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Research Article

Circular Business Model for Vehicle Lead-Acid Batteries in Ethiopia

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Abstract

The increasing generation of end-of-life vehicle lead-acid batteries (LABs) presents significant environmental and resource-management challenges, while also creating opportunities for circular economy (CE) implementation. Although LABs are highly recyclable, circular practices in developing countries remain constrained by economic, institutional, and organizational barriers. This study aims to identify suitable circular strategies for vehicle LABs in Ethiopia, determine the key factors influencing the adoption of circular business models (CBMs), and develop a context-specific CBM for extending battery value and reducing waste. A mixed-method approach was employed, combining expert interviews, thematic analysis, cost-benefit assessment, Grey-Decision-Making Trial and Evaluation Laboratory (Grey-DEMATEL) analysis, and the Circular Business Model Canvas framework. Three circular strategies were identified as particularly relevant to the Ethiopian context: repair for reuse, repurposing, and recycling. Analysis of 23 adoption factors using Grey-DEMATEL identified four critical factors with the greatest influence on CBM adoption: the lack of business models incorporating take-back systems, high costs of handling and processing, inadequate communication and coordination among stakeholders, and insufficient supportive government policies. Based on these findings, a Circular Business Model Canvas was developed to integrate repair, repurposing, and recycling strategies within the vehicle LAB value chain. The proposed model provides a context-specific framework for extending battery service life, recovering material value, reducing waste, and strengthening resource efficiency. The study contributes to the emerging literature on circular business models in developing economies and provides practical insights for policymakers, battery businesses, recyclers, and other stakeholders seeking to establish a more sustainable and circular vehicle battery system in Ethiopia.

Keywords

Circular Strategies, Sustainability, Adoption Factors, Circular Economy, Circular Business Model, Lead-Acid Batteries, Vehicle Batteries, Take-Back Systems

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1. Introduction

1.1. Background

The transition toward sustainable energy and transportation systems is increasing the demand for rechargeable batteries worldwide. Despite the rapid growth of lithium-ion battery technologies, lead-acid batteries (LABs) continue to play an important role in automotive applications because of their relatively low cost, reliability, high power capability, and established manufacturing and recycling infrastructure [1]. Their continued use, however, generates increasing quantities of spent batteries and raises concerns regarding resource recovery, hazardous waste management, and environmental protection. LABs contain valuable materials, particularly lead and plastics, while improper handling can release hazardous substances and contaminate soil, water, and air. Effective management therefore requires approaches that retain product, component, and material value for as long as possible rather than relying solely on conventional end-of-life disposal [2].

The circular economy (CE) provides a framework for achieving this transition by reducing resource consumption and waste generation and keeping products and materials in productive use [3]. Circular business models (CBMs) translate these principles into business practice by creating, delivering, and capturing value while maintaining products, components, and materials within productive cycles [4]. For LABs, circular strategies can be implemented at different levels of the value-retention hierarchy. Repair for reuse can extend battery service life, repurposing can provide second-life applications when batteries are no longer suitable for their original use, and recycling can recover valuable materials from batteries at the end of their useful life [5]. These strategies can complement one another by retaining value at different stages of the battery life cycle.

However, the adoption of circular strategies depends not only on technical feasibility but also on the interactions among organizational, technological, economic, supply-chain, environmental, political, and socio-cultural factors. In particular, ineffective take-back mechanisms can restrict the collection of spent batteries, while high handling, transportation, recovery, and labor costs can reduce economic feasibility. Weak communication and coordination among value-chain actors and inadequate government policies and institutional support can further constrain the development of integrated circular value chains. These challenges are particularly significant in developing countries, where infrastructure, financial resources, institutional capacity, and market coordination may be limited.

Although previous studies have addressed battery recycling and circular economy practices, the literature has given comparatively limited attention to integrated circular business models for vehicle LABs in developing-country contexts, particularly models that consider repair for reuse, repurposing, and recycling together while also examining the factors influencing their adoption. Ethiopia provides a relevant context because increasing vehicle use is accompanied by challenges in the collection, reuse, recovery, and environmentally sound management of spent LABs. At the same time, opportunities exist to develop domestic value chains based on battery repair, second-life applications, and material recovery.

Against this background, this study aims to develop a circular business model for vehicle LABs in Ethiopia. Specifically, the study seeks to: (1) identify suitable circular strategies for extending and recovering the value of vehicle LABs; (2) identify and prioritize factors influencing CBM adoption; and (3) develop a context-specific CBM integrating the identified strategies within the Ethiopian vehicle LAB value chain.

The study makes three main contributions. First, it identifies circular strategies relevant to vehicle LAB management in Ethiopia, focusing on repair for reuse, repurposing, and recycling. Second, it applies Grey-DEMATEL to examine the interrelationships among CBM adoption factors and identify priority factors based on their systemic influence. Third, the findings are translated into a Circular Business Model Canvas that links circular strategies and adoption factors to value creation, delivery, and capture. The resulting framework provides practical insights for policymakers, battery businesses, repair enterprises, recyclers, and other stakeholders seeking to strengthen circularity in the Ethiopian vehicle LAB value chain.

This paper builds on the author's Master's thesis, with substantial rewriting, updating, and reanalysis of the data to present the findings to a broader audience [6].

1.2. Problem Statement

The circular economy for vehicle lead-acid batteries (LABs) in Ethiopia remains at an early stage despite the presence of domestic battery manufacturing and recycling industries. The sector is characterized by low-capacity utilization, limited stakeholder collaboration, insufficient information on battery flows, and economic constraints that hinder the adoption of effective circular strategies. Although substantial quantities of LABs are available in the Ethiopian market, domestic industries utilize only a portion of the available end-of-life battery resources, while significant quantities of battery scrap are exported to neighboring countries.

The sector also relies predominantly on recycling, with limited application of higher-value strategies such as repair for reuse and repurposing. Recycling activities mainly focus on lead recovery, while other potentially valuable materials, including plastics and rubber, receive limited attention. This fragmented approach restricts resource recovery, limits value-creation opportunities, and reduces the competitiveness of domestic LAB industries.

Therefore, an integrated circular business model is needed to identify appropriate value-retention strategies, address the factors constraining their adoption, and improve resource efficiency and value creation across the vehicle LAB value chain in Ethiopia.

1.3. Research Questions

What circular strategies are potential for increasing value retention and supporting the circular economy of vehicle lead-acid batteries?

What are the most influential factors affecting the adoption of CBM for LABs?

How can the identified circular strategies and adoption factors be integrated into a context-specific circular business model for vehicle lead-acid batteries?

1.4. Objectives

1.4.1. General Objective

The general objective of this study is to develop a context-specific circular business model for vehicle lead-acid batteries that enhances value creation, delivery, and capture while promoting resource efficiency, environmental sustainability, and economic viability.

1.4.2. Specific Objectives

To identify potential circular strategies which can create and capture more value in the development of a circular business model.

To identify and prioritize the most influential factors affecting the adoption of circular business models for vehicle lead-acid batteries.

To develop a circular business model that integrates the identified circular strategies and adoption factors for vehicle lead-acid batteries.

1.5. Scope

This study focuses on developing a circular business model for vehicle lead-acid batteries (LABs) in Ethiopia, with emphasis on three circular strategies: repair for reuse, repurposing, and recycling. The industry scope covers one active LAB manufacturing industry and two lead-metal recycling industries in Ethiopia. The study considers the economic, organizational, stakeholder, and institutional factors relevant to implementing these strategies and developing a context-specific circular business model. The findings and recommendations are therefore specific to the Ethiopian vehicle LAB value chain.

