scope	Matches Nepal's situation
ADB (2021)	South Asia	Sustainable transport	Emphasizes integrated EV infrastructure including recycling	Policy-focused	Aligns with Nepal transition
GIZ Nepal (2020)	Nepal	Clean mobility roadmap	Highlights need for lifecycle battery management	Lacks implementation strategy	Directly relevant
Ali et al. (2025)	China and USA	EV battery recycling	Extended Producer Responsibility (EPR) and advance d recycling technologies improved recycling efficiency.	Focuses on developed countries	Supports EPR and hybrid recycling for Nepal.
(Wesselkämper & von Delft, 2024)	Global	Circular EV battery recycling	Proposed circular business models and efficient battery take back systems to improve recycling	Lacks developing country case studies	Guides design of Nepal's battery collection and circular recycling framework
(Jiang et al., 2025)	China	EV battery recycling	Recycling reduced raw material demand and carbon emissions	Limited to Chinas context	Demonstrate the environmental benefits of battery recycling for nepal.
(Li & Wei, 2025)	Global	EV battery recycling policy	Policy incentives improved recycling efficiency	Focuses on blockchain technology	Supports policy development for Nepal
(Nie et al., 2024)	China	EV battery recycling	Government incentives promoted battery recycling	China specific analysis	Supports incentives-based recycling policies in Nepal.
Khadka et al. (2025)	Nepal	Li-ion battery recycling	Direct recycling was found to be technically and economically feasible.	Focuses on technoeconomic analysis only.	Provides a practical basis for Nepal's battery recycling infrastructure.
Jha et al. (2025)	Nepal	EV adoption	Identified policy and infrastructure barriers.	Excludes battery recycling	Supports the need for battery recycling in Nepal.
Timilsina et al. (2025)	Nepal	EV battery waste management	Identified policy gaps and the need for organized battery collection	No empirical stakeholder analysis	Supports Nepal's battery recycling framework

Nepal's current waste management system is largely characterized by informal practices, particularly in the recycling of lead-acid batteries. These systems involve manual dismantling and basic smelting techniques with limited environmental controls.

However, lithium-ion batteries present fundamentally different challenges:

1. Complex chemical composition requiring advanced processing technologies
2. Safety risks, including fire and explosion hazards
3. Absence of regulatory frameworks for handling and disposal
4. Lack of economic incentives for recycling

As emphasized in the proposal, existing informal systems are inadequate for managing LIBs, creating a significant risk of environmental degradation and resource loss. A review of existing studies on EV battery recycling was conducted to identify the current technologies, challenges, policy frameworks, and research gaps. The literature is presented in Table 1.

2.7 Research Gap and Contribution

Despite extensive global research on EV battery recycling, several gaps remain in the context of Nepal:

- Lack of empirical, data-driven studies
- Absence of stakeholder-based analysis
- Limited evaluation of technology feasibility in local conditions
- No integrated policy–technology framework

This study addresses these gaps by combining primary data, policy analysis, and global best practices to develop a context-specific recycling framework for Nepal.

3 Methodology

3.1 Research Design

This study uses a mixed-methods approach, combining quantitative surveys and qualitative analysis to evaluate EV battery recycling in Nepal. This enables data triangulation, enhancing validity by integrating statistical trends with contextual insights.

