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**LIFE CYCLE ASSESSMENT OF E-WASTE:
APPLICATIONS, GAPS, AND FUTURE DIRECTIONS**

Rachel L. Smith¹, Behzad Esmaeilian², Sara Behdad^{1,*}

¹University of Florida, Gainesville, FL, USA

²Tuskegee University, Tuskegee, AL, USA

ABSTRACT

The increasing volume of electronic waste (e-waste) creates significant environmental and economic challenges which demands practical management strategies. Life Cycle Assessment (LCA) has been known as a principal tool for evaluating the environmental impact of e-waste recycling and disposal methods. However, its application is hampered by inconsistencies in methodology, data limitations, and variations in system boundaries. This study provides a review of current LCA tools used in e-waste analysis and identifies gaps and opportunities for improvement. It categorizes studies into three groups: studies that applied LCA to product and process optimization, impact evaluation, and policy development. Findings reveal that LCA has been helpful in assessing the sustainability of different recycling strategies. However, significant variations exist in methodological approaches and data accuracy. Challenges such as the lack of standardized LCA protocols, the limited availability of region-specific impact data, and inconsistencies in assessment methodologies are still barriers to its widespread adoption. Finally, the study discusses emerging trends in LCA aimed at addressing current gaps, including the incorporation of machine learning and artificial intelligence for predictive modeling, dynamic impact assessment frameworks, and the role of real-time data collection via IoT-based sensors.

Keywords: Lifecycle Assessment, Electronic Waste, LCA, Waste Electrical and Electronic Equipment, E-Waste Recycling, WEEE, Impact Assessment

1. INTRODUCTION

The growing global dependence on electronic devices, the rapid advancement of technology, and increasing consumption have resulted in substantial growth in electronic waste (e-waste) generation worldwide [1]. E-waste consists of unwanted, discarded, or non-functional electronic products. In 2022, global

e-waste generation reached 62 million tonnes, with projections estimating this will increase to 82 million tonnes by 2030. However, only 22.3% of e-waste was properly collected and recycled in 2022, which led to the loss of approximately \$62 billion worth of recoverable resources, including rare earth elements (REEs) essential for industries such as energy and e-mobility. Currently, e-waste recycling meets just 1% of the global demand for rare earth with a significant gap in resource recovery [2]. As the lifespan of electronic devices shortens and consumer electronics production expands, e-waste generation is expected to increase even further.

E-waste creates substantial environmental, economic, and health challenges. Overcoming these challenges requires an understanding of the depth and severity of the problem. To measure these impacts, Life Cycle Assessment (LCA) has been known as a tool for modeling the lifecycle of electronics and evaluating their environmental impacts by providing a structured approach to assess energy consumption, material flows, and emissions throughout a product's life cycle. LCA is particularly useful for evaluating the performance of various recycling and recovery methods and guiding policymakers and industry stakeholders toward more sustainable practices.

Given the advantages of LCA, it is widely applied in the literature to assess e-waste management strategies. The objective of this study is to evaluate the current state of LCA applications in e-waste management, highlight the main limitations of existing tools, and suggest potential improvements. The aim is to evaluate both the strengths and weaknesses of these tools to analyze their role in forming policies and practices towards more sustainable e-waste management.

The remainder of this paper is organized as follows. Section 2 provides an overview of the method used for collecting and analyzing the literature. Section 3 provides an overview of LCA. Section 4 categorizes and discusses the literature under three main categories: applications of LCA for product and process

*Corresponding author: sarabehdad@ufl.edu

optimization, LCA as a sustainability assessment tool, and LCA for policy and system decision-making. Section 5 provides a discussion on challenges and research needs in LCA and finally, Section 6 concludes the paper.

2. LITERATURE COLLECTION AND ANALYSIS

A systematic approach has been used to gather and analyze the relevant literature on LCA tools for evaluating e-waste. A combination of predefined keywords such as "Life Cycle Assessment," "electronic waste," "e-waste", "e-waste recycling," "WEEE", "Waste Electrical and Electronic Equipment", "Modeling", "LCA", and "impact assessment" were chosen to search academic databases, including Google Scholar, Scopus, and Elsevier. The literature collected included peer-reviewed journal articles, conference papers, and technical reports. The initial search provided over 200 publications, out of them 40-50 papers have been selected for further analysis. Figure 1 presents the number of publications from 2014 to 2024 containing the keywords "e-waste" or "electronic waste" and "life cycle assessment" or "LCA" in their titles, abstracts, or keywords, according to Scopus.