2. Literature Review

2.1. Circular Economy and Circular Strategies

The circular economy (CE) is an economic approach that seeks to reduce resource consumption and waste generation by maintaining products, components, and materials in use for as long as possible while minimizing environmental impacts [7, 8]. Unlike the linear “take-make-dispose” model, CE promotes resource efficiency, product longevity, reuse, repair, repurposing, and recycling and requires changes in technologies, value-chain relationships, information systems, and business models [9-11].

Circular strategies differ in their ability to retain product and material value. Repair and reuse generally preserve higher value than recycling, while repurposing enables products or components to serve alternative applications. Recycling is particularly relevant when further product or component use is technically or economically infeasible [12, 22]. For vehicle LABs, this study focuses on repair for reuse, repurposing, and recycling as complementary strategies for retaining value throughout the battery life cycle.

2.2. Circular Economy of Vehicle Lead-Acid Batteries

Vehicle LABs remain widely used because of their durability, reliability, relatively low cost, and established recycling infrastructure [13]. However, spent LABs contain lead, sulfuric acid, plastics, and other materials that require appropriate management because of their environmental risks [13, 14]. These materials also represent valuable secondary resources.

Existing LAB circularity research has focused predominantly on recycling, including battery breaking, separation, metallurgical processing, and recovery of lead and other materials [14-16]. Comparatively less attention has been given to repair and second-life applications, particularly for conventional automotive LABs [17, 18]. Since LABs contain lead alloys, lead paste, polymeric components, and electrolyte [15, 17, 18], circular management should consider opportunities to retain product value before material recovery and to recover multiple material streams at end of life.

Accordingly, an integrated approach combining repair for reuse, repurposing, and recycling can provide sequential pathways for value retention, extending battery service life before final material recovery.

2.3. Circular Business Models for Vehicle Batteries

Circular business models (CBMs) translate CE principles into business practice by enabling organizations to create, deliver, and capture value while retaining products, components, and materials within productive cycles [21]. Relevant approaches for vehicle batteries include product-life-extension models, second-life applications, closed-loop recycling, and take-back systems [18, 19, 21].

Unlike linear business models, CBMs require mechanisms for reverse flows, take-back, service relationships, stakeholder collaboration, and alternative value-capture mechanisms. For LABs, integrating repair for reuse, repurposing, and recycling can create value through extended product use, secondary applications, repair services, and material recovery. However, implementation depends on economic, organizational, technological, institutional, and supply-chain conditions.

2.4. Factors Affecting the Adoption of Circular Business Models

CBM adoption is influenced by multiple interrelated organizational, technological, economic, supply-chain, environmental, political, and socio-cultural factors [20, 23, 24]. The factors identified from the literature and considered in this study are summarized in Table 1. These factors are interdependent. For example, inadequate policy support may constrain investment, infrastructure, and stakeholder coordination, while high recovery costs may reduce competitiveness and the economic feasibility of take-back systems. Therefore, an analytical method capable of examining causal relationships among factors is required.

Table 1. *Identified CBM adoption factors for vehicle batteries: Descriptions, and Literature Sources.*

Category	Adoption factors	Description	Sources
Organizational	Lack of Business model with take-back systems	The absence of a business model that includes potential circular strategies with a system for taking back used batteries	[24-27]
	Perceived financial benefits	The perceived economic advantages associated with adopting a circular business model	
	Design limitations for disassembly capability	The constraints in the design of a product that hinder its ability to be easily disassembled for maintenance, repair, or recycling purposes, and incompatibility between product components manufactured from different companies	
	The capability of human resources	lack of adequate skills, knowledge, and expertise within the workforce to effectively manage and implement circular processes.	
	Lack of industrial ecology and by-product synergy	Integration of battery repairing, remanufacturing, and recycling processes with other industries to maximize resource utilization	
	Lack top management support	This refers to the lack of support from top management for the adoption of a circular economy business model.	
	Poor Company culture	Refers to an organizational environment where there is a lack of emphasis to values and norms that promote and support circularity	
Technological	Battery modularization	The limitation of design allowing batteries to be easily replaced and recycled as modular units.	[24, 28-31]
	Unavailability of efficient technologies	The absence of technologies that enable efficient remanufacturing, recycling and reprocessing of battery components.	
	Limitation on Information digitalization technology	Insufficient Digital systems and tools for managing information related to battery lifecycle and circular processes.	
	Lack Proper status checking, diagnosing, and tracking technology	The absence of technologies that enable accurate monitoring and evaluation of battery conditions and performance	
Economical	High cost of handling, transporting, recovering process, and labor	The financial implications associated with managing the processes of handling, transporting, and recovering batteries.	[2, 5, 8, 21, 29, 32, 33]
	Lack of incentives	The absence of economic incentives to encourage circular practices.	
	Low economic value of EOL VBs	The limited economic worth of vehicle batteries at the end of their life-cycle.	
	Risk on investment	Refers to the financial uncertainties and potential losses associated with investing in circular business models for vehicle batteries.	
	Low Market demand and customer preferences	A low level of market demand for repaired, remanufactured, repurposed and recycled batteries.	
Supply-	Low rate of returned batteries	The limited number of end-of-life batteries being returned for circularity.	[5, 7,

Category	Adoption factors	Description	Sources
chain management	Lack of information sharing of End-of-life process	This refers to the lack of information sharing between different supply chain actors about the EOL process.	33-37]
	Uncertainty in supply (number and quality), price/value of VBs	Unpredictability in the supply of used batteries, including concerns about their quantity, quality, and market value.	
	Lack of effective communication and Supply-chain integration/coordination	Inadequate communication and coordination among stakeholders involved in the battery recycling supply chain.	
	Lack of Competitiveness	The level of competition among battery companies, battery scrap exporters and their ability to sustain circular practices.	
Environmental	Stringent (Strict) regulations	Strict and rigorous rules, laws, or guidelines that are established and enforced by governing bodies to protect and preserve the environment in the process of battery repairing, repurposing, remanufacturing, and recycling.	[24, 30, 38-40]
	Lack of attention for conservation and protection of natural resources	The limited emphasis on preserving and safeguarding natural resources.	
	Difficulties in disposing the wastes from recovered batteries (ENF3)	Challenges in effectively managing and disposing of waste materials generated during the repair, remanufacturing, and recycling of batteries.	
	Inadequate infrastructure	The absence of sufficient infrastructure to support the collection and processing of used batteries.	
Political	Political instability	The political volatility, or uncertainty within a region or country.	[39, 41, 42]
	Lack of Supportive government policies and regulations for circular economy adoption	The limited/absence of Government policies and regulations that promote and support the adoption of circular economy practices.	
	Lack collaboration between public and private sectors to promote circularity (PF3)	The lack of partnerships and collaborations between public and private entities to drive circularity initiatives	
	Absence of international agreements and commitments on circularity	Lack of International agreements and commitments that emphasize sustainability and circularity in the battery industry.	
Socio-cultural	Lack of Customer awareness	Lack of awareness of customers on the importance of battery circular economy practices.	[43, 44]
	Perceived quality of the recycled products	Customers' negative perceptions of the quality and reliability of repaired, repurposed, remanufactured, and recycled battery products	

2.5. Analytical Approach for Identifying Influential Adoption Factors

Several analytical approaches have been used to investigate factors affecting circular business model adoption, including the Analytic Hierarchy Process (AHP), factor analysis, influence diagrams, and DEMATEL-based approaches [29, 33, 18, 45].

