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Review Article

Life Cycle Assessment and Material Flow Analysis Research on Electronic Waste in Asia: Trends, Gaps, and Insights

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Abstract
The term "electronic waste" or "e-waste" refers to a broad array of discarded electronic products and electrical appliances that have reached the end of their useful lives. These include computers, smartphones, televisions, and refrigerators. Over the past three years, the volume of e-waste has surged, from 24.9 million metric tons (MMT) in 2019 to 33 MMT in 2022, as reported by the United Nations in The Global E-Waste Monitor 2024. This increase is driven by the expansion of the electronics industry and the increased usage of electronic devices. Life Cycle Assessment (LCA) and Material Flow Analysis (MFA) are key methodologies used to assess the environmental impact and material flow of e-waste management, respectively. However, many MFAs fail to track the flow of secondary materials that are reused, recycled, and reduced in the new products. This study addresses these gaps by analyzing e-waste management trends in Asia using a systematic literature network analysis (SLNA). SLNA combines a systematic literature review (SLR) and bibliometric analysis (BA) to offer a comprehensive review from various perspectives. This study aims to identify underexplored topics and trends, provide insights that can shape future research directions, and inform government policies on e-waste management in Asia.

Keywords: LCA; recycling; SLNA; e-waste management; waste management trends

1. Introduction

The term "electronic waste" or "e-waste" encompasses a wide variety of discarded electronic products and electrical appliances that have reached the end of their practical lifespan (Arain et al., 2022). This can include a wide range of devices, such as computers, smartphones, televisions, refrigerators, and other electronic devices that are no longer functional. An increase in e-waste has been evident over the past three years. The total e-waste in 2019 was 24.9 MMT (Islam et al., 2024). According to the United Nations report in The Global E-Waste Monitor 2024, the amount of e-waste in 2022 reached 33 MMT. This increase in e-waste can be attributed to the growth of the electronics industry and the increased usage of electronic devices.

LCA is a method for analyzing the environmental impacts of the entire range of activities involved in the production and use of a product, including waste management processes (Arushanyan et al., 2014). LCA is used to determine the sustainability of knowledge and evaluate the environmental impact of resource utilization (Visentin et al., 2020). MFA assesses the state and changes in flows that can link the sources, processes (flows), and final outcomes of a material (Brunner & Rechberger, 2020). The detection of materials is challenging because of the lack of tracking systems. Many MFAs focus on the collection of e-waste products but fail to track the flows of secondary materials that have been reused, recycled, and reduced in new products (Arain et al., 2022).

Previous studies have explored the application of life cycle assessment (LCA) in e-waste management in general. For instance, Li et al. (2019) evaluated electrochemical recovery technologies to assess and compare their environmental performance in extracting base metals, precious metals, and rare earth elements (REE) from electronic waste. Similarly, Islam et al. (2024) focused on sustainable systems, examining the lifespan of e-waste and outlining key impacts and strategic approaches to its management. Moreover, methodological approaches to e-waste management have become increasingly important for informing policy development across Asian countries. Addressing this gap, the present study investigates the evolving trends and research gaps in e-waste management in Asia by employing the Systematic Literature and Network Analysis (SLNA) method. SLNA combines the strengths of systematic literature review (SLR) and bibliometric analysis (BA) to provide a more comprehensive and multi-perspective review framework (Colicchia et al., 2019). The primary objective of this study is to identify underexplored or overlooked topics, enabling researchers and policymakers to recognize emerging themes and guide future research based on trend analysis derived from the literature review.

2. Methods

2.1 Concept of the Study

To explore emerging trends and uncover research gaps in life cycle assessment (LCA) studies on e-waste management, this study adopts a methodological approach that combines a Systematic Literature Review (SLR) and Bibliometric Analysis (BA), hereafter referred to as SLNA. This hybrid method enables a comprehensive understanding of the factors that shape LCA in the context of e-waste. The methodological steps were aligned with those proposed by Colicchia et al. (2019) and Wibowo et al. (2024). Although BA serves as a practical and insightful tool for mapping existing research through citation patterns, keyword clustering, and abstract-title networks, it offers limited depth in content interpretation. To address this limitation, the SLR complements the analysis by providing a more detailed and structured review of the literature, delivering richer insights more efficiently than traditional review approaches (Arrigo, 2018; Ramadan et al., 2022).