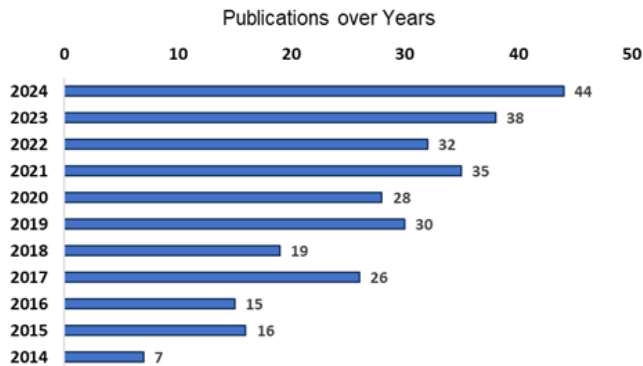


Figure 1: The number of papers published from 2014-2024 with terms "e-waste" or "electronic waste" and "life cycle assessment" or "LCA" in their titles, abstracts, or keywords (obtained from Scopus).

Once relevant sources were identified, each article was reviewed based on the LCA methodology and software tools used, the study's geographic and application domain, and the scope of life cycle inventory data.

The literature was categorized into three groups based on their objectives. These categories reflect the main applications of LCA in e-waste research and are discussed in detail in Section 4. Moreover, the methodological limitations of the studies were examined, including challenges related to data availability, regional variations in e-waste composition, and the accuracy of modeling assumptions. Only articles published within the last decade or those that provide significant contributions were included.

3. OVERVIEW OF LCA

LCA is a systematic methodology used to evaluate the environmental impacts of a product, process, or system. The core idea of LCA is to assess the environmental consequences at every stage of a product's lifecycle, from raw material extraction (cradle) to

its final disposal or recycling (grave). LCA can be conducted using various approaches, depending on the focus and scope of the analysis. The most commonly used approach is "cradle-to-grave," where the entire life cycle of the product is evaluated, from production to disposal. However, other approaches such as "cradle-to-cradle" (emphasizing recycling and reuse in a circular economy) and "gate-to-gate" (focusing only on specific stages, such as manufacturing) can also be utilized based on the study's objectives and scope.

LCA consists of four main stages: (1) *defining the goal and scope*, including the product, functional unit, and system boundaries; (2) *conducting a life cycle inventory (LCI)* to gather data on inputs and outputs; (3) *performing a life cycle impact assessment (LCIA)* to evaluate environmental impacts; and (4) *interpreting results* to draw conclusions and address uncertainties.

The development and application of LCA software packages have advanced over the past few decades. Today, LCA software platforms can have a wide range of capabilities, from simple screening tools to platforms for conducting detailed life-cycle analyses. Examples of widely used LCA software include SimaPro, GaBi, OpenLCA, and Brightway. However, as LCA software continues to develop, significant variations persist in methodology, data availability, and user-friendliness.

Among the literature evaluated in this paper, besides standard LCA software, a portion of the studies utilized grey modeling to evaluate their study, and a portion used material flow analysis (MFA). Grey modeling is a mathematical approach that helps analyze and predict trends in systems with incomplete or uncertain data. It is particularly useful for estimating e-waste generation and environmental impact when historical data is limited. On the other hand, MFA is a method used to track the flow of materials throughout the product lifecycle, and identify resource recovery, waste accumulation, and inefficiencies in recycling systems.

Previous studies have already discussed the importance of LCA methods for e-waste analysis [3]. Withanage and Habib (2021) provided a review of e-waste management research over the past decade and recognized MFA and LCA as underutilized tools in e-waste [4].

Several recent review papers have examined the application of LCA in e-waste management; however, their focus was on specific material recovery processes, such as REEs or lithium-ion batteries (LIBs), or circular economy as a concept, with limited detailed analysis of LCA methodologies and objectives. Table 1 summarizes these existing reviews and their main differences from the present study.

4. LCA STUDIES IN E-WASTE MANAGEMENT

This section categorizes existing literature into three main groups: (1) studies applying LCA for product and process selection and optimization, (2) studies utilizing LCA for impact assessment and comparison, and (3) studies using LCA for policy, system, and infrastructure development.

