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Mapping the End-of-Life Electric Motorcycle Battery System in Indonesia: A Multi-Actor Causal Loop Diagram of OEM, Informal, User, and Government Interactions

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ABSTRACT

Indonesia's rapid electric-motorcycle adoption requires circular end-of-life (EoL) battery management to retain material value and reduce environmental risk. In Yogyakarta, unclear return and processing arrangements risk diverting used batteries into informal channels that are economically attractive but often unsafe and poorly traceable. This study develops a stakeholder-informed Causal Loop Diagram (CLD) to map circular pathways for EoL batteries across OEMs, informal workshops, users, and government, and to support a circular battery supply-chain framework. The model integrates market growth, information, service access, incentives, OEM take-back responsibility, informal repair and reuse, and regulation within a single systems perspective. Variables were identified through literature and policy review, refined with AI-assisted reference exploration, and validated through a survey of 98 users, interviews with 8 dealer/OEM representatives and 4 informal actors, and a focus group discussion (FGD) that assessed variable relevance, causal relationships, polarity, and overall CLD structure. The final model comprises 67 variables, 14 reinforcing loops, and 5 balancing loops. It shows that reduced-performance batteries may enter repair, refurbishment, reuse, storage, transfer, or final treatment pathways. Reinforcing dynamics arise from market expansion, informal economic benefits, and convenience, whereas formal incentives, regulation, and risk mitigation generate balancing effects that can redirect flows toward higher-value circular pathways. Key leverage points include accessible formal collection, operational OEM take-back with diagnostic and downstream capacity, and trained informal workshops linked to traceable handover. As a structural model, the CLD does not quantify parameters or simulate outcomes, but provides a basis for future system-dynamics modelling of material recovery, environmental risk, and circular value creation in electric-motorcycle battery supply chains.

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1. Introduction

The accelerated adoption of electric motorcycles in Indonesia is part of the transformation of the transportation system towards cleaner, lower-emission energy (Dababneh et al., 2025; Fathoni et al., 2025; Nuarta & Sukedi, 2024). However, behind these opportunities, new challenges arise at the end of the vehicle batteries' life cycle (Casals et al., 2019; D. Luo, 2021; Nauri et al., 2024; Rammohan et al., 2024). The limited battery life, especially lithium-ion battery waste, has high-risk characteristics (Kumar & F. Rizvi, 2024) and economic value (Fallah & Fitzpatrick, 2024; Slattery et al., 2024). End of life (EoL) batteries not only have the potential to cause environmental impacts if improperly managed in Purnamasari (2023), but also contain valuable materials such as lithium, nickel, and cobalt that can be reused through collection, recovery, and recycling (Fallah & Fitzpatrick, 2024; Habiburrahman et al., 2025). Therefore, EoL battery management is not merely a technical waste issue, but also a crucial part of the sustainability strategy for the electric vehicle supply chain (Purnamasari, 2023).

In practice, the battery waste management system in Indonesia still faces various challenges. One major issue is the dualism between formal and informal channels (Purnamasari, 2023). Formal channels generally involve manufacturers, official distribution networks, licensed waste managers, and the government as regulator in Slattery et al. (2024) Informal channels, on the other hand, are more flexible, closer to users, and often offer faster economic incentives (Habiburrahman et al., 2025; Mehta, 2025). This condition causes the flow of used batteries to move not always towards the safest or most environmentally efficient facilities, but rather following a combination of price, ease of access, and actor habits (Wang et al., 2024). As a result, some batteries are at risk of escaping controlled management systems, thus underutilizing the opportunity for material value recovery and increasing environmental risks (Purnamasari, 2023).

This issue demonstrates that EoL battery management cannot be understood through a partial approach, for example from the perspective of recycling technology or regulation alone. This system is shaped by complex interactions between producers, users, collectors, workshops, the informal sector, and the government, each of which has different interests, incentives, and constraints (Purwani et al., 2025). Therefore, a dynamic systems approach is needed that can capture the cause-and-effect relationships, feedback loops, and leverage points within the battery management system. One relevant tool for this purpose is the Causal Loop Diagram (CLD), which allows researchers to map how one variable influences another and how these relationships form reinforcing or balancing patterns within the system (Anugrah et al., 2025; Kala et al., 2022; Rahmi & Anikusuma, 2026; Yuniarti et al., 2023).

CLD is important because it can explain why policies that appear logical on paper don't necessarily produce the desired changes on the ground. For example, strengthening regulations can increase formal compliance, but if service access is limited or informal sector economic incentives are more attractive, batteries will still tend to flow into less controlled channels. Conversely, interventions that address user perceptions, incentive design, and partnerships with informal actors can encourage batteries to re-enter the formal system (Purnamasari, 2023). Therefore, the CLD is not only useful for understanding the structure of the problem but also for identifying the most effective intervention points in promoting a sustainable, circular supply chain.

Based on these conditions, the research questions in this study are: how the causal relationships structure the EoL system for electric motorcycle batteries in Indonesia, how battery flows move between formal and informal actors, and what factors influence economic profits and environmental impact management within the system. This research also raises further questions regarding the most strategic leverage points for strengthening safe, economically valuable, and circular battery management. The objective of this research is to develop a CLD (Causal Loop Diagram) that comprehensively describes the EoL system for electric motorcycle batteries, highlighting battery flows, profit generation from value recovery, and environmental impact-management mechanisms.