The methodological framework guiding this study is illustrated in Figure 1, with a thorough explanation of the data collection and analytical procedures provided in subsequent sections. The core of this review comprises three central research questions. First, it investigates the prevailing research interests and identifies existing knowledge gaps, as well as potential directions for future work in the field of e-waste management. Second, it examines how e-waste management is defined and contextualized within the life cycle assessment framework, shedding light on the conceptual clarity across various studies. Third, it aimed to identify the key factors that influence the successful implementation of LCA in e-waste management practices, such as methodological choices, data availability, and institutional or policy-related drivers.

The second stage involved establishing a clear search strategy to extract relevant metadata from scientific literature databases. This process was guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) methodology, as recommended by Page et al. (2021). Details regarding the procedures for selecting, evaluating, and including studies are provided in the subsequent "Data Collection" subsection. For this purpose, the Scopus database was utilized, with the metadata retrieved on March 18, 2024, serving as the foundation for bibliometric and systematic review analysis.

2.2 Data Collection

The data collection steps are briefly described as they can be used to replicate future methodology. First, several keywords were entered in the Scopus database. The selected keywords were "life cycle assessment" AND "waste management" AND "electronic waste" AND "material flows analysis". In this stage, 956 documents were identified. Automatic screening tools were then applied to exclude documents based on the publication year, document type, and country/territory. The publication years considered were from 2015 to 2024 (829 documents), the document types were articles (556 documents), and the countries and territories included were China, Japan, Malaysia, India, Thailand, South Korea, Indonesia, Hong Kong, Sri Lanka, Singapore, Taiwan, Pakistan, Israel, Saudi Arabia, Vietnam, Palestine, the United Arab Emirates, Philippines, Bangladesh, Iran, Qatar, Oman, Nepal, Jordan, Kazakhstan, Lebanon, and Turkey (121 documents). At the end of the screening process, 121 documents related to the entered keywords were obtained. Manual screening was conducted based on titles and abstracts, resulting in 121 documents being included in the BA.

2.3 Data Analysis

This study used two primary software tools, VOSviewer and Orange Data Mining version 3.36.2, to develop bibliographic visualizations, perform mapping, and carry out data analysis. VOSviewer was employed to construct co-authorship networks, including both authors and countries, as well as co-occurrence maps based on keywords and terms extracted from titles and abstracts. It was also used to analyze citation networks of the reviewed documents. To complement this, Orange Data Mining version 3.36.2 provided a more detailed analysis of the keywords, titles, and abstracts. The results from both tools were compared and integrated to produce a comprehensive, insightful, and critical view of the current research landscape. Before the main analysis, several preprocessing steps were conducted, including VOS mapping, word cloud generation, and topic modeling, which were used to develop the network maps.

For the co-authorship analysis of authors, the minimum number of documents per author was set to 2, with a minimum of 10 citations per author, and all sets of networks were displayed on the map. In the co-authorship analysis of countries, the threshold was set at a minimum of 2 documents per country and at least 10 citations per country. For the citation network analysis, the minimum citation count per document was set to 4, and only the most extensive network clusters were displayed. In the co-occurrence analysis of author keywords, a minimum occurrence of 2 was applied, while for terms extracted from titles and abstracts, the threshold was set to 5 occurrences. For the word clouds and topic modeling, preprocessing included transformation steps such as converting text to lowercase, removing accents, and parsing HTML. Multidimensional scaling and marginal topic probability analysis involved tokenization using the regular expression pattern \w+, filtering out English stop words and numbers, and setting the document frequency range to 0.10–0.90. Additionally, Latent Dirichlet Allocation (LDA) was configured with six topics for both titles and abstracts as well as for author keywords.

