

# Development of an Eco-Friendly and Cost-Effective Hydrometallurgical Process for Recycling Lithium-Ion Batteries from End-of-Life Laptops in Ethiopia

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**Abstract:** This study develops a comprehensive implementation framework for establishing lithium-ion battery (LIB) recycling infrastructure in Ethiopia, addressing critical gaps between policy ambitions and operational reality in a rapidly digitalizing economy with 770,123.68 kg of laptop battery imports in 2024. Through integrated systems analysis, policy assessment, economic modeling, and stakeholder mapping, we identify implementation barriers and propose context-specific solutions within Ethiopia's emerging circular economy framework. Our methodology combines qualitative and quantitative approaches, including 32 stakeholder interviews, regulatory gap analysis, discounted cash flow modeling, and scenario planning. Results indicate that a hybrid implementation model—combining decentralized collection with centralized processing—offers optimal viability, requiring ETB 35–45 million in capital investment with potential annual recovery of metals valued at ETB 18.2 million. The framework incorporates regulatory amendments, innovative financing mechanisms, capacity development strategies, and monitoring systems aligned with Ethiopia's Climate-Resilient Green Economy strategy. This research provides essential foundations for practical implementation while contributing to global scholarship on circular economy transition in developing economies, offering a replicable model adaptable to similar contexts across Africa and beyond.

**Keywords:** Battery recycling policy, circular economy implementation, e-waste management systems, lithium-ion battery lifecycle, systems analysis, sustainable materials management

## 1. Introduction

Ethiopia's accelerated digital transformation has precipitated an unprecedented influx of electronic devices, with laptop battery imports surging from 25,405 kg in 2020 to 770,123 kg in 2024—a thirty-fold increase within four years (ERCA, 2024). This technological proliferation, while advancing educational access and economic productivity, has generated a corresponding electronic waste stream that threatens to undermine environmental sustainability and public health. Current end-of-life management for lithium-ion batteries remains predominantly informal, characterized by rudimentary dismantling practices that release toxic electrolytes (including LiPF<sub>6</sub> and fluoro-organic compounds) and heavy metals into soil and water systems (Islam et al., 2022). The absence of formal recycling infrastructure represents not only an environmental liability but also a significant economic opportunity cost, as valuable metals—particularly cobalt, lithium, and nickel—are lost rather than recovered for domestic industrial use or export.

Globally, the imperative for sustainable battery management has intensified with the transition toward electric mobility and renewable energy storage, creating sophisticated recycling ecosystems in industrialized economies. However, these models frequently prove inappropriate for developing contexts like Ethiopia, where capital constraints, regulatory enforcement limitations, infrastructure gaps, and distinctive market characteristics necessitate tailored approaches (Kumar et al., 2023). Ethiopia's existing policy framework, anchored by the Solid Waste Management Proclamation No. 513/2007 and the Climate-Resilient Green Economy (CRGE) strategy, provides foundational principles but lacks specific implementation mechanisms for battery recycling. This study addresses the critical implementation deficit by developing a comprehensive, contextually adapted framework that bridges policy aspirations with practical realization. This research contributes to multiple domains of scholarship and practice. Theoretically, it advances understanding of circular economy implementation in resource-constrained environments, particularly regarding the interplay between formal and informal sectors. Methodologically, it demonstrates the value of integrated multi-method approaches for complex sustainability transitions. Practically, it provides actionable guidance for Ethiopian policymakers, businesses, and civil society seeking to transform e-waste challenges into economic opportunities while protecting environmental and public health. By establishing the policy, economic, and systems foundations for battery recycling, this study creates essential preconditions for subsequent technical research on process optimization and material recovery methodologies.

## 2. Literature Review

### 2.1 Global Battery Recycling Landscape and Implementation Challenges

The global lithium-ion battery recycling sector has evolved rapidly, driven by increasing environmental consciousness, resource security concerns, and regulatory mandates. Mature recycling ecosystems in Europe, North America, and East Asia employ sophisticated technologies including pyrometallurgical smelting, hydrometallurgical leaching, and direct recycling approaches (Baars et al., 2021). However, implementation in developing economies faces distinctive challenges that extend beyond technological transfer to encompass institutional, economic, and social dimensions.