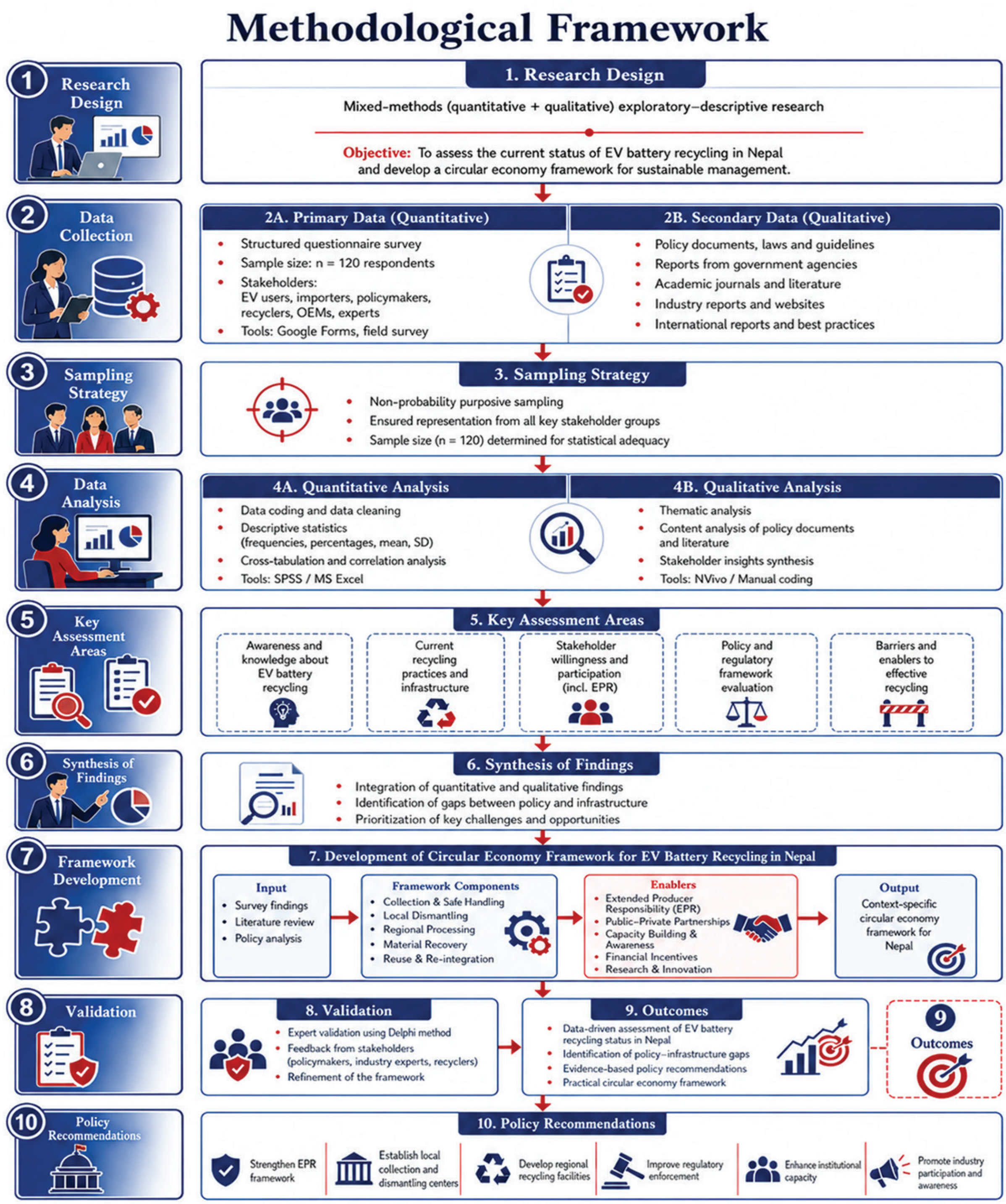

Figure 1: Methodological framework

3.2 Study Area and Context

The study focuses on Kathmandu Valley and Pokhara, key urban centers of EV adoption with high user concentration, infrastructure presence, and emerging e-waste activities.

3.3 Sampling Strategy and Participants

A purposive, stratified sampling techniques was employed to ensure representation from key stakeholders involved in the EV. A total of 120 respondents participated in the study, including EV users (n=50), government and municipal representatives (n=30), importers and distributors (n=20) and recyclers (n=20). This stakeholder-based sampling approach enabled the collection of diverse perspectives on battery recycling awareness, disposal practices, infrastructure readiness, and policy implementation.

