Sustainable Transport Management of Electronic Waste: A Systematic Review of Collection, Recycling and Recovery Strategies in Developing Countries

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Abstract
This systematic review examines the sustainable management of shipments of electronic waste in developing countries, focusing on the interaction between collection, recycling, recovery and transport strategies. Given the growing global problem of waste, particularly in developing countries, this research will address the need for integrated and sustainable solutions. The review is based on a theoretical framework of sustainable development, circular economy principles and integrated waste management concepts, emphasizing the interlinkages between transport and other stages of e-waste management. A systematic search of peer reviewed literature, reports and non-peer reviewed literature was conducted using relevant databases and keyword searches. The review analyzed the predominant collection methods (door-to-door, community drop-off centres), the predominant recycling and re-processing processes (mechanical, chemical, biological) and effective transport management strategies (route optimization, vehicle selection, logistics). Case studies such as Agbogbloshie in Ghana and the E-Parisakha initiative in Rwanda illustrate the diversity of approaches and problems encountered in the real world. The main findings show that successful systems often use hybrid collection models, optimized transport networks and strong public-private partnerships. The review highlights the need for integrated planning, context-specific solutions and cooperation between stakeholders to contribute to mitigation efforts in the area of e-waste by minimizing environmental and health risks, maximizing recovery of resources and promoting circular economies in developing countries.

Keywords: *Electronic waste, sustainable transport, developing countries, recycling, re-manufacturing, circular economy.*

Introduction

The exponential growth in the consumption of electronic devices has unleashed a tsunami of electronic waste, a global crisis with devastating consequences, especially for developing countries (Balde et al., 2017; UNEP, 2021). Alarmingly, the generation of global e-waste is estimated to reach 53.6 million tonnes in 2019, and projections show a continuing upward trend. Developing countries, often burdened by lax environmental regulation and the lure of informal material recovery, are the primary destinations of the growing flow of e-waste around the world (Perkins et al., 2014; Awasthi et al., 2016). In these regions, informal recycling practices, characterized by primitive and hazardous processes such as open burning and acid extraction, expose vulnerable workers and communities to toxic chemicals, leading to serious health and environmental risks

(Grant et al., 2013; Manhart et al., 2019). Effective management of electronic waste, including reliable collection, efficient recycling and sustainable re-manufacturing, is of paramount importance in mitigating these negative impacts and unlocking the potential for valuable resource recovery (Cui and Forsythe, 2010).

A critical but often overlooked element in efficient management of electronic waste is the transport network linking the collection points for electronic waste to the processing facilities. Effective and sustainable transport is a key enabler to minimize environmental damage, reduce logistics costs and maximize resource recovery (Nakamura et al., 2015). However, developing countries often face severely constrained transport infrastructure, complex logistical challenges and the complex issue of integrating the prevailing informal recycling activities into formalized systems (Kiddee et al., 2013; Shabbir et al., 2020). Despite the critical role of transport in the management of electronic waste, there is a considerable gap in the literature on sustainable transport strategies in the wider context of recycling and re-manufacturing of electronic waste in developing countries.

Existing research often focuses on isolated aspects, such as collection methods (Shabbir et al., 2020) or recycling technologies (Li et al., 2018), and does not provide a comprehensive analysis of the synergies between transport strategies and the overall sustainability of the system. Moreover, research often ignores the unique challenges facing developing countries, such as resource constraints, the important role of the informal sector and the need for context-specific solutions (Lundgren, 2012). There is also an urgent need to integrate the principles of the circular economy (Geissdoerfer et al., 2017), such as back-office logistics and closed loop supply chains (Ijomah et al., 2007), into the planning of e-waste.

This research aims to address these critical gaps by a systematic review of sustainable e-waste transport management in developing countries, with a focus on the complex interrelationship between collection, recycling and re-manufacturing strategies. The review, prompted by the urgent need for sustainable and efficient e-waste management systems, aims to answer the following research questions:

1. What are the predominant e-waste collection, recycling and reprocessing processes in developing countries and how do they relate to transport needs?
2. How can transport strategies be optimized to increase the sustainability of electronic waste management systems in developing countries?
3. What are the main challenges and opportunities in implementing a sustainable e-waste transport system in developing countries?
4. What framework could be developed to guide the implementation of sustainable e-waste management in developing countries?