Economic analyses reveal significant scale dependencies, with conventional recycling models requiring substantial capital investment (typically USD 15-25 million for moderate-scale facilities) and high throughput volumes to achieve viability (Harper et al., 2019). These requirements frequently exceed the financial and technical capacities of developing economies, necessitating alternative approaches. Recent research on "frugal innovation" in recycling technologies suggests promising directions, including modular designs, lower-temperature processes, and localized reagent sourcing (Tura et al., 2021). The economic sensitivity of recycling operations to metal price volatility represents an additional challenge, particularly for cobalt-dependent processes, highlighting the importance of flexible business models and risk mitigation strategies (Sommer et al., 2023).

### 2.2 Policy Implementation in Developing Economy Contexts

The implementation of environmental regulations in developing economies frequently encounters what scholars term the "implementation gap"—the disparity between policy formulation and operationalization (Howlett et al., 2020). This gap stems from multiple factors including ambiguous regulatory language, insufficient enforcement capacity, misaligned stakeholder incentives, and limited monitoring systems. In the specific context of e-waste management, additional challenges emerge from the predominance of informal sector activities, consumer behavior patterns, and complex international supply chains (Wang et al., 2022).

Comparative policy analysis reveals diverse approaches to addressing these challenges. Extended Producer Responsibility (EPR) frameworks, widely adopted in developed economies, have shown mixed results in developing contexts where producer accountability mechanisms are weaker (Gupt & Sahay, 2023). Alternative approaches emphasizing community-based collection systems, informal sector integration, and public-private partnerships demonstrate promise but require careful adaptation to local conditions (Oteng-Ababio et al., 2021). The literature increasingly emphasizes polycentric governance models that engage multiple stakeholders across different scales, recognizing the limitations of purely top-down regulatory approaches in complex implementation environments (Morrison et al., 2022).

### 2.3 African E-waste Management Experiences

African experiences with e-waste management provide particularly relevant insights for Ethiopia's context. Ghana's well-documented e-waste sector illustrates both the potential for local value addition and the severe environmental and health consequences of inadequate controls (Amankwaa et al., 2022). Nigeria's evolving regulatory framework demonstrates the challenges of transitioning from informal dominance to formal management systems (Nnorom & Odeyingbo, 2020). Rwanda's ambitious e-waste policies highlight the importance of political commitment and international partnerships, though implementation challenges persist (Mureithi & Wafula, 2023).

These African case studies collectively underscore several critical success factors: (1) alignment with existing waste management systems rather than parallel structures, (2) gradual formalization of informal sector participants with appropriate support mechanisms, (3) realistic implementation timelines that accommodate capacity development, and (4) integration with broader economic development objectives including job creation and industrial diversification (Schluep et al., 2021). Ethiopia's distinctive characteristics—including its growing manufacturing sector, ambitious green economy agenda, and specific institutional landscape—necessitate careful adaptation rather than direct replication of these experiences.

### 2.4 Circular Economy Transitions in Emerging Economies

The conceptual framework of circular economy provides valuable perspectives for battery recycling implementation, emphasizing system-level transformations rather than isolated technological solutions. Recent scholarship on circular economy implementation in emerging economies highlights the importance of context-specific approaches that consider local material flows, institutional arrangements, and economic structures (Schröder et al., 2020). Particularly relevant is research on "circular economy ecosystems" that engage multiple stakeholders across value chains, recognizing that successful implementation requires coordinated action beyond individual businesses or sectors (Konietzko et al., 2020). The social dimensions of circular transitions receive increasing attention, with scholars emphasizing just transition principles that address potential displacement effects, skill development needs, and equitable benefit distribution (Moreau et al., 2023). These considerations are particularly pertinent for battery recycling, where informal sector workers currently engaged in rudimentary dismantling require pathways to safer, more productive employment within formal systems. Research on social entrepreneurship and community-based resource management offers promising models for inclusive circular economy implementation (Ddiba et al., 2022).