4.1. Product and Process Optimization

One application of LCA is to facilitate decision-making in product and process optimization. LCA can be used to evaluate the recovery of valuable materials, such as precious metals,

Table 1: Scope of Existing Review Papers on E-Waste and LCA

Review Paper	Focus
Lee et al. (2024) [5]	Environmental and economic aspects of e-waste recycling; general LCA overview.
Prados et al. (2024) [6]	Application of LCA in rare earth magnet production and recovery.
Li et al. (2024) [7]	Review of LCA methods applied to lithium-ion battery recycling.
He et al. (2024) [8]	Circular economy in e-waste with general LCA coverage.
da Silva Müller Teixeira et al. (2020) [9]	LCA evaluation of plastic recycling within WEEE streams.

rare earth elements, and plastics, as well as the associated energy demands and emissions during recycling. This approach helps stakeholders compare different recycling strategies and make informed decisions about process optimization. In a similar way, designers consider LCA and other impact assessment tools to be a major step in the design process of sustainable devices.

A considerable number of studies have used LCA to guide decision-making for product or process optimization; we categorized them into five groups: (1) metal and REE recovery, (2) lithium-ion battery (LIB) recycling, (3) geographically targeted assessments, (4) studies using techno-economic analysis, and (5) product design evaluation.

4.1.1. REE and Metal Recovery: A wide range of studies have used LCA to compare various metal recovery processes. Schwartz et al. [10] used LCA to evaluate the environmental impact of different metal recovery methods from PCBs, including pyrometallurgy, chemical leaching, bioleaching, and hybrid leaching. They found that pyrometallurgy has the lowest environmental impact when fossil-based electricity is used, while hybrid leaching becomes more sustainable with carbon-free electricity. Regardless of the method, urban mining (metal recovery from e-waste) is always more environmentally friendly than primary metal production [10]. Iannicelli-Zubiani et al. [11] examined the environmental impact of a hydrometallurgical process designed to recover precious metals from small e-waste. The LCA results showed that nitric acid leaching contributed the most to environmental impacts (40%–80%), followed by the adsorption process. Li et al. [12] performed LCA to comparing three different recycling technologies including electrochemical recovery, pyrometallurgical, and hydrometallurgical processes for extracting precious metals and REEs from e-waste. Their results indicated that the electrochemical recovery process is the most environmentally friendly, with lower chemical consumption and reduced energy demand, compared to the other methods. Karan et al. [13] conducted a detailed comparative LCA of the glycerol carbonate synthesis process for extracting silica-alumina from e-waste to assess its sustainability relative to traditional solvents. Their analysis demonstrated that this process is both economically and environmentally superior to commercially available alternatives.

Nan et al. [14] also used LCA for metal recovery analysis. They compared acidic and alkaline leaching for recycling metals from PCBs using process simulation and LCA. Acidic leaching achieved higher metal recovery rates but had a greater environmental impact, mainly due to chemical consumption and

emissions [14]. van Nielen et al. [15] analyzed the environmental benefits of industrial-scale NdFeB magnet recycling using an ex-ante LCA. The outcomes showed that recycled magnets can reduce environmental impacts by over 80% compared to primary production [15]. Wang et al. [16] assessed five major REE recycling technologies for NdFeB magnets using LCA. They concluded that most recycling methods reduce environmental impact, but the double salt precipitation process has a higher carbon footprint than primary production. The magnet-to-magnet process is the most sustainable, while molten salt electrolysis ranks second.

Pokhrel et al. [17] analyzed the environmental and economic feasibility of recycling metals from PCBs and mentioned that gold (Au) recovery is the only environmentally beneficial option, while recycling other metals such as copper (Cu), tin (Sn), and lead (Pb) has higher environmental impacts than mining. Despite this, the economic analysis shows net positive benefits, with gold contributing over 84% of revenue. He et al. [18] run an LCA to analyze different methods for extracting gold from e-waste and note that mechanical and electrochemical methods are the most sustainable compared to traditional gold mining. Hydrometallurgical and pyrometallurgical techniques also show significant improvements, while biotechnological methods, though promising, require further optimization. Wirman et al. [19] investigated copper extraction from PCBs through urban mining by using green electrolysis and LCA. The optimal process achieved 85% copper recovery with a 3-hour reaction time and 1.0 mA current. Compared to conventional mining, the method considerably reduced environmental impacts such as global warming potential, acidification, and human toxicity. Frost et al. [20] evaluated a pilot-scale process for reusing and recovering rare earth magnets from 6,100 end-of-life hard disk drives (HDDs) and compared it to traditional shredding using LCA. They found an 86% reduction in global warming potential, with added benefits from locating recovery operations near data centers to improve data security, reduce e-waste transport, and support practical disassembly.