This study is important as it provides a comprehensive synthesis of existing knowledge on sustainable e-waste management in developing countries, identifies key challenges and opportunities, and highlights the importance of integrating e-waste transport planning into broader strategies. The resulting framework will provide practical guidance for policy-makers, practitioners and researchers. This work will ultimately contribute to the global effort to reduce electronic waste and promote environmentally-friendly and cost-effective solutions that protect human health and advance the sustainable future (Hilty et al., 2015). The efficient and sustainable transport of electronic waste is of the utmost importance in order to minimize environmental

impacts (e.g. emissions, improper disposal) and to maximize resource recovery (e.g. (precious metals) (Hermann et al., 2019). Optimizing transport networks will facilitate the transition to a circular economy in electronics, while reducing virgin material requirements and waste generation (Bocken et al., 2016). By focusing on developing countries, this research addresses the critical need for tailor-made solutions that take into account their specific circumstances and contribute to a more equitable and sustainable global e-waste management paradigm.

Literature Review

The growing generation of electronic waste (e-waste) is a major global challenge and has a disproportionate impact on developing countries, which often are the final destinations of e-waste flows (Balde et al., 2017; Perkins et al., 2014). Effective management of electronic waste, including collection, recycling and recovery, is essential to reduce environmental and health risks (Cui & Forsythe, 2010). However, current practices in developing countries range from high-risk informal recycling operations to more formalized but often more challenging schemes (Awasthi et al., 2016; Grant et al., 2013). While informal recycling offers some livelihoods, it relies on primitive techniques such as open burning and acid baths, which lead to serious environmental pollution and health risks at work (Manhart et al., 2019; Brigden et al., 2005; Lundgren et al., 2012). While formal systems aim to improve environmental performance, they often face constraints in resources, infrastructure and, crucially, in integrating a large and often economically vulnerable informal sector (Kiddee et al., 2013; Sinha-Khetriwal et al., 2012). The move towards a circular economy model for electronics, with emphasis on reuse, re-manufacturing and closed loop systems, has promise (Geissdorf et al., 2017; Ijomah et al., 2007), but its practical implementation requires a strategy and policy framework tailored to the context (Sinha-Khetriwal et al., 2012).

A critical but often overlooked aspect of sustainable management of electronic waste is transport. Efficient and environmentally friendly transport systems are necessary to link electronic waste collection points to processing facilities, minimize environmental impacts and maximize recovery of resources (Nakamura et al., 2015). The existing literature on electronic waste transport can be broadly divided into the following categories: (1) studies on route optimization and logistics (e.g. Soleimani et al., 2017); (2) research exploring the environmental impact of different modes of transport (e.g. Hermann et al., 2019; Hertwich et al., 2015); (3) reverse logistics and closed loop supply chain analysis (e.g. Tibben-Lembke, 2002), and (4) studies examining the social and economic dimensions of electronic waste transport, including the role of the informal sector (e.g. Akenji et al., 2016; Madaan et al., 2020).

While these studies provide valuable insights, they often treat transport in isolation and do not sufficiently address the complex interactions between transport and other stages of e-waste management. In particular, the existing literature does not provide a holistic analysis integrating the three pillars of sustainability - environmental, economic and social - in relation to the transport of e-waste in developing countries. For example, studies such as Hermann et al. (2019) quantifying the environmental impacts of transport modes, often without a thorough discussion of the social impacts, such as the impact on the livelihoods of informal waste collectors. Similarly, while Akenji et al. (2016) explores the social dimension but does not go into the detail of the economic viability of the various transport strategies.

The role of transport goes beyond the mere movement of materials; it has a direct impact on collection efficiency, the economic viability of recycling and re-manufacturing operations and the overall sustainability of the electronic waste management system. Optimized transport routes can significantly reduce collection times and costs, and the choice of suitable transport modes can minimize environmental damage. The integration of informal operators, who often play an important role in the collection and transport of electronic waste in developing countries, into the formal transport networks is a matter of great concern and challenge. While this may increase efficiency and create economic opportunities, it also requires careful management to ensure that the procedures are safe, fair and environmentally sound.

Consideration of the post-COVID era

The COVID-19 pandemic has further complicated the management of electronic waste, especially in developing countries. The explosion of e-waste resulting from the increased dependence of remote work and online learning on electronic devices is putting pressure on existing waste management systems (Balde et al., 2020). In addition, the pandemic disrupted global supply chains and highlighted the need for more localized and resilient electronic waste management systems, prioritizing sustainable transport and recovery (Kirchherr et al., 2021). The post-COVID era provides an opportunity to rethink e-waste transport strategies, focusing on green recovery and integrating the principles of the circular economy (OECD, 2021).

Gaps in literature

Despite the contributions of existing research, there are still major gaps:

(a) Lack of Integrated Studies:
Comprehensive studies are lacking to integrate the different aspects of sustainable e-waste management in the wider context of collection, recycling and re-manufacturing in developing countries.

(b) Need for a Robust Theoretical Framework:
The literature lacks a solid theoretical framework to understand the complex interactions and trade-offs that are inherent in the sustainable transport of electronic waste. In particular, the analysis of the interrelated environmental, economic and social dimensions of electronic waste transport needs to be more fully integrated with systems thinking, stakeholder theory and sustainable development principles.