The Decision-Making Trial and Evaluation Laboratory (DEMATEL) method is particularly useful for analyzing complex systems in which factors influence one another. It identifies direct and indirect relationships among factors and distinguishes between cause-and-effect groups. Grey-DEMATEL combines DEMATEL with Grey System Theory to address uncertainty and incomplete information in expert judgments [25, 38, 45-49]. This is appropriate for the present study because empirical information on CBM adoption for vehicle LABs in Ethiopia is limited and the relationships among adoption factors involve expert judgment. Accordingly, Grey-DEMATEL is employed to identify and prioritize influential adoption factors.

2.6. Circular Business Model Development Framework

Several tools have been proposed to support circular business-model development, including the Business Model Canvas, Circular Business Model Canvas, Circular Economy Model Toolkit, circular business-model innovation approaches, and Circular Economy Value Chain Mapping [50-55].

The conventional Business Model Canvas provides a structured representation of how an organization creates and captures value through elements such as customer segments, value propositions, channels, customer relationships, key activities, key resources, key partnerships, cost structure, and revenue streams. The Circular Business Model Canvas extends this logic by incorporating circular-economy considerations, including mechanisms for take-back and other elements relevant to circular value creation and recovery [43, 56].

The Circular Business Model Canvas is particularly relevant to the present study because the proposed model must integrate multiple circular strategies and stakeholder relationships rather than address recycling as an isolated technical activity. It provides a structured framework for linking customer segments, value propositions, channels, relationships, key activities, resources, partnerships, costs, revenues, take-back mechanisms, and adoption considerations.

Accordingly, this study combines circular strategy identification, Grey-DEMATEL analysis of adoption factors, and the Circular Business Model Canvas to develop a context-specific CBM for vehicle LABs in Ethiopia.

2.7. Research Gap

The literature demonstrates growing interest in circular business models for vehicle batteries, but several gaps remain. Three main gaps are identified. First, existing LAB circularity research focuses predominantly on recycling, with comparatively limited attention to the integration of repair for reuse, repurposing, and recycling as complementary value-retention strategies [15, 20, 57, 58].

Second, although previous studies have identified numerous factors affecting battery circularity, limited attention has been given to their interrelationships and relative influence, particularly in the context of vehicle LABs in Ethiopia.

Third, existing CBM research has largely focused on lithium-ion batteries and developed-market contexts. Limited evidence exists on adapting the CBMC to vehicle LABs in developing-country settings characterized by different infrastructure, market, policy, and stakeholder conditions.

Therefore, this study addresses these gaps by identifying appropriate circular strategies, determining influential CBM adoption factors using Grey-DEMATEL, and integrating the findings into a context-specific CBM for vehicle LABs in Ethiopia.

3. Research Methodology

3.1. Research Design

This study employed a multi-method research design to identify potential circular economy (CE) strategies, determine factors influencing the adoption of circular business models (CBMs), and develop a context-specific CBM for vehicle lead-acid batteries (LABs) in Ethiopia.

Both secondary and primary data were used. Secondary data characterized the Ethiopian vehicle LAB sector, including battery imports, LAB scrap exports, production capacity and actual production of battery manufacturing and lead-recycling industries, and the number of vehicles in the country. Primary data were collected through semi-structured interviews and expert assessments. Interview data were analyzed thematically to identify potential circular strategies, while expert assessments were analyzed using Grey-DEMATEL to determine the most influential adoption factors. The identified strategies and influential factors were then incorporated into a Circular Business Model Canvas.

3.2. Study Context and Data Sources

The study focused on the Ethiopian vehicle LAB value chain, particularly active battery manufacturing and lead-recycling industries. At the time of the study, the sector included one active vehicle LAB manufacturing industry and one active lead-recycling industry. The selection was based on operational status and direct relevance to the vehicle LAB value chain.

Data were obtained from secondary and primary sources. Secondary sources included academic literature, industry reports, government documents, and development plans. Data on LAB imports and LAB scrap exports were obtained from the Ethiopian Customs Commission; production capacity and actual production data for battery manufacturing and lead-recycling industries were obtained from the Manufacturing Technology and Engineering Industry Research and Development Center; and vehicle data were obtained from the Ministry of Transport and Logistics.

3.3. Literature Review and Identification of Adoption Factors

A structured literature review was conducted to identify research on CE strategies, barriers and enablers, stakeholders, CBMs, adoption factors, and circular business-model frameworks for vehicle batteries. Literature was searched using Scopus, Web of Science, ScienceDirect, IEEE Xplore, SpringerLink, Emerald Insight, JSTOR, and Google Scholar. Search terms included combinations of circular economy, circular business model, lead-acid battery, battery life extension, repair, reuse, repurpose, recycling, adoption factors, and circular value chain.

Relevant studies were screened based on titles, abstracts, and relevance to the research objectives. Factors identified across the literature were extracted, synthesized, and classified into seven categories: organizational, technological, economic, supply-chain management, environmental, political, and socio-cultural factors. The resulting literature-derived factors formed the basis for expert assessment and subsequent Grey-DEMATEL analysis.

3.4. Expert Sampling and Data Collection

3.4.1. Expert Selection

Purposive sampling was used to select participants with relevant knowledge and experience in the vehicle battery sector [58]. A total of 20 experts and managers participated in the study. Participants were drawn from production planning and control, supply-chain management, and marketing and finance functions within the selected battery manufacturing and lead-recycling industries. All participants had more than seven years of professional experience.

This sampling approach was appropriate because the study required informed judgments on circular strategies and the interrelationships among CBM adoption factors.

3.4.2. Semi-Structured Interviews

Semi-structured interviews were conducted with the 20 experts to identify potential circular strategies for vehicle LABs. The interview framework considered five strategies identified from the literature: reuse, repair, repurposing, remanufacturing, and recycling. Experts assessed the relevance, advantages, and limitations of these strategies in the Ethiopian vehicle LAB context. The interview data were analyzed thematically to identify recurring patterns concerning the applicability of the strategies.

3.4.3. Expert Assessment of Adoption Factors

Expert assessment was conducted in two stages. First, the 20 experts evaluated the relevance of the adoption factors identified from the literature. Factors that met the predefined relevance criterion were retained for further analysis. Second, the retained factors were evaluated pairwise to assess the degree of influence of one factor on another, providing the judgments required for Grey-DEMATEL analysis.

Following the expert evaluation, the retained factors were assigned category-based designations, which were then used consistently throughout the Grey-DEMATEL analysis and reporting.

3.5. Data Analysis

Descriptive statistical analysis was used to summarize secondary data on LAB imports, exports of LAB scrap, production capacity and actual production of battery manufacturing and lead-recycling industries, and the number of vehicles in Ethiopia. These data were used to characterize battery-resource availability and domestic industry capacity utilization. Interview data were analyzed thematically to identify potential circular strategies for vehicle LABs through coding, grouping of related findings, development and refinement of themes, and validation of the resulting themes. A cost-benefit analysis was also conducted to assess the economic feasibility of battery repair by comparing repair costs with the associated economic benefits.