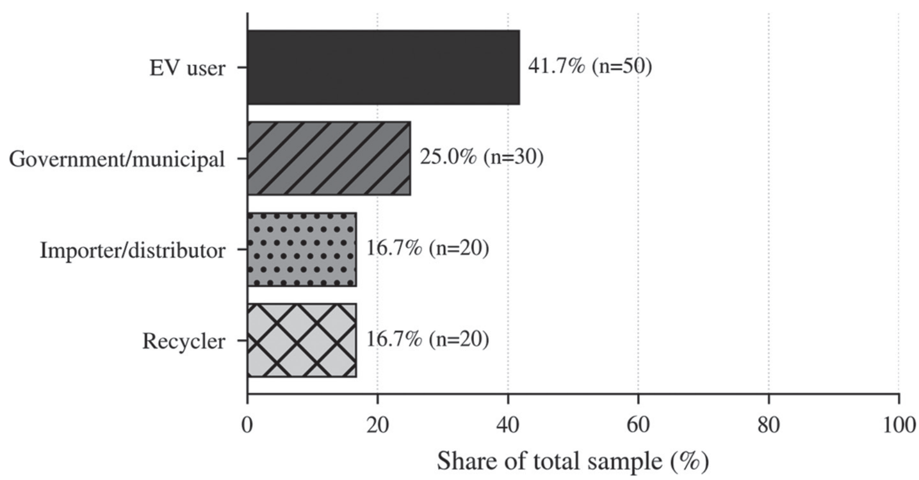

Figure 2: Stakeholder Distribution

As shown in Figure 2, EV users represented the largest proportion of respondents (41.7%), followed by government and municipal representatives (25.0%). Importers/ distributors and recyclers each accounted for 16.7% of the sample. The distribution reflects the relative importance of each stakeholder group within the EV battery value chain and ensure a balanced assessment of technical, regulatory, operational aspects of battery recycling in Nepal.

4 Results and Discussion

The study analyzed responses from 120 stakeholders, including EV users, government officials, importers/ distributors, and recyclers, to evaluate Nepal preparedness for sustainable lithium-ion battery (LIB) recycling. Among them, 50 valid responses from EV users were utilized to analyze EV usage characteristics, battery management awareness, disposal behaviour, and willingness to participate in recycling activities, while responses from all stakeholder groups were used to assess governance and policy readiness.

As shown in Figure 3, electric vehicles accounted for the majority of EV ownership (60%, n=30), followed by two wheelers (22%, n=11) (Fig.3(a)). Most respondents (64%, n=32) used their automobiles for personal transportation, whereas 36% (n=18) used them for business purposes (Fig.3(b)). In terms of ownership time, 48% (n=24) held their EVs for 1-3 years, 24% (n=12) for less than a year, and 28% (n=14) for more than three years (Fig.3(c)). These findings indicates that EV usage in Nepal has only increased in recent years. As a results, a large number of lithium-ion batteries are likely to reach the end of their useful life over the next decade, making it essential to establish effective collection, transportation, and recycling systems before battery waste creation develops dramatically.

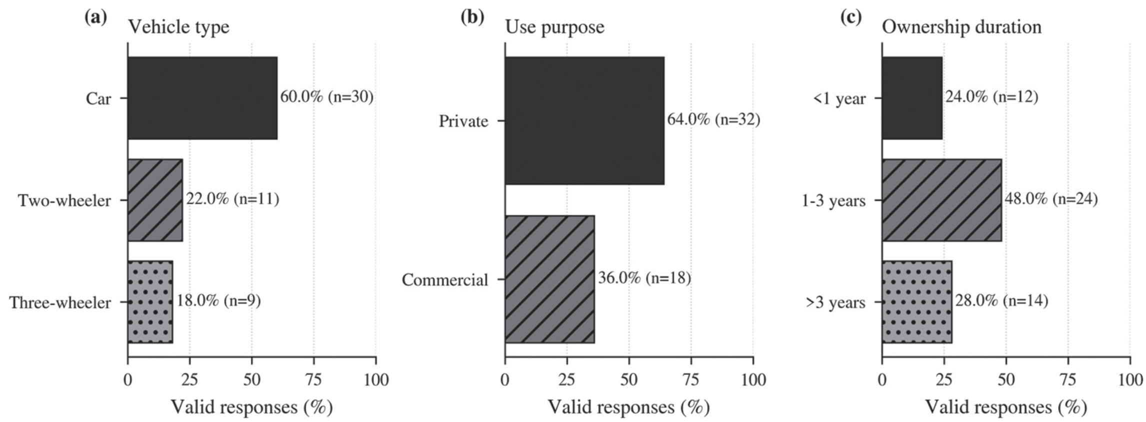

Figure 3: EV user profile. Panel (a) presents EV type, panel (b) presents use purpose, and panel (c) presents ownership duration. Percentages are calculated using valid EV-user responses only (valid n=50)

Despite the growth of EV adoption, understanding of battery lifecycle management remains low. As shown in Figure 4, just 40% of respondents were aware of the estimated lifespan of EV batteries, while 60% had no idea. Similarly, just 46% of respondents recognized the environmental safety dangers associated with incorrect battery disposal, while 54 % were unaware of them. Knowledge of suitable disposal techniques was even more limited, with only 14% of respondents receiving advice on safe battery disposal, while 86% had never received such information. Furthermore, awareness of formal battery collection methods remained low, with only 22% of respondents aware of existing collection routes, 52% unaware and 26% uncertain. These data show that public awareness and information dissemination have not kept up with the growing use of EVs. End of life batteries are more likely to be kept inappropriately or end up informal waste streams if they are not properly handled and disposed of posing environmental and safety issues.