### 3. Methodology

#### 3.1 Research Design and Conceptual Framework

This study employs an integrated mixed-methods research design situated within a systems thinking paradigm. The methodological approach recognizes that successful recycling implementation requires understanding and addressing interconnected technical, economic, social, and institutional dimensions. The research framework builds upon the Multi-Level Perspective on sustainability transitions (Geels, 2019), which conceptualizes system change as the interaction between niche innovations, existing regimes, and broader landscape developments.

The specific analytical framework adapts the Institutional Analysis and Development (IAD) framework (Ostrom, 2011) to the context of battery recycling in Ethiopia. This framework facilitates systematic examination of how institutional arrangements (rules, norms, strategies), physical and material conditions (battery volumes, infrastructure, technologies), and community attributes (stakeholder networks, knowledge systems) interact to shape collective action outcomes. By applying this framework, we identify specific leverage points where targeted interventions can catalyze system transformation toward circular economy objectives.

#### 3.2 Data Collection Methods and Procedures

##### 3.2.1 Qualitative Data Collection

Primary qualitative data collection encompassed three complementary approaches. First, semi-structured interviews were conducted with 32 purposively selected stakeholders representing diverse sectors and perspectives. Participants included senior officials from four government agencies, representatives from eight private sector entities (electronics importers, retailers, repair businesses, potential investors), leaders from five civil society organizations (NGOs, consumer associations, community groups), and academics from three institutions. Interviews followed a standardized protocol with flexibility for domain-specific probing, with sessions lasting 45-120 minutes and conducted between September 2025 and November 2025.

Second, document analysis encompassed multiple categories: (1) policy and regulatory documents (Solid Waste Management Proclamation No. 513/2007, associated regulations, CRGE strategy documents, sectoral policies), (2) trade and economic data (ERCA import statistics 2017-2024, customs declarations, market analyses), (3) industry reports and assessments (electronics market studies, waste management evaluations, feasibility studies), and (4) international case studies and best practice documentation. This analysis employed both systematic content analysis for qualitative documents and statistical analysis for quantitative data, with particular attention to identifying implementation gaps between policy aspirations and operational realities.

Third, observational research at existing e-waste handling locations provided grounded understanding of current practices. Observations focused on operational processes, material flows, safety practices, economic exchanges, and spatial organization, documented through detailed field notes, photographic documentation (where permissible), and informal conversations with workers.

##### 3.2.2 Quantitative Data Collection and Analysis

Quantitative analysis focused on three main areas. First, trade data analysis examined laptop battery import trends from 2017-2024, employing time-series analysis to identify growth patterns and project future volumes. Second, economic modeling utilized discounted cash flow analysis with Monte Carlo simulation to evaluate viability under uncertainty, incorporating probability distributions for key variables including metal prices, collection rates, and operational costs. Third, spatial analysis of waste generation and collection potential employed geographic information systems (GIS) to map distribution patterns and evaluate logistics requirements.

#### 3.3 Analytical Procedures and Integration

##### 3.3.1 Policy and Regulatory Analysis

Policy analysis employed the Comprehensive Policy Implementation Assessment Framework developed by the United Nations Environment Programme (UNEP, 2022), evaluating regulatory provisions across five dimensions: (1) clarity and specificity of requirements, (2) institutional mandates and capacity allocations, (3) compliance mechanisms and enforcement provisions, (4) monitoring, reporting, and verification systems, and (5) adaptive management and review processes. This systematic assessment identified specific amendments needed to transform existing solid waste management regulations into effective battery recycling governance. Gap analysis compared Ethiopia's framework against international standards including the Basel Convention Technical Guidelines on e-waste and the European Union's Battery Regulation (2023/1542).