(c) Limited Focus on Social and Economic Aspects:
More research is needed on the social and economic aspects of e-waste transport in developing countries, including the impact on local communities, the role of women and the development of sustainable livelihoods in informal sectors.

(d) Integration of the Informal Sector:
Existing literature provides limited guidance on how to effectively integrate the informal sector into formal electronic waste transport systems, which is a key challenge for developing countries.

Theoretical Framework

This research proposes a theoretical framework for sustainable e-waste management in developing countries, integrating e-waste management, sustainable transport and the principles of the circular economy. The Framework considers that sustainable e-waste transport is a key enabler for efficient

and environmentally sound e-waste management, which contributes to both environmental protection and resource recovery in the unique context of developing economies.

The framework is based on three basic theoretical foundations:

(a) Sustainable Development (WCED, 1987):

It stresses the need to strike a balance between economic development, environmental protection and social justice. This principle is particularly important in the post-COVID era, where the pandemic has accentuated social and economic disparities and highlighted the need for resilient and sustainable systems (UNEP, 2021).

(b) Circular Economy Principles (Geissdoerfer et al., 2017):

It focuses on the recovery of resources, reuse, re-manufacturing and minimization of waste. The COVID-19 pandemic accelerated the uptake of circular economy practices, as supply chain disruptions highlighted the importance of resource efficiency and local recycling (Kirchner et al., 2021).

(c) Integrated Waste Management Concepts (Wilson et al., 2009):

It highlights the importance of taking into account all stages of waste management, from generation to disposal. The pandemic has further highlighted the need for integrated approaches, as the increased generation of e-waste from distance working and online learning is putting pressure on existing waste management systems (Balde et al., 2020).

Integration of Theories into the Framework

The framework integrates systems thinking, stakeholder theory and the principles of sustainable development to analyze the complex interactions between the factors affecting sustainable e-waste transport. These theories are not only fundamental, but also provide a lens through which to analyze case studies and policy recommendations:

(i) Systems Thinking:

This approach emphasizes the interlinkages between collection, transport, recycling and re-manufacturing processes. For example, in the case of the Rwanda initiative 'E-Parisakha', systems thinking helps explain how formalized transport networks increase the efficiency of the whole e-waste management system, by reducing delays and environmental risks.

(ii) Stakeholder Theory:

This theory emphasizes the importance of the involvement of all relevant stakeholders (for example, government, private sector, informal waste collectors, municipalities) in the management of e-waste. In Agbogbloshie, Ghana, the lack of integration of stakeholders has resulted in unregulated and unsafe transport practices. The theory of the stakeholders is that formalization of the informal sector and the promotion of public-private partnerships could alleviate these problems.

(iii) Sustainable Development Principles:

These principles guide the framework by emphasizing the need for economically viable, environmentally friendly and socially fair solutions. For example, the post-COVID era has seen the push for green recovery policies, which prioritize sustainable transport and waste management as part of wider stimulus packages (OECD, 2021).