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More specifically, this research aims to identify key variables, map interactions between formal and informal actors, and formulate feedback structures that can explain the dynamics of used battery management in Indonesia. The results are expected to provide a conceptual basis for developing more adaptive policies and management models. The scientific contribution of this research lies in the integration of the CLD approach with a circular supply chain perspective in the context of electric vehicle battery waste management. Theoretically, this research enriches studies of systems thinking and the circular supply chain by placing formal and informal actors within a unified analytical framework. Practically, this research is expected to provide policy recommendations regarding the design of battery return flows, strengthening economic incentives, and more effective environmental impact management strategies. Thus, this research contributes not only to the development of knowledge but also to the formulation of relevant solutions for the transition to a more sustainable transportation system.

2. Method

2.1. Research design and study scope

This study used an exploratory systems-thinking design to develop a stakeholder-informed Causal Loop Diagram (CLD) of electric motorcycle battery end-of-life management in the Special Region of Yogyakarta (DIY). The study focused on the causal structure of battery flows among users, OEMs and dealers, formal and informal workshops, collectors, government institutions, and downstream management pathways. The CLD was developed as a conceptual and structural model; it was not designed to estimate numerical parameters, simulate battery stocks and flows, or optimize policy outcomes. Its purpose was to identify the actor roles, causal relationships, feedback mechanisms, and candidate variables required for the subsequent development of a dynamic circular battery supply-chain model.

The stakeholder evidence comprised 98 electric motorcycle users, 8 dealer/OEM representatives, and 4 informal workshop actors in the Special Region of Yogyakarta (DIY). These participants were selected to provide complementary evidence for developing and structurally refining the CLD, rather than to represent the Indonesian electric motorcycle population statistically. User data were collected through a structured questionnaire distributed at charging locations and user communities. The responses provided descriptive evidence on knowledge, perceived costs and benefits, trust in formal actors, return preferences, and willingness to use formal or informal pathways. Dealer/OEM representatives and informal workshop actors were interviewed to clarify after-sales service arrangements, battery-handling practices, repair and refurbishment activities, incentives, and constraints affecting battery flows. Users were selected purposively because they had direct experience of electric motorcycle ownership or battery use, while dealer/OEM representatives and informal workshops were recruited through convenience-based access, availability, and consent. The survey and interviews were used to contextualize and refine the CLD; they were not used for statistical generalization or estimation of causal coefficients.

2.2. Data Collection Procedures

This study used an exploratory systems-thinking procedure to develop a conceptual CLD of electric motorcycle battery end-of-life management (Fig. 1). The procedure integrated documentary evidence, stakeholder inputs, and FGD-based structural review to identify causal relationships, formal–informal battery-flow pathways, and leverage mechanisms within the emerging circular supply chain. Candidate variables were first extracted from scientific literature, policy documents, technical reports, news, and other relevant sources. AI-assisted reference exploration was then used only to identify recurring keywords, organize related concepts, and suggest candidate terms; AI outputs were not treated as evidence and did not determine variable selection, causal polarity, loop classification, or policy recommendations. All candidate variables and relationships were checked manually against original sources, stakeholder interviews, and observations. Variables were retained when they represented distinct and contextually relevant concepts supported by available evidence; redundant or weakly supported variables were merged, revised, or excluded.