##### 3.3.2 Economic Viability Assessment

Economic analysis employed scenario-based discounted cash flow modeling to evaluate three implementation models: (1) centralized industrial-scale facility (1,000+ tons/year capacity), (2) decentralized micro-recycling units (50-100 tons/year each), and (3) hybrid model combining decentralized collection/pre-processing with centralized final processing. Financial projections incorporated capital expenditure estimates based on equipment quotations from international suppliers adjusted for Ethiopian conditions, operational costs derived from local market data, and revenue projections based on London Metal Exchange prices with conservative purity adjustments. Sensitivity analysis identified critical success factors and break-even conditions for each model, while social cost-benefit analysis extended evaluation beyond direct financial returns to encompass environmental and social value creation.

### 3.3.3 Stakeholder and Systems Analysis

Stakeholder analysis employed power-interest mapping techniques combined with social network analysis to identify key actors, relationships, influence patterns, and potential coalitions. This analysis informed recommendations for governance structures, engagement strategies, and partnership models. Systems analysis utilized causal loop diagramming and system dynamics modeling to identify feedback mechanisms, leverage points, and potential unintended consequences within the recycling ecosystem. Scenario planning exercises explored alternative futures under different implementation approaches and external conditions.

### 3.4 Methodological Rigor and Limitations

Methodological rigor was ensured through multiple validation strategies. Interview findings were triangulated across different stakeholder categories and economic assumptions were cross-referenced with international benchmarks and verified through consultation with industry experts. Analytical frameworks were reviewed by experts in environmental policy and circular economy implementation. Member checking with key informants ensured accurate interpretation of qualitative data.

Several limitations merit acknowledgment. The rapidly evolving policy landscape (with new regulations under development during the research period) creates temporal constraints on findings. Data limitations regarding informal sector activities necessitated conservative assumptions in economic modeling. The COVID-19 pandemic's lingering effects on trade patterns and economic activity introduced additional complexity to trend analysis. These limitations are addressed through scenario analysis, sensitivity testing, and explicit acknowledgment of uncertainty ranges where appropriate.

## 4. Results and Discussion

### 4.1 Comprehensive Policy Gap Analysis and Regulatory Recommendations

Our analysis of Ethiopia's regulatory framework reveals a significant implementation gap between policy aspirations articulated in the Solid Waste Management Proclamation No. 513/2007 and operational reality. While the proclamation establishes progressive principles including extended producer responsibility (Article 12), hazardous waste management requirements (Article 14), and recycling promotion (Article 16), specific provisions for battery recycling remain underdeveloped. The absence of dedicated subsidiary regulations addressing battery collection targets, recycling standards, or material recovery requirements creates implementation ambiguities that hinder practical action.

Institutional analysis identifies fragmented mandates across multiple agencies without clear coordination mechanisms. The Ethiopian Environment Protection Authority holds overall environmental oversight, city administrations manage municipal waste collection, the Trade and Industry Bureau regulate commercial activities, and the Ethiopian Investment Commission promotes industrial development. This distributed responsibility creates coordination challenges and potential accountability gaps, particularly for cross-cutting issues like battery recycling that span multiple institutional domains. Capacity assessment reveals significant constraints, with environmental agencies typically allocating less than 5% of inspection resources to e-waste management despite its growing importance (interview data, EEPA official).

Comparative analysis with international frameworks identifies several critical regulatory elements currently absent in Ethiopia's system. The European Union's new Battery Regulation (2023/1542) provides particularly relevant benchmarks, including: (1) mandatory collection targets (63% for portable batteries by 2027, 73% by 2030), (2) minimum recycling efficiencies (90% for cobalt, copper, and lead; 80% for lithium by 2031), (3) recycled content requirements (16% for cobalt, 6% for lithium, 6% for nickel by 2031), and (4) due diligence obligations for supply chain sustainability. While direct replication of these ambitious targets may not be immediately feasible for Ethiopia, they provide directional guidance for progressive implementation.

Based on this analysis, we propose a three-stage regulatory development pathway for Ethiopia. Stage 1 (2025-2026) should focus on developing subsidiary legislation specifically addressing battery waste under Proclamation 513/2007, incorporating realistic but measurable collection targets (recommended: 35% by 2027, increasing to 55% by 2032), basic recycling efficiency standards (minimum 45% material recovery by weight), and clarified producer responsibility obligations. Stage 2 (2027-2029) should establish economic instruments including differentiated environmental fees based on battery recyclability and potential deposit-refund systems for consumer batteries. Stage 3 (2030 onward) should implement advanced requirements including recycled content mandates and design-for-recycling standards as domestic capacity matures.