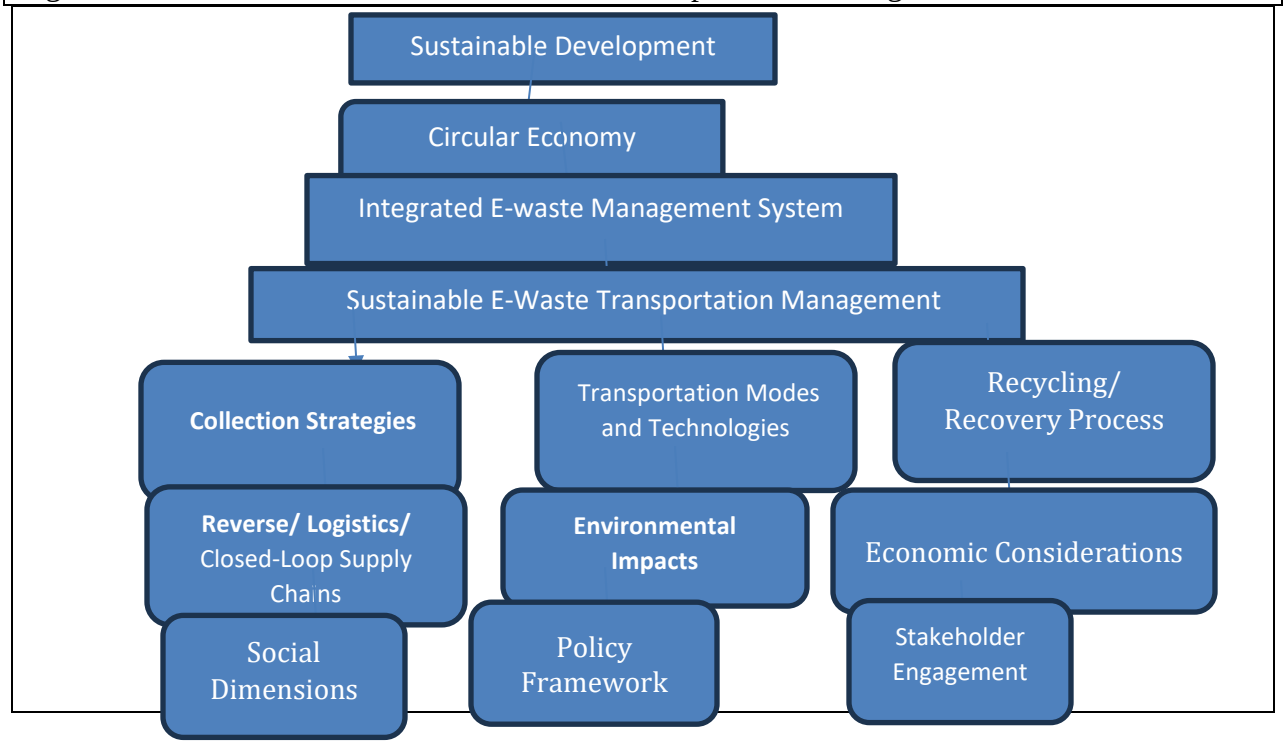
Visual Representation of the Framework

A visual diagram has been developed to better illustrate the theoretical framework (see Figure 1). This diagram summarizes the main components of the framework and their links, and provides a clear and concise representation of the complex interrelationships that are involved in the sustainable management of electronic waste.

Components of the Framework

- **E-waste Collection Strategies:** Recognizing the diversity of collection methods in developing countries (Shabbir et al., 2020), the framework examines how the choice of collection methods (formal, informal, door-to-door, community-based) influences transport planning (types of vehicles, routes, involvement of actors).
- **Transportation Modes and Technologies:** The framework assesses different modes of transport (trucks, vans, rail, waterways) (Hermann et al., 2019), emphasizing the choice of a mode based on distance, volume, infrastructure and environmental impact. It also looks at technological progress (electric cars, route-optimization software) as a way of increasing sustainability.
- **Recycling and Recovery Processes:** The Framework recognizes the inherent link between transport and processing (Li et al., 2018). Effective transport is essential for the timely delivery of electronic waste to the facilities and for the return of the materials recovered. Transport strategies need to be adapted to the specific requirements of processing technologies.

Figure 1: Framework for Sustainable E-Waste Transportation Management



- **Reverse Logistics and Closed-Loop Supply Chains:** The integration of the principles of reverse logistics (Tibben-Lembke, 2002) underpins the proposal for transport systems to

facilitate the return of electronic waste from consumers to producers and recyclers. This includes the design of collection networks, effective routing and supply chain partnerships.

- **Environmental Impacts:** The principle of minimizing the environmental footprint of electronic waste transport (greenhouse gas emissions, air pollution, noise, land use) is at the core of the proposal (Hertwich et al., 2015). Sustainable transport practices (cleaner fuels, optimizing routes, vehicle maintenance) are essential.
- **Economic Considerations:** The framework recognizes the economic viability of a sustainable electronic waste transport, taking into account costs, infrastructure development and local economic potentials. Cost-effective transport systems are necessary to promote the economic sustainability of e-waste management.
- **Social Dimensions:** Addressing social dimensions (informal actor involvement, labor conditions, health and safety, community participation) (Akenji et al., 2016) is crucial. E-waste transportation must be conducted responsibly, protecting workers and communities. Tackling the social dimension (informal actors' involvement, working conditions, health and safety, community participation (Akenji et al., 2016) is essential. Electronic waste transport must be carried out responsibly, protecting workers and communities

Materials and Methods

This study used a systematic review methodology to analyze sustainable management of electronic waste shipments in developing countries, with a focus on collection, recycling and recovery strategies. This rigorous approach has made it possible to analyze the existing literature in a comprehensive way, to identify key trends, challenges and opportunities, and to address identified research gaps (Tranfield et al., 2003; Liberati et al., 2009). The study followed the theoretical framework presented above and highlighted the interlinkages between transport and other electronic waste management processes (Ijomah et al., 2007; Tibben-Lebke, 2002).

(a) Systematic Review Approach

A structured process of searching and selecting was carried out, followed by data extraction and thematic synthesis. This systematic approach has provided a comprehensive and unbiased overview of the existing knowledge and addressed the need for integrated studies on e-waste transport in developing countries, as highlighted by the peer review (Lundgren, 2012; Nakamura et al., 2015). The review was guided by the PRISMA guidelines (preferred reporting items for systematic reviews and meta-analyses) to ensure transparency and reproducibility (Liberati et al., 2009).