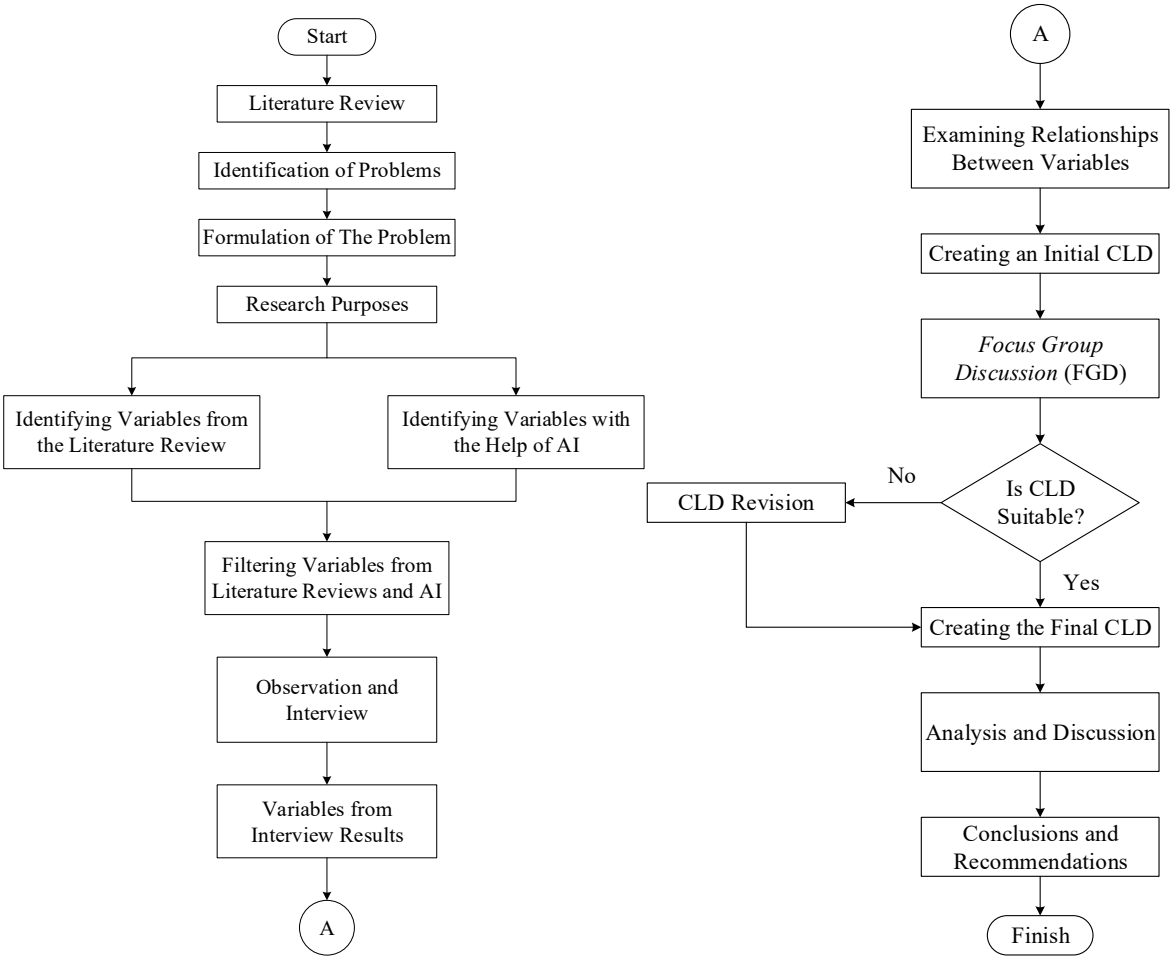


Fig. 1. Research Flow

The final variable set is presented in Table 1, while the causal links and initial loop structures are summarized in Table 2. Variables were represented as nodes and causal relationships as positive or negative arrows in the initial CLD. Positive links indicate that two variables change in the same direction, whereas negative links indicate opposite directional change. The relationships were subsequently organized into reinforcing and balancing feedback loops.

The initial CLD was reviewed through an FGD involving OEMs, dealers, informal workshops, users, provincial and city environmental agencies, academics, and researchers. Participants received an explanatory leaflet, the initial CLD, and structured feedback forms to review variable relevance, actor roles, causal direction, polarity, and loop plausibility. Oral and written feedback was triangulated with documentary evidence, interviews, and field observations. The review refined several variables and links, including the treatment of batteries returned to OEMs, the use of "potential environmental damage" instead of deterministic environmental damage, the addition of regulatory considerations and OEM responsibility, and the representation of pathways to interest in formal management, informal repair and reuse, collectors, storage, or final disposal. This process also helped ensure that the CLD reflected the diverse perspectives of stakeholders and the practical conditions influencing end-of-life battery management. The revisions improved the consistency of the system structure and strengthened the contextual relevance of the identified feedback mechanisms. The final CLD therefore represents stakeholder-informed structural and contextual refinement, rather than numerical parameter validation.

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Table 1. Final Variables of the Electric Motorcycle Battery Waste Management System

No	Variable	Operational definition	Primary actor
1	Electric motorcycle sales volume	Number of new electric motorcycles sold in a given period	OEM/dealer
2	Population	Total population in the study area	Government
3	Number of electric motorcycle users	Number of individuals or households using electric motorcycles	User
4	Electric motorcycle one-time purchase preference	Share of consumers who prefer to buy the motorcycle and battery together rather than separating battery acquisition	User
5	Battery rental and swapping scheme	Extent to which batteries are provided through rental or swapping arrangements rather than full ownership by users	OEM/dealer
6	OEM control over battery circulation	Degree to which OEMs or operators retain ownership and control of batteries throughout their life cycle	OEM/dealer
7	EoL batteries returned to OEM/dealer channels	Quantity or proportion of end-of-life batteries returned by users, workshops, or collectors to OEM or authorized dealer channels	OEM/dealer, user, informal
8	EoL batteries returned to consumers after assessment	Quantity of EoL batteries given back to users after diagnostic or safety assessment	OEM/dealer, user
9	EoL batteries transferred to collectors or scrap dealers	Quantity of EoL batteries sold or handed over to informal collectors or scrap dealers	User, informal
10	EoL battery storage	Quantity of EoL batteries held in storage by users, workshops, dealers, or recyclers before further processing	User, OEM/dealer, informal
11	EoL battery storage by workshops	Quantity of EoL batteries stored by informal or formal repair workshops	Informal
12	EoL battery requiring assessment	Quantity of batteries that have exited primary vehicle use and require technical or safety assessment	OEM/dealer, informal
13	Beyond the warranty period	Share of EoL batteries that are no longer covered by manufacturer warranty	OEM/dealer, user
14	EoL battery successfully repaired	Number of EoL batteries restored to functional condition through repair or refurbishment	OEM/dealer, informal
15	Informal repair and refurbishment activity	Repair and refurbishment of EoL batteries conducted by informal workshops or technicians	Informal
16	Informal reuse activity	Reuse of EoL batteries or battery modules through informal channels	Informal
17	EoL battery recycling activity	Extent of recycling operations applied to non-recoverable EoL batteries	Formal, informal
18	Capacity of engineering and technology	Technical and technological capacity available for EoL battery assessment, repair, and recycling	OEM/dealer, government
19	Investments in equipment and technology	Financial investments in tools, machinery, and facilities for EoL battery management	OEM/dealer, government
20	OEM responsibility for EoL battery take-back	Extent to which OEMs are formally or informally responsible for collecting and managing EoL batteries	OEM/dealer, government
21	EoL batteries successfully recovered	Number of EoL batteries that are successfully repaired, refurbished, or otherwise recovered for further use	OEM/dealer, informal
22	Non-recoverable EoL batteries	Number of EoL batteries that cannot be restored through repair or refurbishment	OEM/dealer, informal
23	Recovered batteries suitable for reuse	Number of recovered batteries or modules deemed technically suitable for reuse or second-life applications	OEM/dealer, informal
24	Recovered batteries not suitable for reuse	Number of recovered batteries or modules deemed unsuitable for reuse and directed to recycling or disposal	OEM/dealer, informal
25	EoL batteries successfully reused	Number of EoL batteries or modules that are actually reused in vehicles or second-life applications	User, informal
26	EoL batteries that could not be reused	Number of EoL batteries that were intended for reuse but ultimately not reused	User, informal
27	Battery management skills	Level of technical skills among technicians and operators for handling EoL batteries safely and effectively	Informal, OEM/dealer