Enforcement capacity represents a critical implementation consideration. Current environmental regulation enforcement in Ethiopia faces constraints including limited inspection resources (approximately one inspector per 500 formal businesses in Addis Ababa), technical expertise gaps in emerging areas like e-waste management, and relatively weak sanctioning mechanisms (maximum fines typically below ETB 50,000). We therefore recommend a graduated implementation approach beginning with voluntary participation incentives—such as green public procurement preferences, simplified import procedures for compliant businesses, and public recognition programs—before transitioning to mandatory requirements as monitoring capacity develops. This phased strategy balances ambitious environmental objectives with practical implementation realities while building compliance culture through positive reinforcement.

## 4.2 Economic Viability Assessment and Financial Model Development

Financial modeling based on Ethiopia's projected battery waste stream reveals economically viable implementation pathways under specific conditions. Our baseline scenario assumes annual processing of 5,040 kg cathode material from 72,000 laptop batteries (based on feasibility study projections), increasing at 15% annually based on import growth trends. Metal recovery assumptions derive from laboratory-scale hydrometallurgical testing literature, with conservative adjustments for industrial-scale implementation: 85% for cobalt, 80% for lithium, and 75% for nickel. Revenue projections utilize five-year average London Metal Exchange prices (cobalt: USD 32,500/ton, lithium carbonate equivalent: USD 18,000/ton, nickel: USD 18,500/ton) with 15% discounts for recovered material purity and market access limitations.

The centralized industrial model requires substantial capital investment of ETB 85-120 million for a facility processing 1,000+ tons annually, achieving viability only with collection rates exceeding 70% and sustained favorable metal prices. Financial modeling indicates a net present value (NPV) of ETB 12.5 million at 12% discount rate over 10 years under optimal conditions, but sensitivity analysis reveals significant vulnerability to metal price fluctuations (30% cobalt price reduction decreases NPV to -ETB 8.2 million) and collection efficiency (each 10% decrease in collection rate reduces NPV by ETB 15 million). This model presents substantial capital mobilization challenges given Ethiopia's limited venture capital ecosystem and presents collection logistics complexities given the geographical distribution of waste generation.

Decentralized micro-recycling units offer lower capital requirements (ETB 8-12 million per unit for 50–100-ton capacity) and logistical advantages through proximity to collection points. Economic analysis indicates basic viability at smaller scales (break-even at 45 tons annually with current metal prices), with projected NPV of ETB 3.8 million per unit under base conditions. However, unit economics are sensitive to labor costs (25% wage increase reduces NPV by 40%) and operational efficiency (20% capacity underutilization reduces NPV by 65%). Aggregated across multiple units, this approach could achieve similar total processing capacity to a centralized facility with distributed risk but requires significant coordination and quality control systems to maintain consistent operations.

The hybrid model—combining decentralized collection/pre-processing with centralized final processing—emerges as the most promising approach for Ethiopian conditions. This model leverages the collection advantages of distributed units (projected 60% higher collection rates than centralized model due to proximity and community engagement) while achieving processing economies of scale at the centralized facility. Our detailed financial projections for a hybrid system serving Addis Ababa initially with expansion to three additional cities within five years indicate capital requirements of ETB 35-45 million, with positive NPV of ETB 28.3 million at 12% discount rate and internal rate of return of 24.7% over a 10-year horizon. The model demonstrates greater resilience to external shocks, with 30% cobalt price reduction decreasing IRR to 18.2% but maintaining positive NPV (ETB 9.8 million).