(b) Inclusion and Exclusion Criteria

The review included peer-reviewed articles, conference proceedings and peer reviewed reports published in English from 2010 to 2023. This time frame reflected the latest developments in the management of electronic waste and sustainable transport. Studies focusing exclusively on developed countries, or specific e-waste streams (e.g. only batteries) or recycling technologies not considering transport have been excluded from the scope of the study. The review focused specifically on research relevant to developing economies, recognizing their unique challenges (Balde et al., 2017). Studies which did not explicitly discuss the role of transport in the management of electronic waste were also excluded.

(c) Data Sources and Search Strategy

Electronic databases such as **Scopus, the Web of Science, ScienceDirect and Google Scholar** were consulted. The search strategy uses a combination of key words and Boolean operators to ensure a comprehensive search for the relevant study. The following key words have been used:

i. **Primary Keywords:** "e-waste," "electronic waste," "sustainable transportation," "logistics," "reverse logistics," "collection," "recycling," "recovery," "developing countries," "informal sector.";

ii. **Boolean Operators:**
   - ("e-waste" OR "electronic waste") AND ("sustainable transportation" OR "logistics" OR "reverse logistics") AND ("collection" OR "recycling" OR "recovery") AND ("developing countries" OR "informal sector"); and
   - ("e-waste transportation" AND "developing countries") OR ("sustainable e-waste management" AND "transportation").

Search has been limited to titles, abstracts, and key words to ensure relevance. The reference lists of the identified studies were then searched manually for other relevant studies (Cooper, 1988). The initial search resulted in 1 250 articles screened on the basis of title and abstract, resulting in 350 articles being submitted for full-text review. After the application of the inclusion and exclusion criteria, a total of 120 articles were selected for the final analysis.

(d) Data Extraction and Analysis

Standardised data extraction form, rigorously tested for consistency, was used for systematic collection of data from selected studies. The form included structured fields to capture key parameters, such as author(s), year of publication, and location of the study. It also documented the specific types of waste examined, together with collection methods - door-to-door or community drop-off centres - and transport strategies such as route optimization, vehicle selection and logistical frameworks. Details of recycling and recovery processes, including those involving a combination of mechanical, chemical and biological approaches, have been documented. The form also included categories for assessing environmental and socio-economic impacts, policy frameworks for e-waste management, challenges to sustainable transport and any theoretical frameworks used in the studies. This comprehensive approach has ensured a coherent approach to the synthesis of the various aspects of the research corpus.

Data were independently verified by two evaluators and any discrepancies were resolved by discussion or consultation with the third evaluator. Thematic analysis based on the framework set out by Braun & Clarke (2006) has been used to identify the main topics and models for sustainable management of electronic waste. This process involved several iterative steps, starting with a re-engagement of the data by a thorough re-reading of selected articles. The initial codes were then systematically developed to encapsulate the key concepts and ideas emerging from the data base. The related codes were then grouped together into provisional themes, which have been closely reviewed and improved to ensure consistency with the underlying data. Following this stage, each theme was defined and given a descriptive name. The analysis was concluded by a final report which included illustrative excerpts from studies to illustrate the identified issues.

(e) Case Study Selection and Analysis

In order to provide concrete examples of sustainable practices for the transport of electronic waste, a pro-active sampling approach was used for the selection of case studies from developing countries. Case studies have been identified through systematic searches of academic databases, international reports (including from the United Nations Environment Programme and the World Bank) and in the open literature. The selection criteria underlined the availability of a comprehensive dossier on the procedures for the management of electronic waste, with particular attention to logistical and operational aspects of transport. Studies were prioritized where they highlighted innovative or non-traditional transport strategies and ensured relevance to the evolving challenges in this area. In addition, the selected cases had to reflect the diverse geographical, economic and infrastructure contexts typical of developing countries. Finally, all sources were subject to a credibility check, with priority given to publications from peer-reviewed journals, established institutions or well-known industry reports.

Two case studies have been selected for in-depth analysis: the Agbogbloshie initiative in Ghana and the e-Parisakha initiative in Rwanda. These cases were selected because they represent contrasting approaches to the management of electronic waste - Agbogbloshie illustrates the problems of informal, unregulated systems, while the Rwanda initiative illustrates the benefits of a formalized, integrated approach. Case studies have been analyzed to identify best practices, challenges and lessons learnt in the field of sustainable e-waste management. This included a thorough review of the case study reports, including information on collection methods, transport logistics, recycling and reprocessing processes, stakeholder engagement and policy frameworks.