2.3.1 VOS Techniques

The metadata collected in this study served as the base for subsequent analyses. Several types of bibliometric mapping were conducted, including co-authorship networks at both the author and country levels, citation networks, and co-occurrence analysis of keywords, titles, and abstracts. These analyses employed the Visualization of Similarities (VOS) technique, which is the core method used in VOSviewer. This technique is widely regarded as offering more effective metadata visualization compared to other distance-based mapping methods, such as VxOrd, Kopcsa-Sciebel, and Multidimensional Scaling (MDS). In VOS, nodes such as keywords or authors are positioned based on the strength of their relationships, with shorter distances indicating stronger associations. As a result, the VOS cluster map avoids overlap between nodes, ensuring clarity in the visualization (Van Eck and Waltman, 2010). The links that appear in the VOS maps represent the relationships between nodes or keywords. Each link has a strength value, where higher values indicate stronger connections. For example, the strength of a link may represent the number of shared references between two documents, joint publications by two authors, or how frequently two terms co-occur in the literature (Ikhlas and Ramadan, 2024). Thicker links and larger nodes reflect stronger and more frequent associations (Sawassi and Khadra, 2021). A more detailed explanation of the statistical principles behind VOS mapping is available in the work of Van Eck and Waltman (2010) and Waltman et al. (2010).

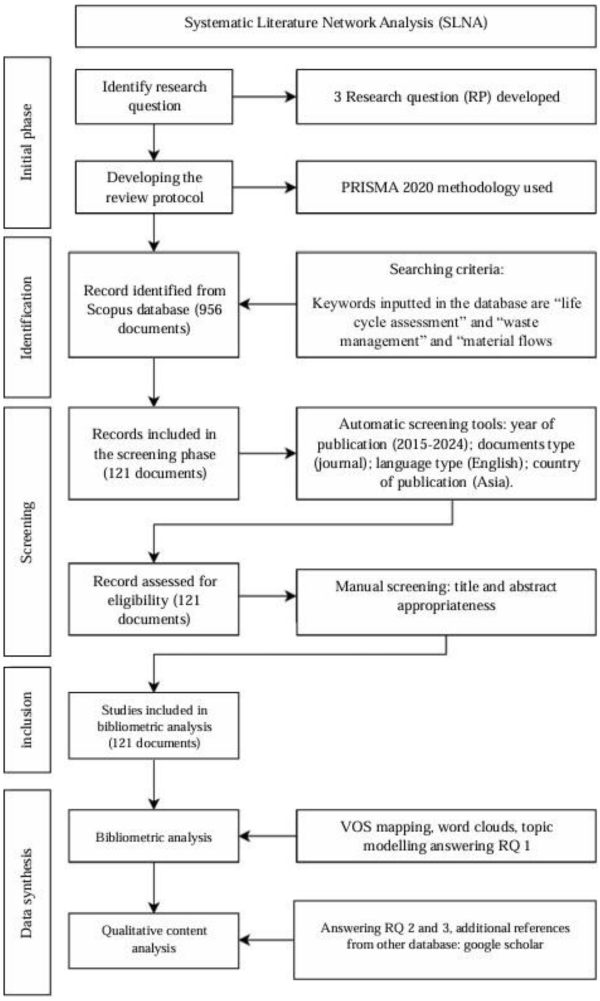


Figure 1. Conceptual framework of review methodologies

This study examined citation and co-authorship networks, focusing on both individual authors and countries. Although the co-authorship country map is included in the manuscript, the results of co-citation and co-authorship analyses are presented in tabular form, highlighting the most frequently cited publications and the most productive authors in the field. The co-authorship analysis aimed to reveal patterns of collaboration among researchers, institutions, and nations within the context of LCA research on e-waste. Such collaboration insights are valuable, as they help promote innovation and offer perspectives on issues such as short-lived climate pollutant emissions.

In line with this, the study also identified the most cited articles in e-waste research to assess the extent and depth of scholarly engagement with the topic across various journals. Additionally, co-occurrence analysis was carried out using keywords and terms extracted from titles and abstracts to capture recent trends and research gaps in LCA-related studies on e-waste. The keyword co-occurrence analysis focused on author-supplied keywords, as well as terms from titles and abstracts within the collected metadata (Ikhlas and Ramadan, 2024). Using VOSviewer, these keywords and terms were grouped into clusters based on their relevance and similarity. In the resulting visualizations, larger nodes indicate the most frequently used terms, representing dominant themes in the literature (Kholidah et al., 2022).