Critical economic success factors identified through sensitivity analysis include: (1) collection efficiency (each 10% increase improves NPV by ETB 7.2 million), (2) cobalt price stability (implementing long-term offtake agreements could reduce volatility impact by 40%), (3) regulatory compliance costs (exceeding 15% of revenue significantly impacts viability), and (4) energy costs (particularly relevant for thermal processing steps, representing 18-25% of operational costs). Policy support mechanisms that address these factors—such as collection incentives (potential ETB 50/kg subsidy increasing collection rates by 25%), price stabilization mechanisms through strategic reserves or forward contracts, graduated compliance timelines with initial support periods, and renewable energy integration incentives—could enhance NPV by 35-50%.

Social cost-benefit analysis extending beyond direct financial returns reveals substantial additional value creation dimensions. Environmental benefits—including avoided soil and water contamination, reduced greenhouse gas emissions from primary metal production, and decreased landfill requirements—are estimated at ETB 6.5 million annually based on damage cost avoidance methodology using Ethiopian-specific valuation parameters (EEPA, 2023). Employment generation (85-120 direct jobs in processing plus 200-300 indirect jobs in collection, logistics, and support services) contributes ETB 15-20 million annually to household incomes based on living wage calculations. Foreign exchange savings (reduced imports of virgin materials) could reach ETB 12 million annually at full implementation, while potential export earnings from recovered metals could add ETB 8-10 million. These broader socio-economic benefits, representing approximately 65% of total system value, justify policy interventions beyond purely market-based approaches.

## 4.3 Stakeholder Ecosystem Mapping and Engagement Framework Development

Our stakeholder analysis reveals a complex ecosystem with diverse interests, capabilities, and influence levels requiring sophisticated engagement strategies. Government agencies exhibit varying and sometimes competing priorities—environmental protection versus industrial development versus municipal service delivery—necessitating coordination mechanisms that align objectives while respecting institutional mandates. Private sector actors range from multinational electronics companies with global sustainability commitments to small-scale importers with minimal environmental awareness, necessitating differentiated engagement approaches that recognize varying capacities and motivations.

Power-interest mapping identifies several critical leverage points for system transformation. Electronics retailers and repair businesses, while having moderate formal power, possess high interest (as battery disposal represents both cost and liability) and extensive networks with consumers, positioning them as critical collection channel partners. Our

analysis suggests that engaging 30-40% of Addis Ababa's approximately 500 electronics retailers could establish 150-200 collection points achieving 60-70% geographic coverage. Financial institutions demonstrate increasing interest in green financing opportunities but require de-risking mechanisms to support recycling investments; development finance institutions (particularly the Development Bank of Ethiopia and international climate funds) show particular promise as early-stage capital providers. Educational institutions offer substantial technical capacity development potential through curriculum integration and vocational training programs; partnerships with technical and vocational education training (TVET) centers could train 200-300 technicians annually within three years.

The research proposes a multi-tier governance structure for battery recycling implementation. A National Battery Recycling Steering Committee (chaired by Environment Protection Authority with membership from relevant ministries, private sector associations, civil society, and academia) would provide strategic direction and inter-agency coordination. An Industry-led Producer Responsibility Organization (PRO), initially established as a non-profit entity with government oversight, would operationalize collection and recycling activities with funding from member fees based on market share. Local Implementation Committees in major cities would coordinate municipal collection systems, informal sector integration, and public awareness campaigns. This structure balances top-down coordination with bottom-up implementation, recognizing Ethiopia's federal system and regional variations.

Engagement strategies must address specific barriers identified through stakeholder interviews. For importers and manufacturers, compliance cost concerns (estimated at 3-5% of product value for full EPR implementation) can be mitigated through phased implementation (starting with reporting obligations before financial responsibilities) and technical assistance programs for small and medium enterprises. For informal sector workers, health and safety risks require targeted interventions including training programs (estimated cost: ETB 2,000 per participant), provision of basic protective equipment (ETB 500 per worker annually), and formalization pathways through cooperatives or micro-enterprise development. For consumers, convenience barriers necessitate accessible collection points (optimal density: one per 10,000 population in urban areas) and potential incentive mechanisms (such as deposit-refund systems with ETB 50-100 rebates). For investors, perceived risks can be addressed through blended finance structures combining commercial debt (50-60%), concessional funding (20-30%), and government guarantees (10-20%).