3.6. Grey-DEMATEL Analysis

Grey-DEMATEL was employed to identify the interrelationships and influential factors affecting CBM adoption [59]. The method combines Grey System Theory with DEMATEL and is suitable for analyzing interdependent factors under uncertainty and expert judgment. The 23 factors retained after expert relevance assessment were evaluated using a five-level linguistic influence scale ranging from 0 (no influence) to 4 (very high influence), represented by grey numbers Table 2.

Table 1. *Grey linguistic scale.*

Linguistic variable	Influence score	Grey number
No influence	0	{0,0}
Very low influence	1	{0,0.25}
Low influence	2	{0.25,0.5}
High influence	3	{0.5,0.75}
Very high influence	4	{0.75,1}

Expert judgments were aggregated across the six expert groups, and the resulting grey values were normalized and defuzzied to obtain the crisp direct-relation matrix.

The Grey-DEMATEL procedure.

The Grey-DEMATEL procedure consisted of the following steps.

Step 1: Normalization of grey values.

The lower and upper bounds of the aggregated grey relation matrix were normalized to transform the grey values into a comparable scale between 0 and 1. The normalized lower and upper bounds were calculated as:

$$\underline{\underline{x}}_{ij}^{p} = \frac{\underline{x}_{ij}^{p} - min_j(\underline{x}_{ij}^{p})}{\Delta_{min}^{max}} \quad (1)$$

$$\bar{\bar{x}}_{ij}^{p} = \frac{\bar{x}_{ij}^{p} - min_j(\bar{x}_{ij}^{p})}{\Delta_{min}^{max}} \quad (2)$$

where,

$$\Delta_{min}^{max} = max_j(\bar{x}_{ij}^{p}) - min_j(\underline{x}_{ij}^{p}) \quad (3)$$

where $\underline{x}_{ij}^{p}$ and $\bar{x}_{ij}^{p}$ represent the lower and upper bounds, respectively, of the grey value describing the influence of factor on factor for expert group p.

Step 2: Calculation of the normalized crisp value.

The normalized lower and upper grey values were converted into a normalized crisp value using:

$$Y_{ij}^{p} = \frac{\underline{\overline{x}}_{ij}^{p}\left(1-\underline{\overline{x}}_{ij}^{p}\right)+(\bar{\bar{x}}_{ij}^{p}\times\bar{\bar{x}}_{ij}^{p})}{(1-\underline{\overline{x}}_{ij}^{p}+\bar{\bar{x}}_{ij}^{p})} \quad (4)$$

where Y_{ij}^{p} denotes the normalized crisp value representing the influence of factor on factor for expert group p.

Step 3: Calculation of the final crisp value.

The normalized crisp values were subsequently transformed into final crisp values according to the adopted Grey-DEMATEL procedure. The resulting values formed the basis for constructing the direct-relation matrix.

$$Y_{ij}^{p} = min_j\left(\underline{x}_{ij}^{p}\right) + Y_{ij}^{p}\Delta_{min}^{max} \quad (5)$$

Step 4: Construction of the normalized direct-relation matrix.

The final crisp values were arranged into the direct-relation matrix and normalized so that the elements of the resulting matrix N were within the range of 0–1.

$$N = S \times Z \quad (6)$$

A normalization factor S was calculated as:

$$S = min\left[\frac{1}{max_{1\le i\le n}\sum_{i=1}^{n} Z_{ij}}, \frac{1}{max_{1\le i\le n}\sum_{i=1}^{n} Z_{ij}}\right] \quad (7)$$

Step 5: Calculation of the total relation matrix.

The total relation matrix T, which incorporates both direct and indirect relationships among the adoption factors, was calculated as:

$$T = N(I - N)^{-1} \quad (8)$$

where N is the normalized direct-relation matrix and I is the identity matrix.

Step 6: Determination of causal parameters.

The total influence exerted and received by each factor was determined from the row and column sums of the total relation matrix. The row sum D_i represents the total influence exerted by factor i, whereas the column sum R_i represents the total influence received by factor i:

$$D_i = \sum_{j=1}^{n} T_{ij} \quad (9)$$

$$R_i = \sum_{j=1}^{n} T_{ji} \quad (10)$$

where T_{ij} represents the total influence of factor i on factor j, and n is the number of factors.

Step 7: Determination of prominence and net effect.

The overall prominence and net effect of each factor were calculated as:

$$P_i = D_i + R_i \quad (11)$$

$$E_i = D_i - R_i \quad (12)$$

where P_i represents the prominence of factor i within the system and E_i represents its net effect. A positive E_i indicates that the factor belongs to the cause group, whereas a negative E_i indicates that it belongs to the effect group.

Step 8: Determination of the threshold value.

A threshold value α was calculated from the average of all elements in the total relation matrix to distinguish relatively strong relationships from weaker relationships:

$$\alpha = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} T_{ij}}{n^2} \quad (13)$$

Relationships with $T_{ij} > \alpha$ were considered relatively strong and were used to construct the influence network among the adoption factors.

Finally, the factors were ranked according to their prominence values (P_i), while the sign of their net effect (E_i) was used to distinguish between cause and effect groups. Microsoft Excel was used to perform the Grey-DEMATEL calculations.

3.7. Prioritization of Influential Factors

The 23 adoption factors were assessed using prominence ($P_i = D_i + R_i$), and net effect ($E_i = D_i - R_i$). Prominence was used to assess the overall importance and interconnectedness of each factor, while net effect was used to distinguish cause and effect factors. Priority factors were selected based on their high prominence and/or strong causal influence and were subsequently considered in developing the proposed CBM.

3.8. Circular Business Model Development

The Circular Business Model Canvas (CBMC) was used to develop the proposed business model for vehicle LABs. The framework extends the conventional Business Model Canvas by incorporating circular-economy elements [43, 60] and consists of 11 building blocks: value proposition, customer segments, channels, customer relationships, revenue streams, key resources, key activities, key partnerships, cost structure, take-back system, and adoption factors.

The proposed CBM was developed by integrating the circular strategies identified through thematic analysis with the most influential adoption factors identified through Grey-DEMATEL. The framework was used to specify the relationships among customers, value propositions, channels, activities, resources, partnerships, costs, revenues, take-back mechanisms, and adoption conditions within the vehicle LAB value chain.

3.9. Assumptions and Limitations

3.9.1. Assumptions

1) Pricing assumption: Repaired vehicle LABs are assumed to be sold at 50% of the price of an equivalent new battery for the economic assessment.
2) Expert judgment: The identified adoption factors and their relationships are assumed to be adequately represented by the participating experts' judgments.

3.9.2. Limitations

1) Expert dependence: The Grey-DEMATEL results are dependent on expert judgments and may therefore contain some degree of subjectivity.
2) Study context: The study was limited to LAB manufacturer and lead-metal recycling industries in Ethiopia; therefore, the findings may not be directly generalizable to other battery technologies or contexts.

3.10. Validation, Research Quality, and Ethical Considerations

The study used expert judgment to validate the identified circular strategies, adoption factors, and proposed CBM. Experts with more than seven years of relevant experience reviewed the results for relevance, practicality, and consistency with industry conditions. Data collection procedures were standardized using interview guides and expert-assessment instruments, with data validation, cleaning, and secure data handling applied throughout the study. Participation was voluntary, informed consent was obtained, and confidentiality and anonymity were maintained. Respondents were informed of their right to withdraw from the study.