4.1.2. Lithium-Ion Battery Recycling: Given the importance of batteries in electronic devices, a considerable number of studies have used LCA to analyze the recovery of LIBs. To name a few studies, Ren et al. [21] assessed hydrometallurgical, pyrometallurgical, and direct recycling processes for lithium nickel manganese cobalt oxide and lithium iron phosphate batteries. Direct recycling emerged as the most sustainable method. Hydrometallurgical recycling was more viable for commercial use, and pyrometallurgical processes had the highest environ-

mental burden. Adhikari et al. [22] conducted a comparative LCA of three LIB recycling processes: electrochemical leaching, peroxide-based leaching, and sulfur dioxide (SO₂)-based leaching. Their analysis showed electrochemical leaching is a more sustainable alternative to conventional LIB leaching methods. Castro et al. [23] conducted an LCA to evaluate the feasibility of a LIB recycling process using citric acid as a green leaching agent. They found that citric acid reuse and process optimization reduced environmental impacts, particularly in terrestrial toxicity, mineral resource scarcity, and human non-carcinogenic toxicity. The economic analysis showed that the process was profitable.

4.1.3. Geographically Targeted LCAs: Some of the studies have been focused on a particular geographical region. Ikhlayel et al. [24] investigated the environmental impact of various e-waste management technologies in Jordan. They applied LCA and assessed five advanced treatment methods, including sanitary landfilling, targeted recycling of metals and valuable materials, and incineration of plastics and hazardous PCB components. With a focus on six major e-waste products that make up a significant portion of Jordan's waste stream, they evaluated 30 different management scenarios to determine the most sustainable approach to e-waste handling [24]. Also, Ismail and Hanafiah [25] evaluated four e-waste management options in Malaysia including landfilling, direct incineration with energy recovery, recycling without energy recovery, and recycling with energy recovery. They used LCA and MFA as the main assessment tools, focused on printed wire boards (PWBs) from mobile phones, and introduced two performance indicators: waste reduction rate and environmental cost-benefit ratio. Due to limited local data, they used various sources for their analysis. Surprisingly, their results showed that direct incineration with energy recovery was the most beneficial method, which contradicted previous studies. In another study, Fiore et al. [26] analyzed e-waste management in a large-scale Italian recycling facility for three common categories of e-waste in EU: cooling equipment, large household appliances, and TVs/screens. They compared two processing methods: partial recycling with landfilling and complete recycling with minimal incineration. The results showed that complete recycling improved recycling rates for cooling equipment, household appliances, and TVs/screens. Although metal recycling provided environmental benefits, transportation and the incineration of polyurethane and rubber contributed the most to environmental impact [26].

4.1.4. Techno-economic Assessment: Besides LCA, some studies have performed techno-economic analyses for product and process optimization. For example, Wu et al. evaluated the techno-economic feasibility of recovering gallium from e-waste using three different extraction methods: primary production from Bayer liquor, acid leaching via hydro-annealing, and bioleaching with microorganisms. The results showed that bioleaching is more cost-effective than acid leaching but still higher in cost than primary production [27]. In another study, Pérez-Cardona et al. compared Molten Salt Electrolysis and Room Temperature Ionic Liquid (RTIL) electrochemical processes for refining REEs such as Dysprosium (Dy) and Neodymium (Nd) from recycled e-waste. RTIL provides environmental advantages,

particularly in lower CO₂ emissions and energy consumption, however, it performs poorly in ozone depletion and is economically unfeasible due to high material costs. The analysis suggests that both processes are currently unprofitable in the U.S. due to high rare earth oxide feedstock costs [28]. Moreover, Jin et al. assessed different value recovery strategies for HDDs using LCA and found that reusing HDDs is the most environmentally friendly option. Magnet-to-magnet recycling and direct reuse of magnet assemblies also provide benefits but require improvements in logistics and infrastructure. Metal recovery methods, such as hydrometallurgical and pyrometallurgical processes, show limited environmental advantages due to high energy consumption and material losses [29]. Deng et al. performed an economic feasibility assessment for the use of gas-assisted microflow extraction (GAME) to recover precious metals from PCBs. Compared to conventional solvent extraction methods, GAME provides higher yield, lower chemical consumption, and better scalability for low-concentration metal recovery [30]. Another study is the work of Sanchez Moran et al., in which they analyzed the techno-economic feasibility and life cycle impact of recovering didymium oxide from HDD shreds using an acid-free dissolution process. The process proves economically viable, with a lower greenhouse gas footprint [31]. Mangmeechai estimated the life cycle of greenhouse gasses and the financial life cycle cost (LCC) of household e-waste, specifically for the top 4 most common types of electronic waste in Thailand. They found that the recycling of all four e-waste types resulted in a net benefits range of 6.8-45 million USD [32].