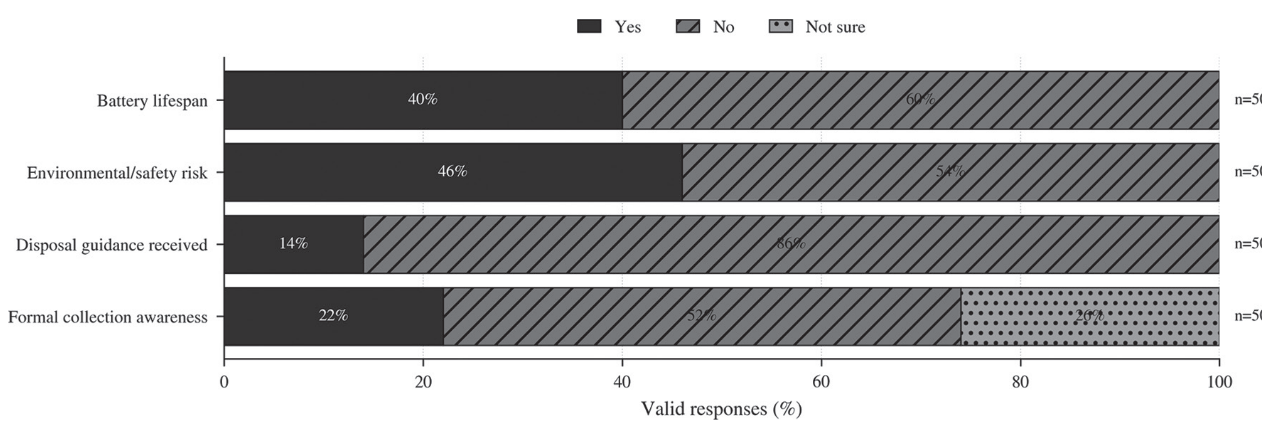

Figure 4: Awareness and information deficit across battery-lifecycle indicators.

The lack of structured battery management system is also reflected in respondents intended disposal behavior, as seen in Figure 5(a). Returning used batteries to dealers was the most favored disposal method (38%, n=19), followed by temporary storage (28%, n=14), while 22% (n=11) were uncertain about how they would dispose of used batteries and just 12% (n=6) expected to sell them as scrap. These data indicate that respondents favor structured disposal techniques but lack access to established collection channels.

However, Fig.5(b) shows a high willingness among stakeholders to participate in formal recycling programs. Approximately 80% of respondents expressed a willingness to return used batteries through organized collection system, with 60% indicating that financial incentives or deposit refund schemes would encourage battery returns. This comparison implies that stakeholder behaviors is not the primary obstacles to battery recycling. Instead, participation is constrained by the lack of formal collection infrastructure, clear disposal pathways, and supportive policy mechanisms. As a result, implementing accessible collection methods and offering economic incentives could significantly enhance battery recovery rates.