4. Results and Discussion

4.1. Industry Context

The Ethiopian vehicle lead-acid battery (LAB) sector presents considerable potential for circular business-model development. Secondary data show substantial underutilization of existing domestic capacity. The combined annual production capacity of LAB manufacturing and lead-recycling industries was 11.194 million kg, compared with average annual production of approximately 1.572 million kg during 2018–2022, representing an average capacity utilization of 14.03%.

During 2016–2022, Ethiopia imported approximately 30.73 million kg of LABs, while approximately 4.16 million kg of LAB scrap was exported during 2018–2023. Vehicle registrations also increased from 935,888 in 2018 to 1,401,114 in 2022 (Figure 1).

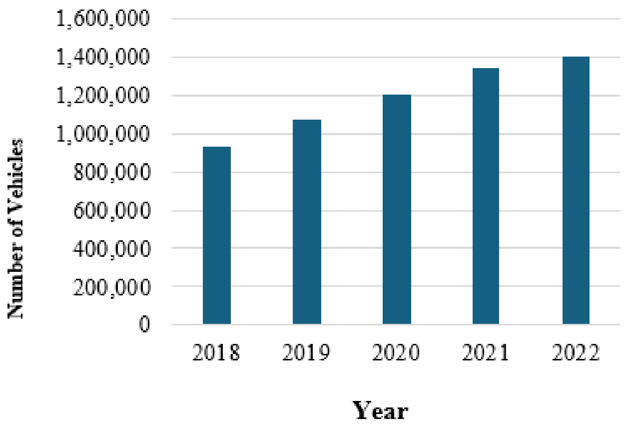

Figure 1. Growth of vehicles registration in Ethiopia.

The combination of increasing vehicle registrations, substantial LAB imports, exported battery scrap, and low domestic capacity utilization indicates an opportunity to retain greater battery-related value within Ethiopia. These conditions support the development of an integrated circular business model based on repair for reuse, repurposing, and recycling.

4.2. Potential Circular Strategies

Based on the literature and interviews with 20 industry experts, five circular strategies—reuse, repair, repurposing, remanufacturing, and recycling—were evaluated for vehicle LABs in Ethiopia. The findings identified repair for reuse, repurposing, and recycling as the most suitable strategies.

Direct reuse without intervention was considered impractical because battery performance deteriorates during use. Therefore, collected batteries should first undergo inspection and diagnosis to determine the appropriate recovery pathway.

4.2.1. Repair for Reuse

Repair for reuse was identified as an important product-life-extension strategy. Expert-identified repair activities included terminal cleaning, vent-cap replacement, electrolyte replacement, plate reconditioning or de-sulfation, reassembly, charging, and performance testing.

The cost benefit analysis conducted in the study further indicates repair-related expenditure was Birr 3,803.86 for a 12 V, 35 Ah battery and Birr 8,454.68 for a 12 V, 100 Ah battery, with estimated profit margins of 22.02% and 53.81%, respectively, under the study assumptions. These results indicate that repair can be economically attractive when the battery can be safely restored at a cost substantially below that of a new battery. However, repair suitability depends on battery condition, diagnostic results, safety, expected performance, repair cost, and customer acceptance.

4.2.2. Repurposing

Repurposing was identified as a suitable pathway for batteries that are no longer appropriate for automotive use but retain sufficient functional capacity. Potential applications include backup power, off-grid energy storage, and UPS systems. Its feasibility depends on remaining capacity, technical condition, safety, conversion requirements, operating costs, and market demand.

4.2.3. Recycling

Recycling provides the downstream recovery pathway for batteries that are unsuitable for repair or repurposing. Because LABs contain valuable materials, particularly lead and plastics, recycling remains economically and environmentally important. The findings therefore support a hierarchy in which recycling is applied when further product or second-life use is no longer technically or economically feasible.

4.3. Integrated Circular Strategy

The findings support an integrated, sequential circular pathway for vehicle LABs, as shown in Figure 2.

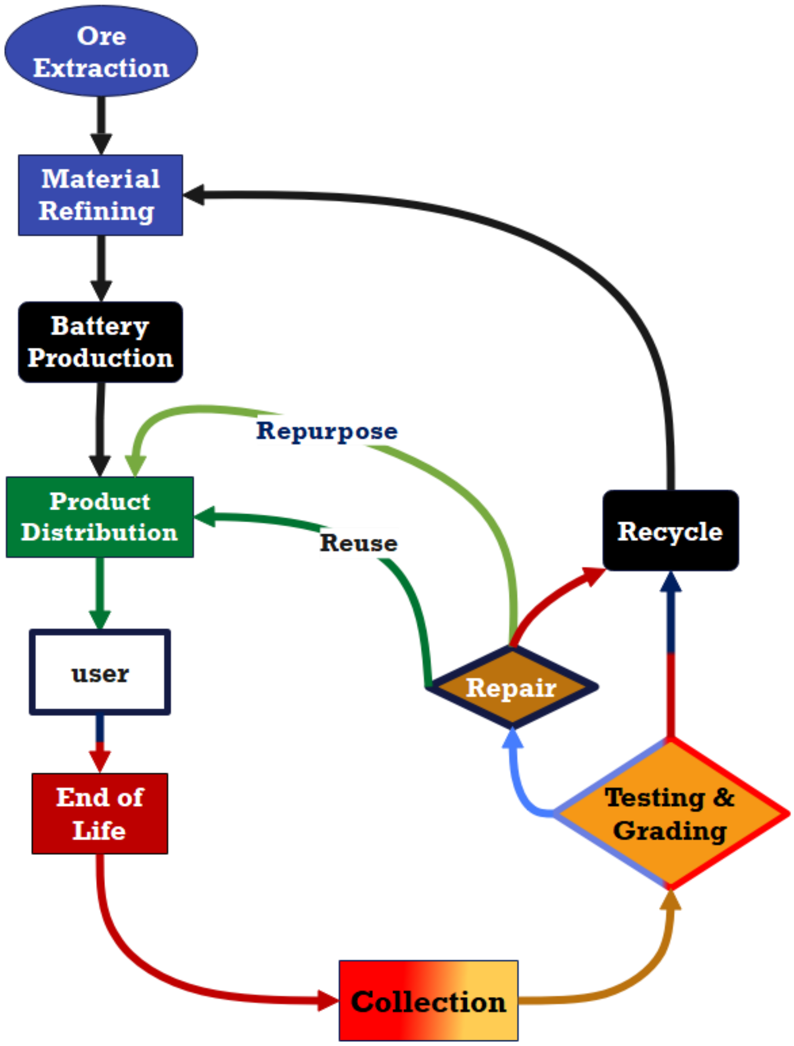

Figure 2. Integrated circular strategy for vehicle lead-acid batteries (source author).

Collected batteries are first inspected and tested. Batteries that can be safely and economically restored are repaired for reuse in automotive applications. Batteries unsuitable for their original application but retaining adequate functional capacity are repurposed for second-life applications. Batteries that cannot be economically or safely reused are directed to recycling for material recovery.

This sequential approach prioritizes value retention: repair for reuse retains product value, repurposing retains value through a second application, and recycling recovers material value when further use is no longer feasible. The integrated strategy can extend battery service life, reduce waste and virgin-material demand, and create additional opportunities for repair, second-life applications, and material recovery.

4.4. Adoption Factors

The literature review identified 31 potential factors affecting CBM adoption for vehicle batteries. These factors were classified into seven categories: organizational, technological, economic, supply-chain management, environmental, political, and socio-cultural.