4.1.5. Product Design: Some of the studies have used LCA for product design evaluation. To name a few, Bahakar et al. [33] assessed the life cycle environmental impact of three common monitor types (CRT, LCD, and LED) in India and China. They performed LCA using Umberto software following ISO 14040 standards for each monitor option. Lu et al. [34] did not conduct an LCA however, they developed an interactive tool for product designer namely, ecoEDA, that helps electronics designers reuse components from discarded devices. The tool keeps a library of salvaged components for easy integration and provides alternative part suggestions. In their review of LCA uses in eco-friendly product design, Kiddee et al. [35] presented many advantages, such as estimating the effects of material consumption, which influences eco-design products and provides better decision-making when considering end-of-life product design. Similarly, Goh et al. [36] conducted LCA to evaluate the environmental sustainability of e-plastic concrete as a potential solution to the e-waste crisis. Their analysis compared e-plastic concrete with four scenarios using different types of binders. In another study, Farkas et al. [37] presented a sustainable alternative to traditional PCBs using flax fiber-reinforced polylactic acid composites to reduce e-waste. Their study demonstrated up to 90% substitution of FR4-based materials, with structural reliability up to 200°C and a 10% reduction in environmental impact based on LCA.

Beyond material selection and structural innovations, product design can also support more sustainable end-of-life outcomes through strategies such as reuse and remanufacturing. Nikolic et al. [38] assessed the environmental and economic impact of dif-

ferent end-of-life strategies for coffee machines. They compared manufacturer-led take-back systems (reuse, remanufacturing, and component recycling) with conventional e-waste disposal methods. LCA results revealed that reuse and remanufacturing can reduce GHG emissions by 15–39% compared to standard e-waste recycling. Also, remanufacturing and reuse lower production costs (by up to 66.5%) [38].

4.2. Environmental Impact Evaluation Tool

Another common application of LCA is for environmental impact evaluation and comparison purposes. LCA can be used to evaluate the environmental impacts of e-waste disposal through landfill or incineration and help with quantifying the long-term consequences of these disposal methods.

4.2.1. Environmental Sustainability: Peydayesh et al. used LCA tools to compare the environmental sustainability of their proposed method of gold extraction from e-waste to conventional e-waste management practices. They showed a 43–53% decrease in ecosystem damage by utilizing pea protein-based aerogels [39]. To address the limited availability of detailed LCAs on gold recycling from e-waste, He et al. [18] conducted a comparative assessment of alternative recycling methods versus traditional mining. Their analysis incorporated cumulative energy demand as a sustainability indicator to evaluate the environmental impacts associated with each method. To evaluate the environmental impacts of three alternative recycling methods for valuable materials from e-waste, Li et al. [12] showed that the electrochemical recovery process outperformed both hydrometallurgical and pyrometallurgical approaches in most impact categories, with hydrochloric acid identified as the main environmental burden in the electrochemical method.

4.2.2. Geographic Sensitivities: Besides being used as an evaluation tool, the geographical location of studies appears to significantly influence impact assessments. The accuracy of e-waste impact assessments greatly depends on the availability of region-specific data. Song et al. [40] used LCA to investigate formal e-waste recycling enterprises in China. They incorporated a sensitivity analysis to address concerns on variations in assumptions and methodological choices as potential sources of LCA inaccuracies. In a review conducted by Ismail et al., 40% of the 150 analyzed papers utilized LCA, with a common limitation being the lack of technical system availability, particularly due to insufficient data. They specifically cited Song et al., [40] who had to omit the evaluation of the management chain in electronic waste recycling and recovery from their LCA of an e-waste treatment enterprise in China, as the country lacked an established collection and transportation system necessary for a detailed assessment [41].

Rasheed et al. [42] performed an LCA to evaluate the environmental impact of recycling laptop computers and LCDs in Pakistan. Their overall findings were that 80% of the resulting impact on Pakistan's natural resources could be reduced by implementing efficient electronic recycling facilities. They paired this outcome with a Material Weight Recycling indicator to determine that proper recycling could have a significant positive economic impact on the country. The strategic combination of

multiple impact assessments distinguished their work and showed the lack of studies on e-waste processing in developing countries that consider both economic and environmental sensitivities [42].

Figure 2 presents the number of papers published from 2010 to 2025 with the terms "e-waste" or "electronic waste" and "life cycle assessment" or "LCA" in their titles, abstracts, or keywords, based on country or territory (obtained from Scopus). Although publication location does not necessarily show the actual geographic focus of the study, Figure 2 may provide information about the distribution of research output.