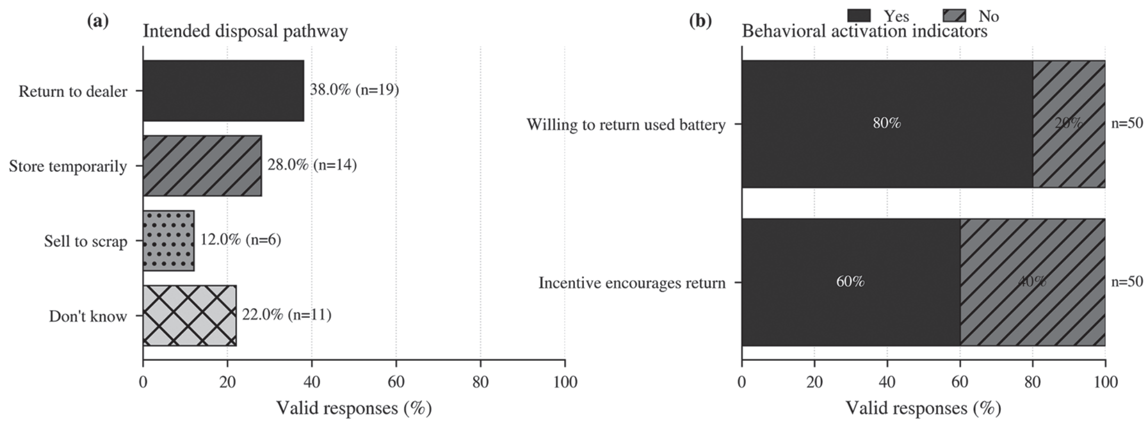

Figure 5: Intended disposal behavior and incentive readiness. Panel (a) shows expected disposal pathways, and panel (b) shows willingness to return used batteries and response to incentives. The visualization indicates that responsible behavior can be activated if formal channels and incentives are available.

The stakeholder perceptions regarding governance and institutional responsibility are presented in Fig.6(a). Government institutions were identified the major actor in managing EV battery recycling, whereas 26% (n=13) preferred a shared responsibility model comprising the government, importers, and consumers. Importers (18%, n=9) and users (14%, n=7) received smaller levels of primary responsibility. These findings show that stakeholders expect strong government leadership while also recognizing that effective battery recycling requires coordination between regulators, industry, and consumers.

The assessment of policy readiness shown in Fig.6(b) supports this observation. Half of the respondents (50%) supported Extended producer Responsibility (EPR), with 60% believing it was a reasonable policy strategy for Nepal. In comparison, only 17% agreed that proper battery recycling policies exist now, while 67% perceived existing regulations as absent or insufficient. This significant gap between stakeholder support for EPR and confidence in the current regulatory framework highlights the urgent need for comprehensive legislation, clearly defined institutional responsibilities, and effective policy implementation. Developing a systematic battery collection and recycling system would require an institutional foundation which would be provided by strengthening regulatory frameworks.

Based on these empirical data, Fig.6(c) provides a hybrid circular economy pathway for managing end of life EV battery management in Nepal. The proposed framework starts with EV use and followed by battery return and collection through dealers or EPR collection points, local sorting and safe storage, reginal processing using advanced recovery technologies, and finally the reintegration of recovered materials into new battery production and other industrial applications. The framework outlines numerous critical enablers, such as EPR laws, deposit- refund procedures, PPP based collection systems, standardized safety protocols, and reginal collaboration for advanced recycling. Considering Nepal current technical and industrial capacity, this hybrid method offers a practical and financially viable path to building a sustainable EV battery recycling system that maximizes resources recovery while minimizing environmental impacts.