(f) Quantitative Data Integration

Although the review is based primarily on qualitative data, quantitative data have been included where available to improve the robustness of the analysis. For instance, data on transport costs, emissions and recovery rates were extracted from selected studies and case reports. Where quantitative data were limited, this limitation was explicitly recognized and the paper discusses how future research could close this gap by collecting and analyzing data more comprehensively.

Case Study Analysis

In order to illustrate the practical consequences of the results of the systematic review and to provide concrete examples of the management of electronic waste in developing countries, this section presents two contrasting case studies. These cases highlight the different challenges and opportunities of transporting electronic waste and highlight the importance of solutions tailored to the context.

Case Study 1: Informal recycling and transport of electronic waste in Agbogbloshie, Ghana

Agbogbloshie, Accra presents a comprehensive and relevant case study on the informal recycling and transport of electronic waste (Grant et al., 2013). The region has become a major destination for electronic waste, with a large proportion of it imported and processed to a large extent by informal waste collectors and small traders. Electronic waste enters the Agbogbloshie market via a highly decentralized and unregulated network. Individuals and small businesses collect electronic waste from a variety of sources, including households, businesses and landfills, often using primitive methods.

Transport under this informal system is also disorganized and relies on a variety of transport modes, ranging from hand carts and bicycles for local collection to overloaded and often poorly maintained trucks for long-distance transport out of town. The transport system is characterized by a lack of planning of routes, coordinated logistics and compliance with safety and environmental regulations. This informality is a direct contributor to the serious environmental and health risks associated with the processing of electronic waste in Agbogbloshie.

The reckless transport of electronic waste often leads to spills, dispersal of dangerous materials and increased exposure of workers and the surrounding community to toxic substances. The lack of formal transport infrastructure and regulated processing facilities also prevents the recovery of precious materials from being effectively utilized. Electronic waste is often processed on the spot using primitive and highly polluting methods, such as open burning for metal extraction (Manhart et al., 2019). This practice releases toxic fumes into the atmosphere, which pose a serious health hazard for workers and citizens alike. In addition, the absence of formal transport arrangements and regulated disposal mechanisms prevents safe and controlled handling of hazardous components, which contributes to widespread contamination of soil and water (Lundgren, 2012).

The Agbogbloshie case powerfully illustrates the negative effects of unregulated and informal electronic waste transport practices and underlines the urgent need to move to more formalized and sustainable systems.

Case Study 2: E-Parisakha initiative in Rwanda

The Rwanda e-Parisakha project is a contrasting example of a move towards formalized and integrated e-waste management. Faced with growing volumes of electronic waste, Rwanda has proactively put in place a national electronic waste management system. The e-Parisakha initiative includes the establishment of designated collection points throughout the country where electronic waste can be deposited by individuals, businesses and institutions. The transport of collected electronic waste from these collection points to a central, officially approved recycling facility is contracted out to a formal waste management company, often through public-private partnerships.

This structured transport system, using designated vehicles and pre-planned routes, allows for better monitoring of e-waste flows, reduces the risk of contamination of the environment during transport and makes it easier to process e-waste in a centralized facility. The e-Parisakha initiative also highlights the creation of capacity and jobs in the formal recycling sector of e-waste (Awasthi et al., 2016) and promotes a more sustainable and economically viable approach. By formalizing the transport process and integrating it into a regulated recycling system, Rwanda is developing a more controlled and sustainable electronic waste management model, away from the environmental and social problems associated with informal recycling.

This case illustrates the positive impact of PPPs, supportive policy frameworks and the focus on formalizing the transport of e-waste in the development of efficient and sustainable e-waste management systems.

Comparative Analysis of the Selected Case Studies

Feature	Agbogbloshie, Ghana	E-Parisakha, Rwanda
Transportation System	Informal, disorganized and different modes (trucks, vans)	Formal, organized, designated vehicles
Environmental Impact	High pollution, health risks from spills and open burning	Lower pollution, controlled disposal
Resource Recovery	Limited, inefficient due to on-site processing	Potential for increased and more efficient recovery at centralized facility
Stakeholder Involvement	Primarily informal waste pickers and traders	Government, private sector, community involvement
Sustainability	Low, environmentally and socially unsustainable	Higher potential for environmental and economic sustainability
Connection to Review Themes	Illustrates the problems of informal transport and the need for integration and regulation	It demonstrates the benefits of formalization, PPPs (public-private partnerships) and structured transport systems..

Lessons Learned and Implications

The contrasting experiences of Agbogbloshie and Rwanda highlight the critical lessons of the sustainable management of electronic waste. The central message is the need to transform from informal to formal systems. Unregulated practices, such as in Agbogbloshie, exacerbate environmental and health risks, while structured approaches such as the Rwanda E-Parisakha show how formalization of transport systems can reduce these risks. This shift requires strong frameworks to ensure responsibility and safety across e-waste handling processes.