Twenty experts evaluated these factors using a five-point scale from 0 (irrelevant) to 4 (very highly relevant. Factors with low relevance scores were removed, leaving 23 factors for subsequent Grey-DEMATEL analysis.

The selected factors and their designations are presented in Table 2. The designations were retained throughout the analysis to ensure consistency in the expert assessment, relation matrix, and Grey-DEMATEL results.

Table 2. *Relevant CBM adoption factors identified through expert evaluation.*

Category	Designation	Adoption factor
Organizational	OF1	Lack of business models with take-back systems
	OF2	Design limitations for disassembly
	OF3	Human resource capability
	OF4	Lack of industrial ecology and by-product synergy
	OF5	Poor organizational culture
Technological	TF1	Unavailability of efficient technologies
	TF2	Limitations in information digitalization
	TF3	Lack of proper status-checking, diagnostic, and tracking technologies
Economic	EF1	High cost of handling, transportation, recovery processes, and labor
	EF2	Lack of incentives
	EF3	Low economic value of end-of-life vehicle batteries
	EF4	Low market demand and customer preference
Supply-chain management	SCM1	Uncertainty in supply, including quantity, quality, and battery value
	SCM2	Lack of effective communication and coordination
	SCM3	Lack of competitiveness
Environmental	ENF1	Stringent environmental regulations
	ENF2	Lack of attention to conservation and protection of natural resources
	ENF3	Difficulty in disposing of waste from recovered batteries
Political	PF1	Political instability
	PF2	Lack of supportive government policies and regulations for circular economy adoption
	PF3	Lack of public–private collaboration to promote circularity
Socio-cultural	SF1	Lack of customer awareness
	SF2	Perceived quality of recycled products

The identified factors indicate that CBM adoption is multidimensional, involving organizational, technological, economic, supply-chain, environmental, political, and socio-cultural conditions. The interdependence among these factors necessitated the use of Grey-DEMATEL to determine their relative influence and causal relationships.

4.5. Grey-DEMATEL Results

Grey-DEMATEL was applied to the 23 adoption factors retained after expert evaluation. The aggregated expert judgments were converted into crisp values and used to construct the total relation matrix.

A threshold value of α = 0.144 was obtained from the total relation matrix. Relationships exceeding this value were considered relatively strong and used to construct the cause–effect network (Figure 3). The results demonstrate substantial interrelationships among the organizational, technological, economic, supply-chain, environmental, political, and socio-cultural factors affecting CBM adoption.

The row sums (D_i) and column sums (R_i) were used to calculate prominence ($D_i + R_i$) and net effect ($D_i - R_i$). Prominence represents the overall importance and interaction of a factor, whereas net effect identifies its causal position. Positive values indicate cause factors, while negative values indicate effect factors.

As shown in Table 3, lack of business models with take-back systems (OF1) had the highest prominence, followed by high cost of handling, transportation, recovery processes, and labor (EF1), lack of competitiveness (SCM3), and lack of public–private collaboration to promote circularity (PF3). Regarding causal influence, lack of supportive government policies and regulations for circular economy adoption (PF2) recorded the highest net effect, followed by human resource capability (OF3), lack of proper status-checking, diagnostic, and tracking technologies (TF3), and lack of competitiveness (SCM3). These results indicate that both highly interconnected factors and strong causal drivers are important in shaping CBM adoption.

Table 3. Prominence and Net Effect Results.

Factors	D_i	R_i	$D_i + R_i$	$D_i - R_i$	Percentage $(D_i + R_i)$	Cumulative percentage
Lack of business models with take-back systems (OF1)	4.162	4.095	8.258	0.067	5.41	5.41
High cost of handling, transportation, recovery processes & labor (EF1)	4.079	3.698	7.777	0.380	5.10	10.51
Lack of competitiveness (SCM3)	4.285	3.369	7.653	0.916	5.01	15.52
Lack of public–private collaboration to promote circularity (PF3)	3.929	3.683	7.612	0.246	4.99	20.51
Lack of industrial ecology and by-product synergy (OF4)	3.533	3.900	7.434	-0.367	4.87	25.38
Low economic value of end-of-life vehicle batteries (EF3)	3.140	4.072	7.212	-0.932	4.72	30.10
Lack of effective communication and coordination (SCM2)	3.467	3.460	6.927	0.008	4.54	34.64
Lack of proper status-checking, diagnostic & tracking technologies (TF3)	3.957	2.963	6.919	0.994	4.53	39.17
Uncertainty in supply, including quantity, quality, and battery value (SCM1)	3.283	3.632	6.915	-0.349	4.53	43.71
Design limitations for disassembly (OF2)	3.496	3.250	6.746	0.246	4.42	48.13
Unavailability of efficient technologies (TF1)	3.483	3.152	6.635	0.332	4.35	52.47
Stringent environmental regulations (ENF1)	3.064	3.541	6.605	-0.477	4.33	56.80
Lack of incentives (EF2)	2.880	3.608	6.489	-0.728	4.25	61.05
Low market demand and customer preference (EF4)	3.012	3.356	6.369	-0.344	4.17	65.22
Difficulty in disposing of waste from recovered batteries (ENF3)	2.619	3.735	6.355	-1.116	4.16	69.39
Perceived quality of recycled products (SF2)	2.795	3.443	6.238	-0.648	4.09	73.47
Political instability (PF1)	2.585	3.635	6.220	-1.050	4.08	77.55
Lack of supportive government policies and regulations for circular economy adoption (PF2)	3.944	2.108	6.052	1.836	3.97	81.51
Human resource capability (OF3)	3.492	2.371	5.863	1.121	3.84	85.36
Lack of customer awareness (SF1)	2.654	3.180	5.834	-0.525	3.82	89.18
Poor organizational culture (OF5)	3.175	2.617	5.792	0.557	3.79	92.97
Lack of attention to conservation and protection of natural resources (ENF2)	2.767	2.834	5.600	-0.067	3.67	96.64

Factors	D_i	R_i	$D_i + R_i$	$D_i - R_i$	Percentage $(D_i + R_i)$	Cumulative percentage
Limitations in information digitalization (TF2)	2.513	2.611	5.124	-0.098	3.36	100.00
Total			152.630	0.000		
Average			6.636	0.000		
Maximum			8.258	1.836		
Minimum			5.124	-1.116		
Standard-Deviation			3.134	2.952		