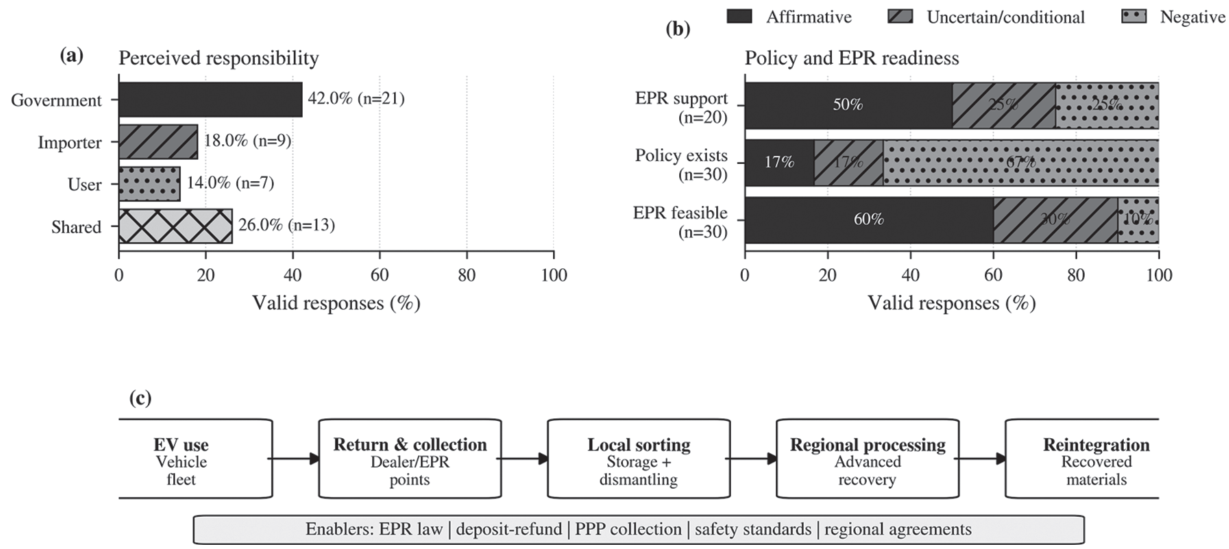

Figure 6: Governance, EPR readiness, and proposed hybrid circular economy pathway. Panel (a) summarizes perceived responsibility, panel (b) summarizes policy/EPR readiness, and panel (c) translates the empirical results into a feasible local-collection/regional-processing architecture for Nepal

Overall, the study found a strong "willingness- infrastructure gap" in Nepal EV battery recycling ecosystem. Although stakeholders are eager to participate in battery return program and generally support EPR based policies, limited awareness, insufficient regulatory frameworks and a lack of formal collection and recycling infrastructure currently impede effective end of life battery management. These Findings indicate that improving EV battery recycling in Nepal necessitates a comprehensive strategy that includes public awareness campaigns, supportive legislations, institutional coordination, financial incentives, investment in collection infrastructure, and regional collaboration for battery processing.addresiing these interconnected difficulties is critical for creating a sustainable circular economy for lithium ion batteries and assuring ecologically responsible management of Nepal's fast increasing EV sector.

5 Conclusion and Policy Framework

This study used a mixed methods approach to assessed Nepal's readiness for sustainable electric vehicles (EV) battery recycling, integrating stakeholder survey, policy assessment, and circular economy principles. The findings show that, while EV use has grown fast, the institutional, technical, and regulatory systems required for end-of-life lithium-ion battery management remain underdeveloped. While respondents had a moderate awareness of battery recycling and disposal practices, they expressed willingness to participate in organized collecting and recycling program, especially when supported by appropriate policy measures such as Extended Producer Responsibility (EPR). However, the absence of dedicated recycling infrastructure, poor institutional coordination, and fragmented regulatory frameworks continue to impede the establishment of a viable battery recycling ecosystem.

Table II summarizes the findings of the study by combining empirical evidence with the present system status, identified gaps, and their policy implications. The analysis clearly shows that although behavioral readiness among stakeholders is high, significant deficiencies remain in infrastructure, governance, institutional coordination, and policy implementation. These interrelated difficulties underline the importance of a complete and coordinated approach, rather than isolated interventions.

Table 2: Integrated Findings Matrix

Dimension	Empirical Evidence (n=120)	System Status	Gap Identified	Implication
Awareness	Moderate, uneven distribution	Partially developed	Information asymmetry	Awareness alone insufficient
Willingness	High across stakeholders	Strong behavioral readiness	Underutilized potential	Policy can activate participation
Infrastructure	Non-existent	Critically weak	Structural absence	Immediate investment required
Policy	Fragmented, unclear	Weak governance	Regulatory vacuum	Need for EPR framework
Institutional Coordination	Low	Disconnected agencies	Governance failure	Central authority required

Based on these findings, a multilevel policy framework is developed to address the identified constraints. Rather than relying on a single intervention, the framework combines regulatory reform, infrastructure development, technological adoption, financial incentives, governance strengthening, and capacity building. Table III summarizes the proposed policy pillars and their implementation strategies.

Table 3: Policy Framework for Sustainable EV Battery Recycling in Nepal

Policy Pillar	Core Problem	Strategic Intervention	Implementation Mechanism	Expected Outcome
Regulatory Framework	No legal structure	Introduce EPR legislation	Mandatory compliance for importers	Formalized recycling system
Infrastructure	No facilities	Collection + storage centers	Public-private partnerships	Safe battery handling
Technology Model	No processing capability	Hybrid model (local+ regional)	Export agreements + local dismantling	Cost-efficient recycling
Economic Incentives	Low investment	Deposit-refund + subsidies	Fiscal policy instruments	Increased participation
Governance	Institutional fragmentation	Central authority	Inter-ministerial coordination	Policy coherence
Capacity Building	Limited expertise	Training + research	Academic-industry collaboration	Technical sustainability

Based on stakeholder feedback and international best practices, this study further proposes a hybrid recycling system tailored to Nepal's current technical and economic capacity. The framework combines local collection, sorting, and temporary storage with regional recycling via established facilities in neighboring countries before recovered materials are reintegrated into battery manufacturing. The proposed system design summary is presented in Table IV.