International partnerships offer valuable support mechanisms, particularly through technology transfer, capacity building, and market access for recovered materials. Strategic alignment with global initiatives including the Global Environment Facility's e-waste programming, the World Economic Forum's Global Battery Alliance, and the African Circular Economy Alliance can provide technical resources, visibility, and potential financing while ensuring Ethiopian solutions reflect local contexts rather than merely replicating external models. South-South cooperation with countries like Rwanda and Ghana that have advanced e-waste policies could provide particularly relevant learning exchanges.

#### 4.4 Systems Analysis and Implementation Framework Development

Systems analysis reveals multiple interconnected feedback loops within the battery recycling ecosystem that must be managed for successful implementation. Positive reinforcing loops include: (1) collection infrastructure development → increased recovery volumes → improved economics → further infrastructure investment; (2) public awareness → higher participation rates → visible impact → sustained engagement; and (3) policy success → investor confidence → expanded operations → demonstrated feasibility → strengthened policy. Balancing loops that require careful management include regulatory compliance costs potentially limiting participation, market saturation effects on recovered material prices, and capacity constraints in rapidly scaling systems.

The research proposes a phased implementation framework spanning three phases over eight years, aligned with Ethiopia's current development planning cycles. Phase 1 (2025-2026) focuses on foundation building: completing regulatory framework development, establishing pilot collection systems in Addis Ababa (targeting 50 collection points and 20% collection rate), conducting detailed capacity assessments, and mobilizing stakeholder coalitions. Phase 2 (2027-2029) emphasizes scaled implementation: expanding collection networks to major regional cities (Bahir Dar, Hawassa, Mekelle), establishing first processing facilities (hybrid model with central facility in Addis Ababa and three regional pre-processing centers), formalizing informal sector participants through recognized associations, and developing markets for recovered materials through industrial partnerships. Phase 3 (2030-2032) targets system optimization and expansion: achieving nationwide coverage, implementing advanced recovery technologies, integrating design for recycling principles into product standards, and developing export markets for recovered materials.

Critical success factors across all phases include: (1) adaptive management systems with regular monitoring and course correction mechanisms, (2) transparency systems building stakeholder trust through open reporting, (3) incremental approach allowing learning and adjustment, (4) integration with broader circular economy initiatives (particularly plastic and metal recycling to achieve synergies), and (5) continuous innovation responding to changing battery technologies and market conditions. Implementation should prioritize "quick wins" that build momentum—such as high-visibility collection campaigns in institutional settings (universities, government offices) and partnerships with prominent businesses—while addressing longer-term structural requirements.

Monitoring and evaluation frameworks should employ balanced scorecard approaches tracking both outcome metrics (collection rates, recovery efficiency, environmental impacts) and process metrics (stakeholder engagement, policy implementation, capacity development). We propose 15 key performance indicators across five categories: environmental (e.g., tons of batteries diverted from landfill), economic (e.g., value of recovered materials, jobs created),

social (e.g., informal sector participation, consumer awareness), operational (e.g., collection network coverage, processing efficiency), and institutional (e.g., policy implementation progress, stakeholder satisfaction). Regular independent assessment, combined with participatory review processes involving all major stakeholder groups, will support continuous improvement and accountability.

## 5. Conclusion

This research provides a comprehensive, contextually adapted implementation framework for establishing lithium-ion battery recycling in Ethiopia, systematically addressing the critical gap between policy aspirations and practical realization. By integrating policy analysis, economic assessment, stakeholder mapping, and systems thinking, we demonstrate that viable pathways exist despite current constraints, with the hybrid decentralized-collection/centralized-processing model offering particular promise for Ethiopian conditions. The framework's strength lies in its balanced approach, combining ambitious environmental objectives with pragmatic implementation strategies that acknowledge Ethiopia's distinctive institutional landscape, economic structure, and development priorities.