No	Variable	Operational definition	Primary actor
28	Consumer education on EoL battery environmental impacts	Extent of educational interventions aimed at improving consumer understanding of EoL battery environmental risks	Government, OEM/dealer
29	Government subsidy	Financial subsidies provided by government for electric motorcycles, batteries, or EoL battery management	Government
30	Promotion	Marketing and promotional activities related to electric motorcycles and EoL battery management services	OEM/dealer
31	Environmentally conscious consumers	Share of consumers who consider environmental impacts in their purchase and disposal decisions	User
32	Battery and electric motorcycle information	Availability and clarity of information provided to consumers about batteries and EoL management options	OEM/dealer
33	Consumer perception of EoL battery return options	Consumer attitudes and beliefs regarding returning EoL batteries to formal or informal channels	User
34	Interest in formal EoL battery management	Degree of consumer willingness to use formal channels for EoL battery return or management	User
35	Consumer knowledge about electric motorcycles	Level of consumer understanding of electric motorcycle technology and operation	User
36	Perception of high prices	Consumer perception that formal EoL battery management or repair services are too expensive	User
37	Corporate image	Public perception of OEMs' reputation and trustworthiness in managing batteries and environmental responsibilities	OEM/dealer
38	Consumer trust in OEMs	Degree of consumer confidence in OEMs' commitments and practices regarding battery management	User
39	Consumer benefit from EoL battery management options	Perceived economic or functional benefits to consumers from available EoL battery management options	User
40	Benefits of the formal economy	Perceived advantages of using formal channels for EoL battery management (safety, warranty, compliance)	OEM/dealer, government
41	Benefit of the informal sector	Perceived advantages of using informal channels for EoL battery management (price, convenience, accessibility)	Informal, user
42	Collector purchase price for EoL batteries	Price paid by collectors or scrap dealers for EoL batteries	Informal
43	Consumer repair-service price	Price paid by consumers for battery repair or refurbishment services	User, informal
44	Formal EoL battery flow quantity	Quantity of EoL batteries flowing through formal collection, repair, reuse, or recycling channels	OEM/dealer, formal
45	Informal EoL battery flow quantity	Quantity of EoL batteries flowing through informal workshops, collectors, or scrap dealers	Informal
46	Access to informal management facilities	Ease with which users and workshops can access informal EoL battery management services	User, informal
47	The high cost of managing formal channels	Perceived or actual high operational costs of formal EoL battery management	OEM/dealer, government
48	Preference for informal channels	Degree of user or workshop preference for informal over formal EoL battery management options	User, informal
49	Promotion of EoL battery return services	Marketing efforts specifically aimed at encouraging EoL battery return to formal channels	OEM/dealer, government
50	Incentives provided by formal operators to consumers	Financial or non-financial incentives offered to encourage formal EoL battery return	OEM/dealer
51	Consumer understanding of EoL battery impacts	Level of consumer comprehension of environmental and safety impacts of EoL batteries	User

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No	Variable	Operational definition	Primary actor
52	Public awareness campaign on EoL battery impacts	Government or public campaigns raising awareness about EoL battery environmental risks	Government
53	Access to formal recycling sites	Ease with which EoL batteries can be delivered to formal recycling facilities	OEM/dealer, government
54	Formal EoL battery collection and processing activity	Extent of formal activities for collecting and processing EoL batteries	OEM/dealer, formal
55	Formal service quality	Perceived or measured quality of formal EoL battery management services	OEM/dealer, user
56	Availability of formal service facilities	Number and geographic distribution of formal facilities for EoL battery management	OEM/dealer, government
57	Other products produced	Secondary products or materials generated from EoL battery processing (e.g., recycled materials, second-life applications)	OEM/dealer, informal
58	Launch of a new information channel	Introduction of new communication channels to disseminate information about EoL battery management	OEM/dealer, government
59	Opportunities for technicians	Employment or business opportunities created for technicians in EoL battery management	Informal, OEM/dealer
60	Quality of formal EoL battery management	Overall quality and safety performance of formal EoL battery management systems	OEM/dealer, government
61	Consumer benefit from battery rental and swapping	Specific benefits perceived by consumers from battery rental and swapping schemes	User, OEM/dealer
62	Workshop decision to accept and transfer EoL batteries	Decisions by workshops to accept EoL batteries for repair or transfer them to other actors	Informal
63	Dealer decision to receive EoL batteries	Decisions by dealers to accept EoL batteries from users or workshops	OEM/dealer
64	Potential environmental risk from EoL battery mismanagement	Likelihood and severity of environmental harm resulting from improper EoL battery handling or disposal	Government, OEM/dealer
65	Government concern about EoL battery environmental risk	Level of government attention and priority given to EoL battery environmental risks	Government
66	Regulatory oversight of EoL battery management	Extent of government regulation and monitoring of EoL battery collection, processing, and disposal	Government
67	Development of EoL battery management tools	Creation and deployment of tools, systems, or technologies to improve EoL battery management	Government, OEM/dealer

3. Results and Discussion

3.1. Variable Identification

Variable identification combined documentary review, AI-assisted reference exploration using Perplexity and Claude, stakeholder interviews, and field observations. AI was used only to support keyword exploration, concept grouping, and identification of candidate terms; it did not determine variable selection, causal polarity, loop classification, or conclusions. All AI-assisted outputs were reviewed against original sources and stakeholder evidence. The process produced 67 final variables representing market development, user behavior, OEM and dealer responsibility, formal and informal battery-management activities, repair and refurbishment, reuse, incentives, regulation, environmental risk, and value recovery (Table 1).