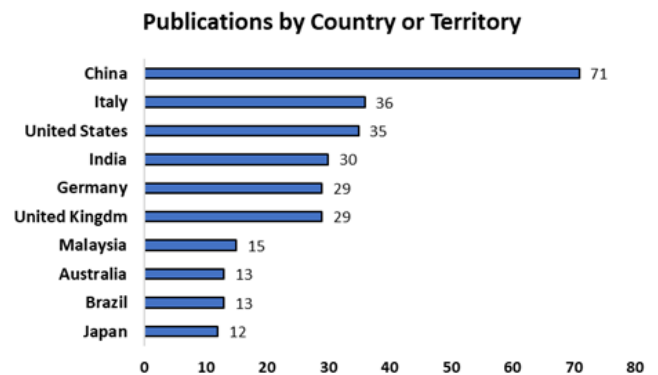


Figure 2: Geographic distribution of e-waste and LCA publications (2010–2025) based on country of author affiliation (Scopus).

4.3. Policy and System Development

Impact assessment tools are valuable for guiding policy and recycling infrastructure development, including evaluating extended producer responsibility (EPR) schemes, infrastructure performance, and opportunities to improve recycling rates.

4.3.1. Policy and Infrastructure: To name several studies that use LCA for policy and system analyses, Jaunich et al. [43] analyzed the costs and environmental impacts of e-waste management under EPR policies. They used data from Washington State's EPR program and developed a quantitative framework to assess collection, transportation, processing, and disposal. Their findings show that drop-off collection using fossil-fuel-powered vehicles significantly increases costs and emissions. Islam and Iyer-Raniga [44] examined the environmental impact of recycling PCBs by comparing local recycling in Australia to the current practice of overseas processing. They used SimaPro and Ecoinvent databases and analyzed four recycling scenarios. Their findings showed that integrated material and energy recovery in Australia was the most sustainable option, while landfilling and direct incineration were the least favorable. Local recycling significantly reduced global warming impact (by 53%) and fossil resource scarcity (by 98%) compared to overseas processing. Hong et al. [45] showed that recycling with an end-of-life disposal plan is the most environmentally sustainable option for e-waste. Landfilling has a lower impact than incineration, but both are less favorable than recycling. They stressed the need for clear responsibilities among manufacturers, retailers, recyclers, and consumers for a more sustainable system.

Studies have also analyzed policies such as energy sources and take-back programs. Torrubia et al. [46] examined copper recovery from e-waste using pyrometallurgical processes and LCA. They compared conventional recovery, hydrogen-based recovery with green energy, and hydrogen-based recovery using grid electricity. Results showed that green hydrogen can cut emissions by up to 97%, while hydrogen from grid electricity may increase emissions beyond conventional methods. Also, burning plastics in waste PCBs significantly contributes to CO_2 emissions, which shows the need for pre-sorting plastics before smelting [46].

4.3.2. Social and System Impacts: Social Life Cycle Assessment (S-LCA) is an underused LCA approach that evaluates social impacts for all stakeholder groups throughout the product life cycle. Traverso et al. utilized S-LCA to conduct a social hotspot analysis of e-waste management in Ghana and Nigeria to identify potential risks to e-waste workers and local communities. They acknowledged the importance of collecting site specific data and recommended that future studies include an assessment of indicators relevant to the economic aspect of the informal sector in e-waste recycling [47]. Cataldo et al. [48] analyzed the environmental impact of formal and informal LCD monitor waste management in Santiago, Chile. They concluded that formal treatment companies outperform informal recyclers in all environmental categories. Their municipal-level analysis showed that collaborating with the informal sector for collection while using formal recycling delivers the best circularity outcomes. Esopere et al. assessed e-waste management in Yaoundé, Cameroon, using LCA and System Dynamics model analysis. They noted informal recycling and open burning of plastics as major contributors to environmental and health risks [49].

5. DISCUSSION

This section discusses the main limitations and emerging solutions in applying LCA to e-waste systems by elaborating on data challenges, methodological gaps, and opportunities provided by digital and hybrid approaches (as summarized in Figure 3).