Table 4: Proposed Hybrid Recycling System

Stage	Activity	Location	Responsibility	Output
Stage 1	Battery use	Nationwide	EV users	Used batteries
Stage 2	Collection	Urban centers	EPR system	Aggregated batteries
Stage 3	Sorting& dismantling	Local facilities	Private operators	Separated components
Stage 4	Advanced recycling	Regional (India/China)	Export partners	Material recovery
Stage 5	Reintegration	Global supply chain	Manufacturers	Recycled materials

The practical feasibility of implementing the proposed framework was also assessed considering Nepal's existing institutional and technical conditions. As shown in Table V, policy readiness and market acceptance are highly favorable due highly favorable due to significant stakeholder willingness, however technical capacity and institutional coordination must be developed gradually through phased investment and capacity building activities.

Table 5: Feasibility Assessment of the Proposed Recycling Framework

Factor	Current Status	Proposed Change	Feasibility Level	Risk
Capital Investment	Low	Moderate (phased)	High	Low
Technical Capacity	Limited	Gradual development	Medium	Medium
Policy Readiness	Weak	EPR introduction	High	Low
Market Response	Positive (high willingness)	Incentivized system	Very High	Low
Institutional Capacity	Fragmented	Central coordination	Medium	Medium

To put circular economy principles into practice in Nepal's EV sector, the suggested framework creates a closed loop battery lifetime that starts with battery use and continues through collection, processing, recycling, and material reintegration. This approach tries to maximize resource recovery wile minimizing the environmental impact of battery waste. Table VI, shows the whole circular economy pathway.

Table 6: Proposed Circular Economy Framework for EV Batteries

Lifecycle Phase	Input	Process	Output	Sustainability Impact
Production	Imported batteries	EV usage	Energy mobility	Reduced emissions
Collection	Used batteries	Reverse logistics	Aggregation	Waste reduction
Processing	Battery components	Dismantling	Separated materials	Resource recovery
Recycling	Processed materials	Metal extraction	Secondary raw materials	Reduced mining
Reintegration	Recovered materials	Manufacturing	New batteries	Circular economy

The study provides several contributions to research and practice. It presents the concept of the policy infrastructure gap, which shows that stakeholder willingness exceeds the availability of supporting recycling systems. Furthermore, it provides one of the first empirical assessment of EV battery recycling preparedness in Nepal and proposes a context specific hybrid recycling framework that integrates policy, technology, and governance. These contributions are presented in Table VII.

Table 7: Research Contributions

Contribution Type	Description	Impact Level
Theoretical	Willingness–Infrastructure Gap concept	High
Methodological	Mixed-method + stakeholder model	Medium
Policy	Context-specific EPR framework	Very High
Practical	Hybrid recycling model	High
Regional	South Asia applicability	Medium

Although the proposed framework offers a practical pathway for Nepal, additional research is required to support large scale implementation. Future research should assess the proposed systems environmental, economic and technological performance using modern analytical tools. The recommended research program is shown in Table VIII.

Table 8: Future Research Directions

Area	Research Need	Method
Environmental Impact	LCA of recycling systems	Simulation
Economic Feasibility	Cost-benefit analysis	Financial modeling
Policy Effectiveness	EPR evaluation	Longitudinal study
Regional Collaboration	Cross-country comparison	Comparative research

Overall, the proposed policy framework shows that sustainable EV battery recycling in Nepal requires coordinated action across regulatory, technological, institutional, and economic dimensions. This study provides a practical roadmap for developing a resilient battery recycling ecosystem that can reduce environmental risks, improve resource efficiency, and support Nepal's long-term transition to sustainable electric mobility.

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Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this manuscript, generative AI and AI-assisted technologies were used only for language editing, grammar correction, paraphrasing, and improving readability. All scientific content, analyses, interpretations, and conclusions were independently developed, verified, and approved by the authors, who take full responsibility for the published work.

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Conflicts of Interest

The authors declare that they have no known competing financial interests, personal relationships, or institutional conflicts that could have appeared to influence the work reported in this paper.

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