3.2. Causal Loop Diagram Development

Variables were retained when they represented distinct concepts relevant to electric motorcycle battery end-of-life management and were supported by documentary evidence, stakeholder input, or both. Redundant terms were merged, while variables with weak relevance or insufficient support were removed. The final variable set therefore provides the structural basis for the CLD rather than a set of quantified parameters. In the next modelling stage, selected variables will be translated into measurable stocks, flows, and parameters for a dynamic circular battery supply-chain model.

The 67 variables were connected through causal relationships to develop an initial CLD. Each variable was represented as a node, and each relationship was assigned a polarity based on the

expected direction of change. A positive link indicates that two variables move in the same direction, whereas a negative link indicates that they move in opposite directions. Relationships with conditional or inconsistent evidence were reviewed, reformulated, or excluded. The resulting causal structures were first organized into partial loops, summarized in Table 2, and subsequently integrated into the initial CLD.

Table 2. Variable Mapping Loops in the Battery Waste Management CLD

Code	Loop Name	Circle
R1	Promotion of electric motorcycle sales volume	Population (+) → Number of electric motorcycle users (+) → Promotion (+) → Electric motorcycle sales volume (+) → Formal-channel economic benefits (+) → Promotion
R2	Environmentally conscious consumers	Population (+) → Quantity of electric motorcycle users → Promotion (+) → Environmentally conscious consumers (+) → Electric motorcycle sales volume (+) → Formal channel economic profit (+) → Promotion
B1	Battery and electric motorcycle information	Population (+) → Quantity of electric motorcycle users → Promotion (+) → Battery and electric motorcycle information (+) → Consumer knowledge about electric motorcycles (+) → Perceived of high prices (-) → Electric motorcycle sales volume (+) → Formal-channel economic benefits (+) → Promotion (+)
B2	Government subsidies	Government subsidy (+) → Promotion (+) → Perceived high price (-) → Electric motorcycle sales volume (+) →Formal-channel economic benefits (+) → Promotion
B3	The battery is faulty and successfully repaired	Electric motorcycle sales volume (+) → electric motorcycle outright purchase (+) → Problematic battery (+) → After-sales service (+) → Formal battery-flow quantity (+) → Battery successfully repaired (+) → Battery waste (-) → Corporate image (+) → Consumer confidence in OEMs (+) → Electric motorcycle sales volume
R3	The battery is damaged; then consult the OEM	Electric motorcycle sales volume (+) → Electric motorcycle outright purchase (+) → Problematic battery (+) → After-sales service (+)→ Formal battery-flow quantity (+) →Defective batteries (+) →Defective batteries returned to OEM (+) → Potential environmental risk (+) → Regulatory attention (+) → OEM EoL management performance (+) → Corporate image (+) → Consumer trust in OEM (+) → Electric motorcycle sales volume
R4	Defective battery returned consumer	Electric motorcycle sales volume (+) → Electric motorcycle outright purchase (+) → Problematic battery (+) → After-sales service (+) → Formal battery-flow quantity (+) → Defective battery (+) → Defective battery returned to the consumer (+) → Potential environmental risk (+) → Regulatory considerations (+) → OEM EoL management performance (+) → Corporate image (+) → Consumer confidence in OEMs (+) → Electric motorcycle sales volume
R5	Damaged batteries are given to collectors	Electric motorcycle sales volume (+) → electric motorcycle outright purchase (+) → Problematic battery (+) → After-sales service (+) → Formal battery-flow quantity (+) → Damaged batteries (+) → Problematic batteries transferred to collectors (+) → Potential environmental risk (+) → Regulatory considerations (+) → OEM EoL management performance (+) → Image company (+) → Consumer confidence in OEM (+) → electric motorcycle sales volume
B4	Battery leasing and leakage control	Electric motorcycle sales volume (+) → Battery leasing (+) → Full company control over batteries (+) → Problematic battery (+) → After-sales service (+) → Formal path battery-flow quantity (+) → Successfully repaired batteries (+) → Final battery waste (-) →Corporate image (+) → Consumer trust in OEM (+) → electric motorcycle sales volume
R6	Economic Benefits Consumer	Formal Channel Battery Flow Quantity (+) Formal-channel economic benefits → (+)Incentives Provided by Managers Formal for Consumers → Interest in formal management → (+) Quantity of Formal Battery Flow