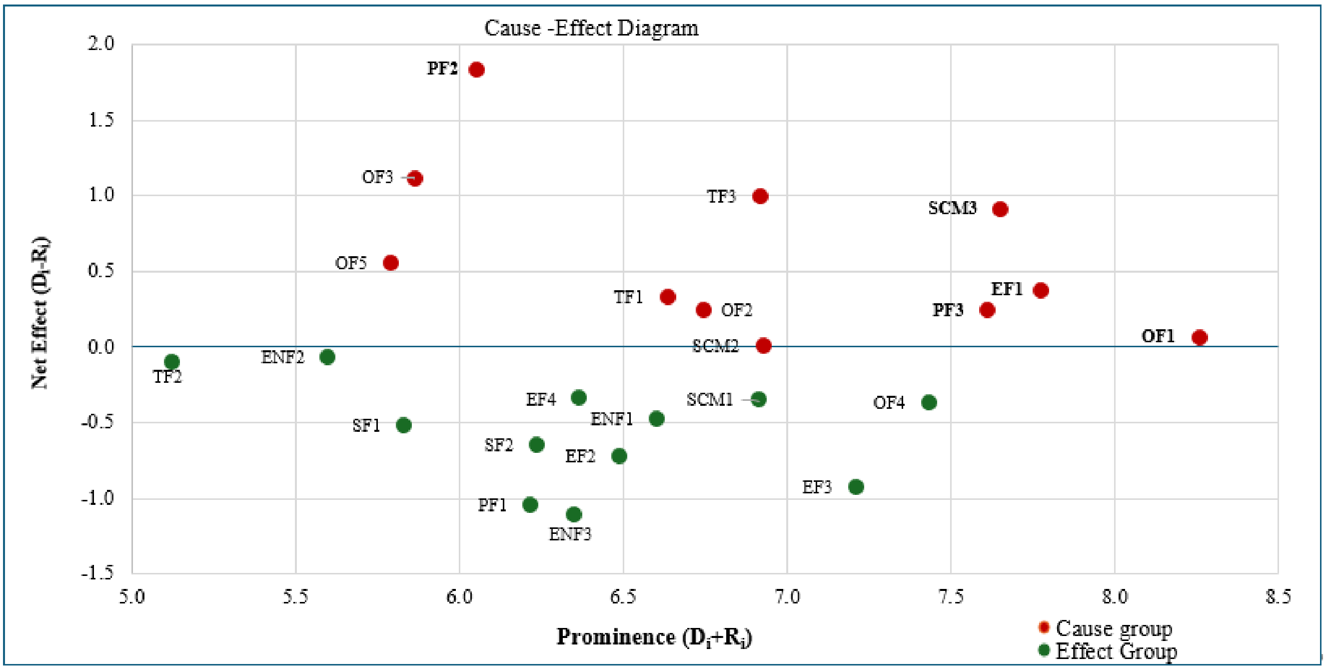

Figure 3. *Grey DEMATEL Cause-Effect Diagram.*

4.6. Priority Factors

Based on their prominence and causal influence, five factors were identified as priorities for CBM development: OF1, EF1, SCM3, PF3, and PF2 (Table 4). OF1 had the highest prominence, while PF2 had the strongest causal influence. SCM3 combined high prominence with a strong positive net effect.

Together, these five factors highlight five critical dimensions of CBM adoption: take-back business models, economic feasibility, competitiveness, public–private collaboration, and government policy support. They therefore provide the primary basis for developing and evaluating the proposed circular business models for vehicle LABs in Ethiopia.

Table 4. *Priority factors and their interpretation.*

Priority factor	Prominence	Net effect	Interpretation
Lack of business model with take-back systems (OF1)	8.257	+0.067	Highest prominence; highly interconnected with other adoption factors.
High cost of handling, transporting, recovering processes, and labor (EF1)	7.777	+0.381	High prominence; constrains the economic feasibility of circular operations.

Priority factor	Prominence	Net effect	Interpretation
Lack of competitiveness (SCM3)	7.654	+0.916	High prominence and strong causal influence on the adoption system.
Lack of collaboration between public and private sectors to promote circularity (PF3)	7.612	+0.246	High prominence; emphasizes the need for public–private coordination.
Lack of supportive government policies and regulations for circular economy adoption (PF2)	6.052	+1.836	Highest causal influence; a major enabling condition for CBM adoption.

Lack of business models with take-back systems (OF1) had the highest prominence (8.257), indicating that it is the most highly interconnected factor in the CBM adoption system. The absence of an organized mechanism for collecting used batteries is a major constraint on circularity.

Repair, repurposing, and recycling all depend on the availability of used batteries at appropriate locations and in suitable conditions. Without an effective take-back mechanism, batteries may remain with customers, enter informal collection channels, or leave the formal domestic value chain. Therefore, an effective take-back system should be incorporated as a central component of the proposed CBMs.

High cost of handling, transporting, recovering processes, and labor (EF1) had the second-highest prominence (7.777). These costs directly affect the economic feasibility of collection, repair, repurposing, and recycling activities.

The finding is consistent with the repair cost-benefit analysis, which indicates that repair can be economically viable under appropriate cost and market conditions. Improving collection efficiency, reducing transportation distances, increasing process efficiency, and utilizing existing infrastructure could therefore improve the economic feasibility of circular operations.

Lack of competitiveness (SCM3) had a high prominence of 7.654 and a positive net effect of +0.916, indicating that it is both highly interconnected and a significant causal driver within the CBM adoption system.

Limited competitiveness can weaken the ability of circular businesses to compete with conventional battery supply and disposal practices. Strengthening operational efficiency, reducing costs, improving product quality, and utilizing existing infrastructure can enhance the competitiveness of repair, repurposing, and recycling activities. Consequently, competitiveness should be considered when designing viable CBMs for vehicle LABs.

Lack of collaboration between public and private sectors to promote circularity (PF3) had a prominence value of 7.612, placing it among the most interconnected adoption factors. This indicates that effective CBM implementation requires coordination between government institutions and private-sector actors.

Public–private collaboration can support the development of collection systems, enforcement of appropriate standards and regulations, access to infrastructure, information sharing, and investment in circular activities. Strengthening such collaboration can therefore facilitate the implementation and scaling of circular business models for vehicle LABs.

Lack of supportive government policies and regulations for circular economy adoption (PF2) recorded the highest net effect (+1.836) among all 23 factors. Although its prominence (6.052) was lower than that of several other priority factors, its strongly positive net effect indicates that it is the strongest causal driver of the adoption-factor system.

This finding highlights the importance of an enabling policy and regulatory environment for CBM implementation. Appropriate policies can support take-back systems, establish responsibilities for battery collection and recovery, encourage investment in circular activities, and strengthen coordination among relevant stakeholders. Government policy and regulatory support should therefore be treated as a key enabling condition for the transition toward circular management of vehicle LABs.

4.7. Proposed Circular Business Model

Based on the identified circular strategies and priority adoption factors, a circular business model for vehicle LABs was developed using the Circular Business Model Canvas (CBMC).

The proposed model integrates repair for reuse, repurposing, and recycling into a coordinated circular value chain. Its central logic is to retain battery value at the highest technically and economically feasible level before proceeding to the next recovery pathway.

Table 5 presents the proposed circular business model for vehicle lead-acid batteries in Ethiopia, integrating repair, repurposing, and recycling strategies within a common circular value chain. The model incorporates a take-back system to facilitate the collection of end-of-life batteries and links key stakeholders, resources, activities, customer segments, value propositions, channels, partnerships, cost structures, and revenue streams.

Table-5. Proposed Circular Business Model for Vehicle Lead-Acid Batteries.