5.1. Current Challenges

Data Availability and Quality: A fundamental limitation of LCA in e-waste studies is the scarcity of high-quality and representative data. Villares et al. [50] investigated the application of ex-ante LCA in product design and noted its uncertainties due to the predictive nature of early-stage assessments. They emphasized that uncertainty is a fundamental characteristic of ex-ante LCA as it depends on assumptions about future technologies, material flows, and production processes that have not yet been realized. Even in retrospective LCAs applied to existing products and services, they identified major sources of uncertainty, including boundary definition, site-specific variability, data limitations, functional unit selection, spatial heterogeneity, allocation methods, and environmental uniqueness. About the ex-ante application, they reported three main challenges: defining the goal and scope of the LCA at such an early predictive stage, processing data uncertainty caused by diminished quality, and establishing confidence in data analysis. Also, Van Schaik et al. [51], in their development of a dynamic framework of recycling performance, found that current impact assessment tools lacked the knowledge

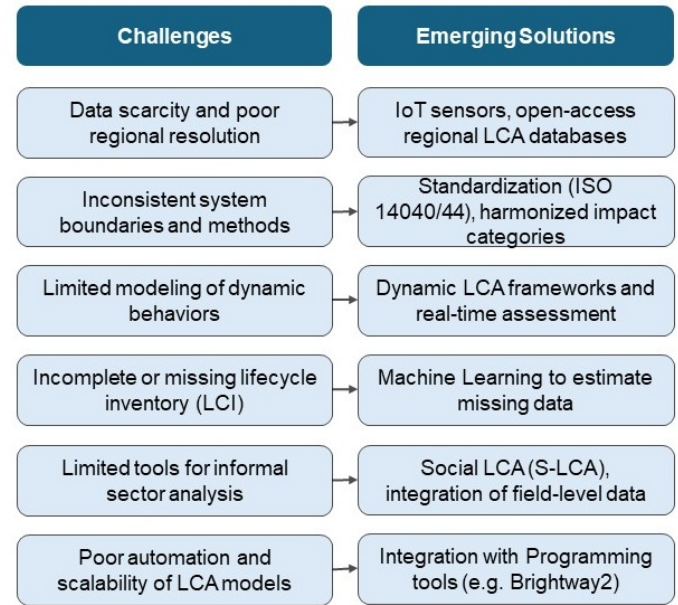


Figure 3: Summary of Challenges and Emerging Solutions.

for accurate prediction of recycle quality and recycling performance from product design.

Streicher-Porte et al. [52] discussed the challenge of assessing informal e-waste recycling systems in Delhi due to incomplete economic and material flow data, which impacted model accuracy. Hong et al. [45] encountered similar limitations when conducting an LCA on China's e-waste management system, where they depended on European datasets due to the unavailability of domestic chemical production data.

Methodological Inconsistencies: Another major challenge in LCA is the lack of methodological standardization which results to inconsistencies in system boundaries, impact categories, and functional unit definitions. To address this, adopting standardized frameworks such as ISO 14040/44 and the use of consistent impact assessment categories will improve comparability among studies. He et al. [8] identified significant variability in LCA outcomes within the formal e-waste recycling sector and emphasized the need for standardized protocols to improve data reliability. They found that the diverse methodologies applied to the formal e-waste recycling sector have resulted in a wide range of findings. This inconsistency, driven by differing assumptions and variables, contributes to conflicting results, increasing the risk of misinterpretation and personal bias. As a solution, they emphasized the need for standardized protocols to improve the quality and comparability of LCA studies within the formal e-waste recycling sector [8].

Scope and Spatial Gaps: Defining system boundaries, selecting functional units, and incorporating spatial heterogeneity are other methodological challenges in LCA applications. Villares et al. [50] emphasized difficulties in setting the goal and scope of ex-ante LCAs, which further compound data uncertainty and limit predictive accuracy. Arduin et al. [53] found that transport-related emissions in e-waste recycling were often omitted or estimated without region-specific data, which results to inaccuracies in impact assessments.

5.2. Emerging Solutions and Opportunities

Novel Methodological Approaches: Several studies have tried to address LCA limitations through methodological modifications and data-driven approaches. To name several studies, Chen et al. [54] developed their own method to process the incomplete data and make predictions more accurate. They found two complications that make e-waste recycling models more sensitive to modeling errors: limited e-waste supply data and discrepancies with purchase and demand that temporarily destabilizes the supply chain. In order to mitigate these complications, they utilized a control method that they likened to the modern control method in order to process incomplete information. Another example of challenges with utilizing LCA software to its full potential is Streicher-Porte et al. [52], who employed a software-supported MFA to examine the life cycle chain of a personal computer. The emphasis was on the informal sector of the Delhi recycling industry. They acknowledged that a limited database significantly impacted the accuracy of model predictions but found that combining a systematic analysis of material flows with economic data and field assessments yielded promising results.

Duman et al. [55] developed a nonlinear multivariate grey Bernoulli model to reliably forecast electronic waste generation and flow predictions with limited data. Juanich et al. [43] presented a quantitative framework to estimate life-cycle impacts and costs of e-waste management. Their model addresses the noted lack of variability of life-cycle data, specifically in e-waste aggregation. Arduin et al. [53] found that transport during e-waste end-of-life management was either completely omitted or the distances used were solely based on estimates instead of the actual distance. As such, they attempted to identify the contribution of transportation in e-waste recycling LCA outcomes using a tablet recycled in France as a case study.