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Code	Loop Name	Circle
R7	Consumer Understanding Against Environmental Impact Environment	Formal Channel Battery Flow Quantity (+)→ Formal-channel economic benefits (+)→ Socialization of Related Impacts Battery (+)→ Understanding the Impact of Battery Waste (+)→ Interest in formal management (+)→ Formal Battery Flow Quantity
R8	Access Management at Official	Battery Flow Quantity (+)→Formal Economic Profit (+) → Formal Management Activity (+) → Availability of Formal Service Facilities (+)→ Access to formal management facilities (+) →Consumer Trust Towards OEM (+) → Formal Management Interest (+)→ Formal Battery Flow Quantity
R9	Formal Service Quality	Battery Flow Quantity(+) → Formal Economic Profit (+) → Formal Management Activity (+) → Formal Service Quality (+)→Consumer Trust in General OEM (+)→Interest in Management in General Formal(+)→ Formal(+) → Battery Flow Quantity
R10	Repair activities and improve the benefits of informal channels	Informal channel battery flow quantity (+) → Battery repair and refurbishment activities handled by informal channels (+) → Number of batteries successfully discontinued from repair and refurbishment activities (+) → Line profit; informal (+) → Marketing ideas (+) → Consumer preference for informal services (+) → Informal battery-flow quantity
R11	Benefits for consumers from repair activities and refurbish	Informal channel battery flow quantity (+) → Battery repair and refurbishment activities handled by informal channels (+) → Number of batteries successfully stopped from repair and refurbishment activities (+) → Increased service life (+) → Benefits for consumers (+) → Consumer preference for informal services (+) → Informal battery-flow quantity
R12	Reuse activities increase profits in informal channels	Informal channel battery flow quantity (+) → Battery repair and refurbishment activities handled by informal channels (+) → Number of batteries that successfully stopped repair and refurbishment activities (+) → Remaining cells from repairs and refurbishment that are suitable for reuse (+) → Battery reuse activities handled through informal channels (+) → Total batteries successfully used (+) → Other products produced (+) →Inormal-channel economic benefits (+) → Marketing activity (+) → Consumer preference for informal services (+) → Quantity of informal battery flow
R13	Capacity development in technical and technological areas	Informal channel benefits (+) → Investment in equipment and technology (+) → Technical and technological capacity (+) → Number of batteries that successfully complete repair and refurbish activities (+) → Profit from informal channels
R14	Capacity development for informal sector businesses	Benefits of informal channels (+) → Opening of new informal channel businesses (+) → Job opportunities for technicians (+) → Battery management skills (+) → Quality of informal path battery management (+) → Benefits of informal channels
B5	Environmental-risk control	Potential for environmental damage (+) → Government attention to environmental damage (+) → Supervision and provision of final battery waste management facilities (+) → Creation of final battery waste management facilities (-) → potential environmental damage

Table 2 identifies 14 reinforcing loops and 5 balancing loops. Reinforcing loops amplify an initial change, whereas balancing loops counteract change and stabilize the system. For example, R1 links population growth, the number of electric motorcycle users, promotion, electric motorcycle sales, and formal-channel economic benefits: higher sales strengthen formal-channel economic benefits and promotional activity, which can further increase sales. In contrast, balancing loops reflect mechanisms that limit or redirect system growth, such as information, subsidies, battery leasing, repair outcomes, and environmental control.

Rather than interpreting the loops as isolated chains, they are used in the following discussion to identify leverage mechanisms affecting battery-flow allocation, environmental risk, and recovered economic value. The preliminary loops in Table 2 were integrated into an initial CLD and reviewed

through a stakeholder-informed FGD involving OEMs, dealers, informal workshops, users, provincial and city environmental agencies, academics, and researchers. The review focused on the relevance of variables, actor roles, causal directions, polarity, and the plausibility of the loop structures in the Yogyakarta context. Oral and written feedback, obtained through explanatory materials and structured feedback forms, was triangulated with literature, interviews, observations, and policy documents before the model was revised.

The FGD produced several substantive refinements. Batteries returned to OEMs were no longer assumed to reduce waste automatically, because insufficient storage or downstream treatment capacity may lead to accumulation within the formal system. "Environmental damage" and "environmental pollution" were reformulated as potential environmental damage and environmental-pollution risk to reflect the conditional nature of impacts. The term "problematic battery" was also distinguished from final waste because a battery with reduced performance may still be repaired, refurbished, reused, transferred to collectors, stored, or directed to formal treatment. Regulatory considerations and OEM responsibility were added, battery collection was clarified as part of the management chain, and a link was added between usable residual cells from workshops and collectors. These changes revised selected causal links and loop configurations, resulting in the final CLD shown in Fig. 2.

3.3. Discussion

The final causal loop diagram (CLD) in Fig. 2 contains 67 variables, 14 reinforcing loops, and 5 balancing loops. Its contribution is not the number of loops alone, but its integration of market expansion, user information, formal after-sales services, OEM responsibility, informal repair and reuse, incentives, regulation, and environmental risk in the end-of-life management of electric-motorcycle batteries in Yogyakarta. Stakeholder feedback shows that a battery with reduced performance does not immediately become waste. Depending on battery condition, available facilities, and responsible actors, it may be returned, repaired, refurbished, reused, transferred through collectors, stored, recycled, or finally treated. The CLD therefore shifts the analysis from a linear use–discard model to a circular supply-chain perspective.

Formal and informal channels compete for battery flows, but they may also be complementary when informal workshops are connected to screening, traceability, safe storage, and authorized handover (Purnamasari, 2023). The promotion and information loops show that government and OEM incentives can increase electric-motorcycle adoption, while environmental awareness strengthens consumer interest (Santos et al., 2025). However, market expansion also creates future battery flows. Promotion and subsidies should therefore be linked to information about battery safety, ownership, return locations, and end-of-life responsibilities; otherwise, adoption policies may increase future accumulation in informal or unmanaged channels.