2.3.2 Big Data Analytic

To visualize the research corpus, this study employed a combination of word cloud analysis, topic modeling, multidimensional scaling (MDS), and VOSviewer, as shown in Figure 2. In the word cloud, the size of each word reflects its frequency in the dataset (Feicheng and Yating, 2014). Words that appear more frequently are displayed in larger fonts and placed closer to the center, while less frequent terms are smaller and positioned toward the edges (Ikhlas and Ramadan, 2024). Latent Dirichlet Allocation (LDA) was used to uncover hidden topics within the titles, abstracts, and keywords of studies focusing on LCA in e-waste management. As a widely adopted technique in natural language processing (NLP), LDA uses machine learning algorithms to detect term co-occurrence patterns and group related words into thematic categories (Li et al., 2021; Mohr and Bogdanov, 2013).

In contrast to the clustering methods used in VOSviewer, LDA permits overlapping of keywords across different topics, making it particularly effective in identifying nuanced or less visible themes that may not be captured through traditional VOS mapping. To validate the outcomes of the topic modeling, the study applied both Multidimensional Scaling (MDS) and marginal topic probability (MTP) analyses. MDS was used to evaluate the similarity among topics, where a shorter distance between data points indicates a closer conceptual relationship. This method is useful for simplifying complex datasets while retaining their essential structure (Yao et al., 2022; L. Yao et al., 2016). An MTP bar plot was also generated to illustrate the prominence of each topic within the corpus, enabling the identification of both dominant and less emphasized themes based on the LDA model results (Abayomi-Alli et al., 2022).

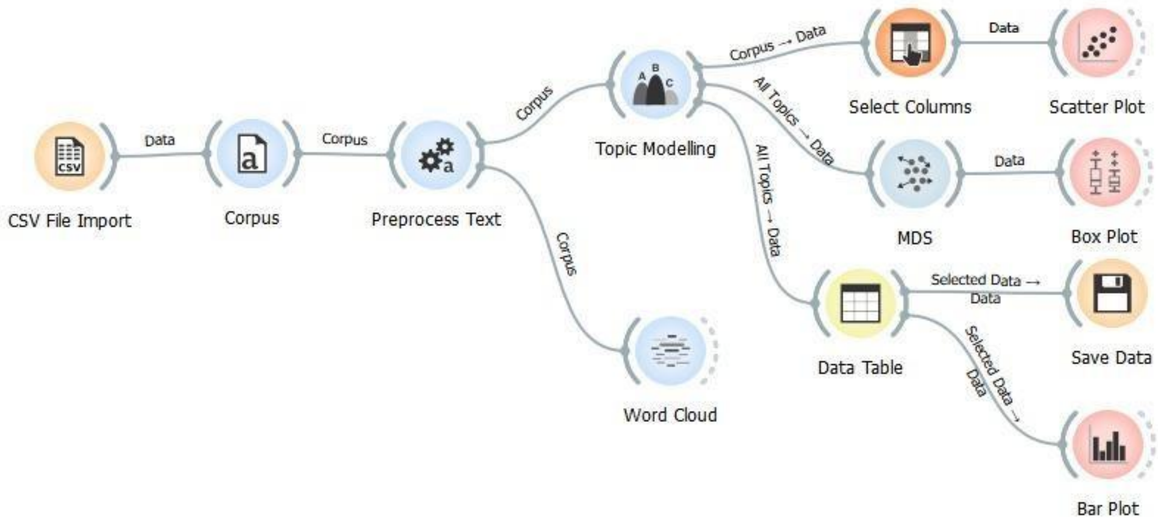


Figure 2. Big data modeling framework using Orange Data Mining 3.36.2

2.3.3 Qualitative content analysis

Qualitative content analysis was applied to examine and interpret the literature on LCA in e-waste management. A mixed approach, combining both inductive and deductive methods, was used to define, review, and synthesize key concepts based on the available body of research. This analytical approach is sufficiently robust to capture research trends, clarify conceptual definitions, and extract relevant insights from the literature, offering a comprehensive understanding of the current state and direction of studies in this field (Mayring, 2015).

3. Result

3.1 Bibliometric analysis results

This subsection focuses on the results of BA, encompassing the phases of identification, screening, and inclusion. The analysis emphasizes the outcomes of VOS techniques, word clouds, and topic modeling.