Public-private partnerships and political support are equally important. Rwanda's progress shows how government-led initiatives, combined with private sector cooperation, can drive efficient solutions for e-waste. Policies that encourage sustainable practices and provide clarity on regulations create a favourable environment for innovation and compliance.

Moreover, nuanced solutions are necessary on a contextual basis. Transport strategies need to be adapted to regional infrastructure, resources and socio-economic realities. The Rwandan model, while successful, may not be directly applicable in contexts such as Ghana, where different political environments and infrastructural capacities require tailor-made approaches. Flexibility and local planning are key to tackling unique challenges.

Finally, the commitment of stakeholders and public awareness are the building blocks for long-term success. The inclusion of informal workers in formal systems ensures inclusiveness and reduces resistance to change, while educating communities on the risks of electronic waste promotes collective responsibility. These elements, when combined, strengthen the resilience and sustainability of the efforts to manage e-waste at global level.

Discussion and Implications

This systematic review provided key insights on sustainable management of e-waste shipments in developing countries, highlighting the key interaction between collection, recycling and recovery

and transport strategies. Our findings are in line with and expand on existing literature. The identification of three main collection strategies (door-to-door, community and drop-off centres) and the related transport challenges (Table 2) is in line with previous research highlighting the diversity of collection models (Shabir et al., 2020; Awasthi et al., 2016). However, the review goes further by explicitly linking these collection strategies to the specific transport needs and emphasizing the importance of taking into account factors such as route optimization, availability of vehicles and logistics planning.

Table 2: E-waste Collection Strategies and Transportation Challenges

Collection Strategy	Description	Advantages	Disadvantages	Transportation Challenges
Door-to-door	Collection from households/businesses	Convenient, high collection rates	Resource-intensive, logistically complex	Route optimization, vehicle accessibility, scheduling
Community-based	Designated collection points	Cost-effective, community involvement	Requires public awareness, potential for illegal dumping	Strategic location of points, efficient transport to processing facilities
Drop-off centers	Centralized collection facilities	Convenient for individuals, organized collection	Infrastructure investment, potential for long travel distances for some	Regular transport from centers to processing facilities
Hybrid Approach	Combination of strategies	Maximizes collection rates, adaptable to local context	Requires careful planning and coordination	Integrating diverse transport needs and logistics

A comparative analysis of e-waste management strategies (Table 3) reinforces the interlinkages in the system and shows how transport choices affect the efficiency of recycling and reprocessing processes. The need for specialized transport for hazardous waste from chemical recycling processes, for example, underlines the importance of integrating transport planning into the overall strategies for the management of electronic waste.

Table 3: Comparative Analysis of E-Waste Management Strategies

Strategy Category	Strategy	Advantages	Disadvantages	Interlinkages with Transportation
Collection	Door-to-door	Convenient, high collection rates	Resource-intensive, logistically complex	Requires optimized routes, appropriate vehicles
	Community-based	Cost-effective, community involvement	Requires public awareness	Needs strategic collection point locations, efficient transport
	Drop-off centers	Convenient, organized collection	Infrastructure investment	Regular transport from centers to processing facilities
Recycling/Recovery	Mechanical	Lower cost, simpler technology	Limited material recovery	Type and volume of materials influence transport needs
	Chemical	Recovers valuable materials from complex e-waste	High cost, specialized expertise	Requires specialized transport for hazardous waste
	Recovery	Resource conservation, waste reduction	Limited by standardization and market demand	Transport of refurbished products to markets
Transportation	Route optimization	Minimizes distance, fuel use, emissions	Requires data and software	Directly impacts collection efficiency and costs
	Vehicle selection	Cost-effective, environmentally sound	Requires consideration of local conditions	Affects type and volume of transportable e-waste
	Logistics systems	Improves efficiency and coordination	Requires investment in technology	Essential for integrating collection, recycling, and recovery

Policy Recommendations

The results of this review have had a significant impact on policy and practice in developing countries. In order to promote the sustainable transport of electronic waste, governments and policy makers should consider the following specific and actionable recommendations:

(a) Incentivize Sustainable Transportation Practices:

Governments should provide financial incentives to encourage the adoption of sustainable transport technologies such as electric vehicles (EVs) and route-optimization software. For instance, tax breaks or subsidies could be offered to e-waste management companies investing in electric (EVs) or other low-emission vehicles. In addition, carbon credit schemes could be introduced to reward companies for reducing their transport emissions.

(b) Develop Public-Private Partnerships (PPPs):

Public-private partnerships can play a key role in formalising electronic waste transport systems. Governments should cooperate with private sector players to develop integrated electronic waste management systems, which include efficient transport networks. For example, in the Rwanda e-Parisakha initiative, the government has partnered with private waste management companies to set up a formalized transport system. Similar models could be replicated in other developing countries, with clear guidelines on roles, responsibilities and mechanisms for sharing the benefits.