The formal after-sales-service and OEM-responsibility loops demonstrate that returning a battery to an OEM or dealer does not guarantee safe management. Returned batteries may accumulate when dealers lack diagnostic equipment, safe storage, take-back procedures, or links to licensed downstream facilities. OEM responsibility should consequently cover the complete pathway from collection to battery condition assessment, repair, refurbishment, second-life use, recycling, and documented final treatment (Winda & Ardi, 2023). This requirement is particularly important because Indonesia still lacks an optimal electric-vehicle battery-waste system, although the government targets a national recycling industry by 2030 (Aqmarina et al., 2024). Evidence from North America shows that OEMs can decide whether batteries are repaired, reused, converted for energy storage, or recycled, while authorized dealers assess batteries and receive technical safety guidance (Slattery et al., 2024). This supports a recovery hierarchy for Yogyakarta: diagnosis should precede repair, second-life use, recycling, or final treatment. A battery reaching approximately 80% of its initial capacity may still support a second life of 4–9.5 years, depending on the SOH (State of Health) upon retirement from the vehicle (Fallah & Fitzpatrick, 2024). Recycling remains essential because direct-recycling processes can reduce environmental impacts by approximately 54% while recovering materials and restoring performance (Chen et al., 2024; Ji et al., 2023; Jiang et al., 2025; Wesselkämper et al., 2025).

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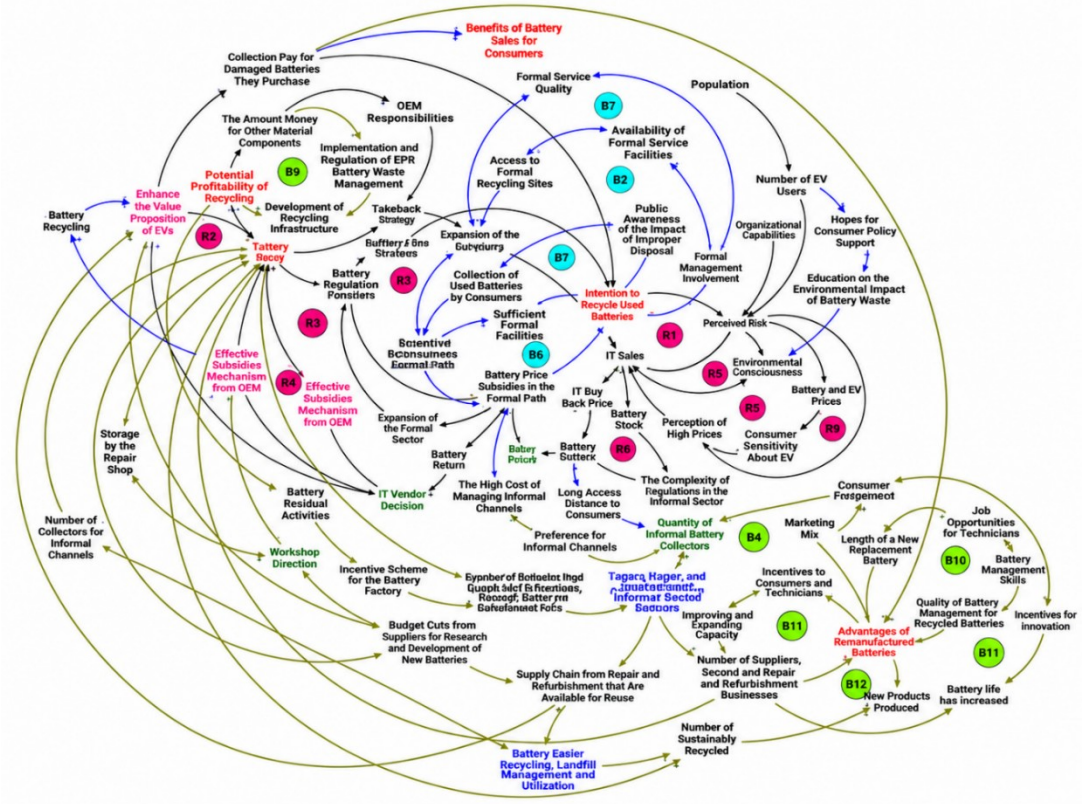


Fig. 2. Causal loop diagram final

The formal–informal balance is shaped by convenience, access, information, and financial returns. Limited facilities and low awareness have encouraged informal flows in Australia (Islam et al., 2022), China (Guo & Huang, 2023; Zuo et al., 2025) and the United States (Elements, 2023). Similar infrastructure limitations have been reported in Australia (Luo et al., 2025), while transparent manufacturer-led management remains limited in Yogyakarta (Purwani et al., 2025). Formal collection is also constrained by weak incentives: (Chemical Abstracts Service, 2024) reported that approximately 25% of electric-vehicle batteries enter formal recycling systems, and (Wei et al., 2022) reported approximately 30% formal recycling in China. Consumers often prefer informal operators because they offer faster, door-to-door, and better-paid services (Guo & Huang, 2023). Consequently, approximately 70% of battery waste in China has been estimated to flow through informal channels (Qin et al., 2022; Zhang & Ayele, 2022), while electric-bicycle battery recycling remains below 60% where formal capacity and policy implementation are weak (Wang et al., 2024). Combined subsidy and education policies can increase formal collection by more than 100% (Chen et al., 2024), and recycling prices and environmental responsibility also influence channel choice (Fan et al., 2022).