To support end-of-life decision-makers, Hong et al. conducted an LCA to assess the environmental ramifications of e-waste management in China. They specifically addressed uncertainties arising from the lack of region-specific data, as both the formal and informal recycling sectors require quantified impact assessments. Due to the absence of domestic chemical production data, they used European datasets and conducted sensitivity and uncertainty analyses to improve the credibility of their findings. [45]. Similarly, Debnath et al. [56] discussed that the absence of standardized data prevented them from conducting a full LCA, where they had to use generalized comparative analyses instead. Variability in transportation modeling further complicates LCA reliability. They developed two conceptual frameworks for integrated metal recovery from e-waste technology. The impact of these two options were evaluated with a generalized comparative analysis using the principles of LCA [56].

LCA models often do not represent the complexity of e-waste flows between different disposal and recycling pathways. Hybrid LCA approaches that combine process-based, economic input-output (EIO), and dynamic modeling provide a better assessment of environmental impacts.

AI and Internet of Things: In response to the significant issue is data scarcity, particularly in developing regions, where e-waste management is often informal, and material flow data is limited, global data integration through open-access LCA databases

can help centralize impact factors. Also, the emergence of the Internet of Things (IoT), AI, and smart devices could be one solution to address data gaps in LCA. Iqbal et al. [57] discussed how embedding IoT sensors to track voltage, current, door closures, and blade rotations would improve appliance lifespan assessment and facilitate strategies such as reuse, repair, remanufacturing, and cascading.

Missing or incomplete data is another limitation that lead to many assumptions that reduce the precision of LCA outcomes. Machine learning (ML) and AI algorithms can be trained on existing datasets to predict missing values and improve the quality of life cycle inventory data. Recent studies have acknowledged the application of ML for LCA. According to Ghoroghi et al. ML helps with managing large datasets, filling missing data gaps, and optimizing impact assessments [58]. Romeiko et al. [59] performed a review of studies that applied ML for LCA and reported that Artificial Neural Networks (ANNs), Random Forest, and Support Vector Machines are the most commonly used models, often trained on small datasets in such studies. In another direction, Fatriansyah et al. described the use of deep learning to predict LCA scores for detergent plastic packaging products [60].

Traditional LCA tools are static and do not consider real-time shifts in material recovery rates, supply chains, and regulatory changes. The development of AI-powered LCA tools that integrate real-time IoT sensor data and predictive modeling will facilitate dynamic updates to impact assessments and making LCA more responsive to changing conditions. Martínez-Ramon et al. [61] provided a review of ML applications in LCA for process modeling. They identified three main frameworks for integrating ML into LCA workflows: (1) using ML as a surrogate model to replace full process simulations for rapid life cycle inventory (LCI) predictions, (2) substituting complex subprocesses within simulations with ML models to reduce computational demands, and (3) applying ML to directly correlate system characteristics with LCI or LCA performance indicators for optimization.

LCA Automation: Also, efforts have been made by the research community to automate LCA [62, 63]. There is a growing effort to integrate programming languages with LCA software to improve automation and data analysis [64]. Python, in particular, has been used in LCA research, with tools such as Brightway2 to create an open-source framework for life cycle modeling [65]. However, challenges exist in terms of user accessibility, the steep learning curve for non-programmers, and the need for standardized databases and methodologies.

6. CONCLUSION

This paper reviewed the application of LCA in e-waste management by categorizing studies into product and process optimization, environmental impact evaluation, and policy development. LCA has shown promise in identifying sustainable recycling strategies and supporting informed decision-making. However, its broader adoption is hampered by challenges such as inconsistent methodologies, limited region-specific data, and lack of standardized protocols. Recent advancements such as hybrid modeling, machine learning, and IoT-enabled data collection provide promising directions to improve LCA accuracy.

This review has several limitations. Given the diversity of

processes, products, and regional domains, fully categorizing the literature was challenging. The variation in methodologies, system boundaries, and scope of analysis complicates direct comparisons between studies. Also, this review provides only a qualitative overview of existing research with limited quantitative analysis. Future work should apply meta-analysis or data-driven approaches to compare outcomes and assess methodological consistency. Moreover, the study does not fully discussed real-world implementation barriers, such as cost constraints and industry implementation. Expanding the review to include empirical validation and real-world case studies would improve its impact.

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