Building Block	Repair	Repurpose	Recycle
Value Propositions	• Repaired LABs with a minimum price • Cost-effective and efficient battery repair services, • Extend the life of lead acid batteries, • Save customers money • Reduced waste and environmental impact	• Sustainable energy storage for off-grid systems • Cost-effective repurposed batteries as an alternative to new energy storage products. • Reliable backup power	• Recovered valuable materials (lead, plastic, sulfuric acid and hardening agent such as antimony & calcium) • Convenient and affordable way to recycle LABs • New products from recycled LABs
Customer Segments	• Vehicle owners (Individual consumers) • Auto repair shops. • Resellers and Retailers • Businesses that use lead acid batteries, such as construction companies, Government agencies and fleet managers (operators)	• Off-Grid Power Users • Emergency Services • Education and Research activities • Telecommunications companies • Data center operators • Uninterruptible power supply (UPS) companies • Businesses or Homes that need backup power	• Battery manufacturers, and recyclers, • Companies that use recycled lead, plastic and sulfuric acid in their products • Vehicle owners • Fleet managers
Customer Relationships	• Offer with a satisfaction guarantee • Provide educational resources to customers about lead acid battery and maintenance, • Build trust and loyalty by providing high-quality repairs and excellent customer service • Timely repair services	• Offer with a satisfaction guarantee • Provide technical support to customers on how to install and use repurposed batteries • Build trust and loyalty by providing high-quality repurposed batteries and excellent customer service	• Provide excellent customer service to build trust and loyalty. • Educate customers on the benefits of circular strategies for lead acid batteries recycling. • Compliance with recycling regulations.
Channels	• Direct sales to customers, • Partnerships with vehicle manufacturers and battery retailers • Online market platform	• Business-to-business (B2B) partnerships with renewable energy installers • Workshops and Events • Online and offline retail stores,	• Battery Collection centers • Online platforms to reach customers and promote circular strategies. • Partnerships with battery manufacturers and distributors to collect used batteries.
Key Resources	• Retired lead-acid Batteries • Repairing tools and equipment • Battery replacement parts & materials	• Collection & transportation networks, infrastructure and facilities	• Skilled battery repair technicians • Battery recycling facilities & technology
Key Activities	• Collect retired lead acid batteries • Diagnose and repair lead acid batteries • Test and certify repaired batteries • Deliver repaired batteries to customers • Battery • Battery repair	• Collect retired LABs • Diagnose and repair • Test and certify • Repurpose lead acid batteries • Deliver repurposed batteries to customers	• Collect retired lead acid batteries • Diagnose and recover valuable materials • Quality Control (Test and certify recovered materials) • Deliver recovered materials

Building Block	Repair	Repurpose	Recycle
Key Partnerships	manufacturers • businesses • Local Automotive Repair Shops • Vehicle manufacturers, • Battery retailers • Logistics providers	• Solar Panel Manufacturers • Renewable Energy Installation Companies • Automotive parts suppliers • Battery recycling companies • Waste management companies	• Battery manufacturers • Battery repair businesses • Local Automotive Repair Shops • Environmental Organizations
Cost Structure	• Collection costs, and Labor costs • Cost of replacement battery parts and materials • Cost of tools and equipment	• Operational costs (storage, transportation, marketing, and administrative activities)	• Recycling costs
Revenue Streams	• Repaired Battery sales • Battery repair fees, • Battery replacement fees	• Sale of repurposed batteries • Installation services • Battery maintenance and monitoring services	• Sale of recycled materials (lead, plastic, and sulfuric acid) • Sale of unretired battery parts
	• Funds from environmental organizations and agencies that support circular initiatives		
Take-back system	• Develop partnership for stakeholders: Establish partnership with automotive repair shops, battery manufacturers, battery repair businesses, and battery recycling companies to create a network of convenient collection point. • Offering a variety of return options, (drop-off locations and mobile collection services) • Incentive Programs: Offer customers the option to exchange their old batteries for either repaired or new ones at a discounted price		
Adoption factors	Organizational capabilities ✓ Competent Human Resources with Team Motivation ✓ Robust Organizational Culture ✓ Effective Knowledge Management System ✓ Motivation and Training Initiatives	External factors Technological Factors: ✓ Utilize advanced technologies and stay updated on the latest innovations. ✓ Leverage digital information and data management technologies Political Factors: ✓ Benefit from government policies and regulations that promote the circular economy. Sociocultural Factors: ✓ Tap into the increasing consumer awareness of environmental issues and circular practices. Economic Factors: ✓ Explore government-provided economic incentives and funding opportunities from environmental organizations and agencies supporting circular initiatives.	

5. Conclusion and Recommendation

5.1. Conclusion

This study developed a circular business model (CBM) for vehicle lead-acid batteries (LABs) in Ethiopia by integrating circular strategies, adoption-factor analysis, and business-model design. The study identified repair for reuse, repurposing, and recycling as the most relevant circular strategies for retaining the value of vehicle LABs and reducing end-of-life losses.

The assessment of potential adoption factors initially identified 31 factors, of which 23 factors were retained following expert evaluation. The Grey-DEMATEL analysis demonstrated that these factors are interconnected and that CBM adoption cannot be effectively addressed through isolated interventions. The analysis highlighted differences in both the overall prominence and causal influence of the factors, providing a basis for identifying the conditions requiring greater attention.

Five priority factors were identified: lack of business models with take-back systems (OF1), high cost of handling, transporting, recovering processes, and labor (EF1), lack of competitiveness (SCM3), lack of supportive government policies and regulations for circular economy adoption (PF2), and PF3. These factors indicate that effective circularity requires an organized take-back mechanism, economically viable operations, competitive circular activities, and an enabling institutional environment.

Based on these findings, a CBM integrating repair, repurposing, and recycling was proposed. The model incorporates the collection and take-back of used batteries and links the major activities, resources, stakeholders, customers, value propositions, channels, cost structures, and revenue streams required to retain battery and material value. The proposed model provides a practical framework for transitioning vehicle LAB management from a predominantly linear system toward a more circular value chain in Ethiopia.

5.2. Recommendation

Based on the findings, the following recommendations are proposed:

Establish organized take-back systems involving manufacturers, distributors, service providers, recyclers, and other value-chain actors.

Improve economic viability by increasing collection and transportation efficiency, utilizing existing infrastructure, and recovering both functional and material value.

Strengthen competitiveness through efficient repair, repurposing, and recycling operations and improved quality of recovered products.

Develop supportive policies and regulations covering battery take-back, responsible handling, reuse, repurposing, recycling, and resource recovery.

Strengthen public–private collaboration to support infrastructure, information sharing, investment, and coordinated implementation of circular activities.

6. Future Research Directions

Future studies could evaluate the proposed CBM through pilot implementation and scenario-based analysis, including economic, environmental, and social performance assessment. Further research could also investigate digital traceability technologies, life-cycle assessment of repurposed LABs, and policy and regulatory mechanisms for supporting circular battery value chains.

Abbreviations

CBM	Circular Business Model
CBMC	Circular Business Model Canvas
CE	Circular Economy
DEMATEL	Decision-Making Trial and Evaluation Laboratory
EOL	End-of-Life
LAB	Lead-Acid Battery
LCA	Life Cycle Assessment
VB	Vehicle Battery
OF	Organizational Factor
TF	Technological Factor
EF	Economic Factor
SCM	Supply-Chain Management Factor
ENF	Environmental Factor
PF	Political Factor
SF	Socio-Cultural Factor

Author Contributions

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Delelegn Gizaw Toga: Data curation, Formal Analysis, Investigation, Supervision, Visualization, Writing – review & editing

Seyidu Wohabrebi Abrah: Data Curation, Formal Analysis, Investigation, Supervision, Validation, Visualization

Ermias Tesfaye: Formal Analysis, Investigation, Supervision

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request. Due to confidentiality considerations related to the expert assessments and participating organizations, the underlying individual-level data are not publicly available. Aggregated data and methodological details are provided in the manuscript and its supplementary materials to support transparency and reproducibility.

Conflicts of Interest

The authors declare no conflicts of interest.

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