Informal workshops should therefore be treated as potential circular-economy entry points, not simply eliminated. NMC and NCA batteries are widely used because of their high energy density (Nurdiawati & Agrawal, 2022), and stakeholder feedback confirms that local workshops already perform repair, upgrades, refurbishment, and reuse. Nevertheless, handling without SOH testing, electrical isolation, fire prevention, personal protective equipment, traceability, and a route for non-recoverable components can cause thermal runaway, fire, injury, and pollution (Santos et al., 2025). The results of interviews and observations indicate that workshops are willing to cooperate but need training, spare parts, clear regulations, final-disposal facilities, and viable incentives. The principal leverage point is therefore gradual integration through registration, technical standards, formal partnerships, and incentives for documented handover.

The environmental-regulatory loop is balancing: increasing potential environmental-pollution risk should stimulate government attention, supervision, and management facilities. Because outcomes depend on storage, repair, transport, reuse, and downstream treatment, the terms "potential environmental damage" and "environmental-pollution risk" are more appropriate than deterministic claims of pollution. End-of-life batteries should be managed within the hazardous-waste framework, supported by clear responsibilities, safe handover, traceability, and authorized facilities (Purnamasari, 2023). Regulation alone will not displace informal channels unless it also addresses their advantages in accessibility and price.

Three leverage points emerge from Fig. 2, accessible formal collection and downstream capacity; operational OEM responsibility from take-back to final treatment; and progressive integration of informal workshops and collectors. Unlike studies that examine formal recycling or informal leakage separately, this CLD connects market decisions, recovery pathways, OEM responsibility, regulation, and environmental risk. Its limitation is that it remains conceptual: it does not quantify decision parameters or predict battery flows. Future studies should validate causal polarities and loop classifications, assign values to incentives, collection distance, service quality, awareness, OEM capacity, diagnostic accuracy, and handover rates, and conduct baseline, sensitivity, and scenario analyses before claiming quantitative outcomes.

The contribution of the final CLD is not merely the identification of 14 reinforcing and 5 balancing loops. Its main contribution is to organize these loops into a structural foundation for an integrated circular battery supply-chain framework. The model connects battery ownership and return decisions, formal after-sales services, informal repair and reuse, collector-mediated recovery, OEM responsibility, regulatory response, and environmental-risk management. By incorporating stakeholder feedback, the final structure distinguishes problematic batteries from final waste and recognizes that a battery may pass through several recovery pathways before becoming non-recoverable.

The analysis identifies three connected leverage areas. First, formal channels require accessible collection, transparent return procedures, and downstream treatment capacity; otherwise, returned batteries may simply accumulate. Second, OEM responsibility must be linked to take-back, diagnostics, storage, and authorized recovery pathways rather than expressed only as a general obligation. Third, informal workshops should be progressively integrated through training, registration, traceability, and handover incentives, because they already provide repair capacity and local collection access. The CLD does not estimate numerical parameters or forecast outcomes; rather, it provides the causal structure needed for subsequent system-dynamics modelling of battery quantities, environmental risk, and recovered economic value.

3.4. Recommendations

First, the government should clarify OEM and dealer responsibilities for take-back, registration, safe storage, transport, diagnosis, second-life assessment, recycling, and final treatment. End-of-life batteries should be managed consistently with hazardous-waste requirements, and every transfer should be traceable. Second, OEMs and dealers should establish accessible collection points, communicate return procedures clearly, and provide buy-back, trade-in, deposit, or replacement-discount schemes. Incentives should be linked to verified handover, while public information should explain SOH, safety risks, environmental impacts, and return locations. Formal services must be as accessible and practical as informal alternatives. Third, OEM responsibility should extend beyond collection. OEMs should provide diagnostic protocols, safety guidance, storage standards, and documented decisions regarding repair, refurbishment, reuse, recycling, and final treatment. A return system is ineffective if batteries remain stored without a safe downstream destination. Fourth, informal workshops and collectors should be progressively integrated through registration, technical training, basic testing equipment, personal protective equipment, fire-safe storage, record keeping, and incentives for transferring non-recoverable components to authorized facilities. This approach preserves their local accessibility and repair capacity while reducing uncontrolled dismantling and occupational risk.

Finally, stakeholders should establish a Yogyakarta pilot that records batteries sold, returned, repaired, reused, stored, recycled, and transferred to untracked channels. The CLD should then be extended through parameterization, structural and stakeholder validation, baseline simulation, sensitivity analysis, and scenario testing. Because the present model is conceptual and geographically limited to Yogyakarta, its findings should not be generalized without local data and further validation. A safer circular system therefore requires formal accountability and downstream capacity combined with the accessibility and technical contribution of informal actors.

4. Conclusion

This study developed a stakeholder-informed Causal Loop Diagram (CLD) to map the dynamics of end-of-life (EoL) electric-motorcycle battery management in Indonesia, with empirical evidence collected in the Special Region of Yogyakarta (DIY). The final model, comprising 67 variables, 14 reinforcing loops, and 5 balancing loops, shows that EoL battery flows are shaped by reinforcing dynamics linked to market expansion, informal economic benefits, and convenience, as well as balancing dynamics driven by formal incentives, regulatory oversight, and environmental-risk mitigation. The theoretical contribution lies in integrating formal and informal actors within a single CLD of the EoL battery supply chain in an emerging-economy context, thereby extending circular supply-chain and system-dynamics literature beyond formal, technology-centric perspectives. Practically, the findings support clearer Extended Producer Responsibility (EPR) schemes, operational OEM take-back with diagnostic capacity, and gradual integration of trained informal workshops into traceable handover arrangements. However, the empirical evidence was collected exclusively in Yogyakarta, and the CLD is conceptual rather than quantitative, limiting statistical generalizability and predictive capability. Future research should validate and extend this model across regions and develop a full system-dynamics simulation to test policy scenarios for their effects on battery flows, environmental risk, and recovered value.

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