(c) Strengthen Regulatory Frameworks:

Governments should adopt and enforce regulations mandating the use of sustainable transport practices in the management of electronic waste. This could include setting emission standards for electronic waste vehicles, requiring the use of route-optimisation software and mandating the safe handling of dangerous materials during transport. Regulatory frameworks should also include mechanisms for monitoring and enforcement to ensure compliance.

(d) Promote Community-Based Collection Models:

Community collection models such as collection points and mobile collection units can reduce transport costs and increase the efficiency of collection. Governments should invest in developing infrastructure to support these models, including strategically placed collection points and transport services to move electronic waste from these points to treatment plants.

Integration of the Informal Sector

The informal sector plays an important role in collecting and transporting electronic waste in developing countries, but its integration into formal systems remains a major challenge. The following specific strategies should be considered to address this issue:

(a) Formalization of Informal Workers:

Governments should develop programmes to formalize informal e-waste workers by granting them legal recognition, access to social security and training in safe and sustainable e-waste transport practices. In India, for example, the government has implemented programmes to register informal waste collectors and to include them in formal waste management systems. Similar initiatives could be taken in other developing countries.

(b) Inclusive Stakeholder Engagement:

Integration of the informal sector requires the involvement of all stakeholders. Governments should create platforms for dialogue between informal workers, formal waste

management companies and policy makers to address the needs and concerns of informal workers. This could include the creation of cooperatives or associations to represent and defend the rights of informal workers.

(c) Capacity Building and Training:

Informal staff should be provided with training and capacity building programmes to improve their skills in the collection and transport of electronic waste. This could include training on safe handling of dangerous materials, sustainable transport technologies and the importance of protecting the environment. Governments and non-governmental organizations could work together to implement such programmes.

Future Research Directions

While the review provides valuable lessons, there are a number of areas where future research could further advance the field of sustainable management of electronic waste:

(a) Life Cycle Assessment (LCA):

Future research should carry out life-cycle assessments of the various e-waste transport strategies in order to quantify their environmental impact. This could include an assessment of emissions, energy consumption and recovery rates related to different modes of transport and technologies.

(b) Network Analysis:

Network analysis could be used to model the flow of electronic waste through transport networks and identify bottlenecks and opportunities for optimization. This could help policy makers and practitioners to design more efficient and sustainable modes of transport.

(c) Impact of COVID-19 on E-Waste Transportation:

The COVID-19 pandemic had a major impact on the generation and transport of electronic waste. Future research should examine how the pandemic affected the practice of e-waste transport in developing countries, including changes in collection methods, routes and the role of the informal sector.

(d) Gender Dimensions of E-Waste Transportation:

The role of gender in the transport of electronic waste is largely neglected in the literature. Future research should examine the impact of gender on participation in the transport of e-waste, the distribution of benefits and access to training and resources.

(e) Innovative Financing Mechanisms:

Research should explore innovative financing mechanisms for sustainable electronic waste management, such as green bonds, impact investing and crowdfunding. Such mechanisms could provide the necessary financing to enable the adoption of sustainable transport technologies and infrastructure.

Conclusion

This systematic review has illuminated key aspects of sustainable management of e-waste shipments in developing countries and highlighted key links between collection, treatment and transport strategies. The findings show that hybrid collection models, adapted to local contexts, are often the most effective to maximize the recovery of e-waste while also addressing logistical problems. Optimized transport networks, supported by route optimization and appropriate vehicle selection, are necessary to link collection points seamlessly with recycling and reprocessing facilities. Case studies such as Agbogbloshie, Ghana and the e-Parisakha initiative highlight the stark contrast between informal and unregulated systems and formalized integrated approaches

and highlight the importance of public-private partnerships, stakeholder involvement and supportive policy frameworks to achieve sustainable e-waste management.

The review also identifies key challenges such as integration of the informal sector, infrastructure constraints and the need for solutions to be tailored to the context. Addressing these challenges requires innovative strategies, including formalizing the informal sector, investing in sustainable transport technologies and adopting the principles of the circular economy. The post-COVID era presents both challenges and opportunities, as the explosion of e-waste generation and disrupted supply chains have accentuated the need for resilient and localized e-waste management systems.

Future research should focus on quantifying transport costs, emissions and recovery rates, and developing context-specific transport models that involve informal operators while protecting their livelihoods. Advanced analytical techniques such as life cycle assessment and network analysis could further improve our understanding of the complex interactions in electronic waste management systems. By addressing these shortcomings, future studies may contribute to more efficient, fair and sustainable solutions for the transport of electronic waste in developing countries.

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