The study makes several original contributions to knowledge and practice. Theoretically, it advances understanding of circular economy implementation in developing economy contexts, particularly regarding the institutional arrangements that facilitate transitions in complex, resource-constrained environments. Methodologically, it demonstrates the value of integrated, multi-method approaches for analyzing and designing sustainability transitions, bridging qualitative and quantitative perspectives. Practically, it provides actionable guidance for Ethiopian policymakers, businesses, and civil society, offering specific recommendations across regulatory development, financial structuring, stakeholder engagement, and implementation sequencing.

Implementation will inevitably face challenges, including capital mobilization in a constrained financial environment, coordination complexity across multiple stakeholders, market volatility affecting recycled material values, and rapid technological change in battery chemistries. However, the potential benefits—environmental protection, resource security, job creation, economic diversification, and positioning within global circular value chains—justify concerted effort and strategic investment. With committed leadership, collaborative action, and adaptive management, Ethiopia can establish battery recycling as both an environmental imperative and an economic opportunity, serving as a model for sustainable industrial development in Africa.

### 5.1 Recommendations for Immediate Action

Based on research findings, five priority actions should commence within the next 12 months to maintain momentum and build implementation foundations:

1. **Establish Multi-Stakeholder Implementation Task Force:** Convene key stakeholders from government, private sector, academia, and civil society to develop detailed battery recycling regulations under existing solid waste legislation, with draft regulations completed within six months.
2. **Launch Pilot Collection Systems in Addis Ababa:** Partner with 20-30 electronics retailers and repair businesses to establish pilot collection points, complemented by institutional collection programs at three universities and two government complexes, aiming for 10-ton collection within first year.
3. **Conduct Detailed Feasibility Studies for Hybrid Processing:** Commission technical and financial feasibility studies for hybrid processing facilities, including site identification, technology assessment, environmental impact screening, and detailed financial modeling with investor-ready documentation.
4. **Develop Vocational Training Curriculum and Programs:** Collaborate with technical and vocational education institutions to develop and pilot training programs for battery handling, disassembly, and safety procedures, targeting 50 trainees within first year.
5. **Initiate Comprehensive Public Awareness Campaign:** Design and launch multi-channel awareness campaign emphasizing proper battery disposal and recycling benefits, utilizing media partnerships, community events, and school programs to reach minimum 30% awareness in Addis Ababa within first year.

### 5.2 Research Implications and Future Directions

This study establishes the policy, economic, and systems foundations for battery recycling implementation but identifies several areas requiring further investigation to support successful realization:

1. **Technical Process Optimization:** Subsequent research should address detailed technical process optimization under Ethiopian conditions, including laboratory-scale testing of alternative leaching agents, pilot-scale validation of selected technologies, and adaptation to mixed battery chemistries prevalent in Ethiopian markets.

2. **Behavioral Studies and Intervention Design:** Research exploring consumer disposal decisions, incentive effectiveness, and behavioral intervention design would enhance collection strategy development, particularly regarding deposit-refund systems, convenience optimization, and social norm influences.
3. **Supply Chain and Market Analysis:** Detailed analysis of supply chains for recovered materials, identifying specific market opportunities, quality requirements, and value addition potential would strengthen economic viability and support business model development.
4. **Longitudinal Implementation Tracking:** Establishing monitoring frameworks and conducting longitudinal studies of implementation progress would generate valuable learning for adaptive management and contribute to broader scholarship on circular economy transitions.
5. **Comparative Policy Analysis:** Expanded comparative analysis with other African countries implementing e-waste policies would identify transferable lessons and support regional harmonization efforts.

The methodology and framework developed through this research offer potential application beyond Ethiopia to other developing economies facing similar e-waste challenges, contributing to global knowledge on sustainable materials management in resource-constrained contexts while respecting local specificities and development priorities.

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#### Declaration of Generative AI

The authors used Generative AI for language editing and formatting support. All aspects of the research design, data collection, data analysis, interpretation of results, and scientific conclusions were conducted independently by the authors. The AI tool was employed only as an editorial assistant to improve clarity, coherence, and structure of the manuscript and did not influence the intellectual content or findings of the study.

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