3.1.1. Current Research Trends and Atatus

Research on the LCA of e-waste, as depicted in scientific literature, can be examined based on the publishing journal and the countries of the researchers' affiliations, as illustrated in Figure.3. When looking at the affiliations of the research contributors by country, China leads the pack, followed by the United Kingdom, United States, Japan, and Germany. The most recent studies on the LCA of e-waste originated in Indonesia, Singapore, and Taiwan, whereas the earliest studies were from Japan, Malaysia, and Sri Lanka. As shown in Figure 3 (b), it is possible to form various clusters that represent the collaborating countries and the closely related themes of their papers. For example, research from China, Canada, India, and Singapore are marked in blue, indicating that similar or closely related research focuses on the LCA of e-waste.

3.1.2. Title, Abstract, and Keywords Mapping

The text mining of titles and abstracts can yield several insights. The earliest terms, such as waste mobile phones, metals, printed circuit boards, and landfills, suggest that the focus of research prior to 2018 was on the sources of e-waste. The most recent terms, including emission control, e-waste, economic and social effects, and sustainability, signal a shift in research towards the potential impacts of climate change and the economic value derived from LCA and MFA. These methodologies can enhance e-waste management by considering the environmental impacts and material flows, ultimately leading to economic advantages.

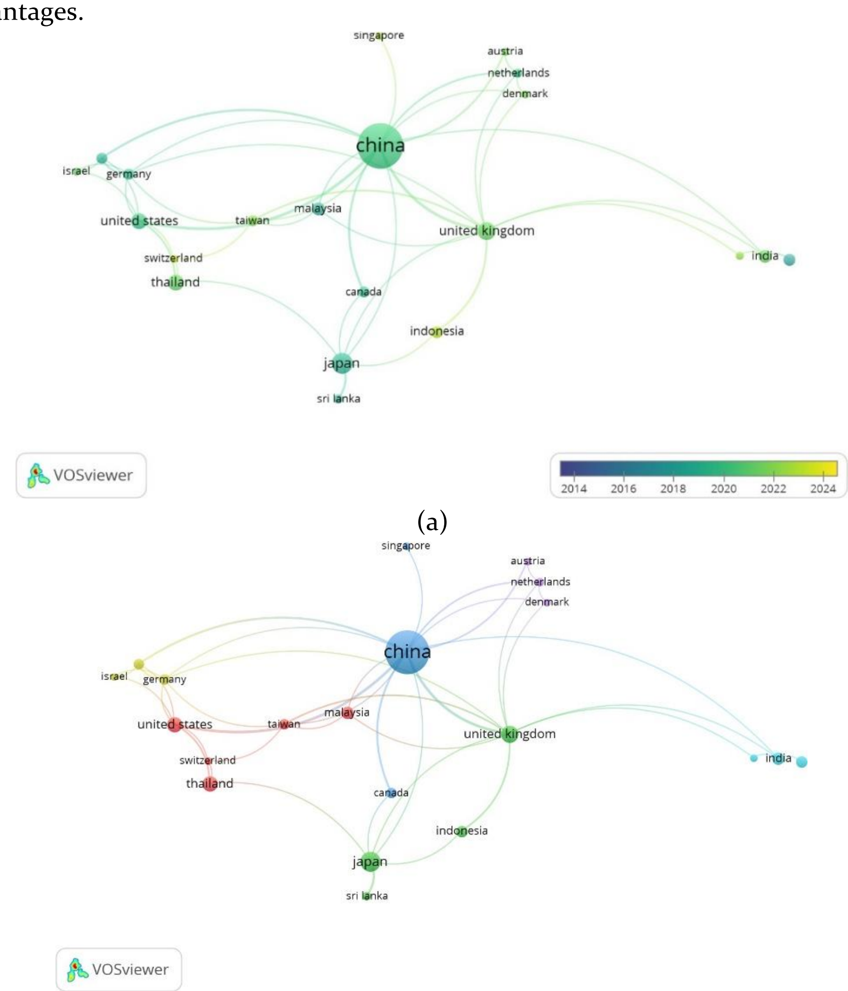
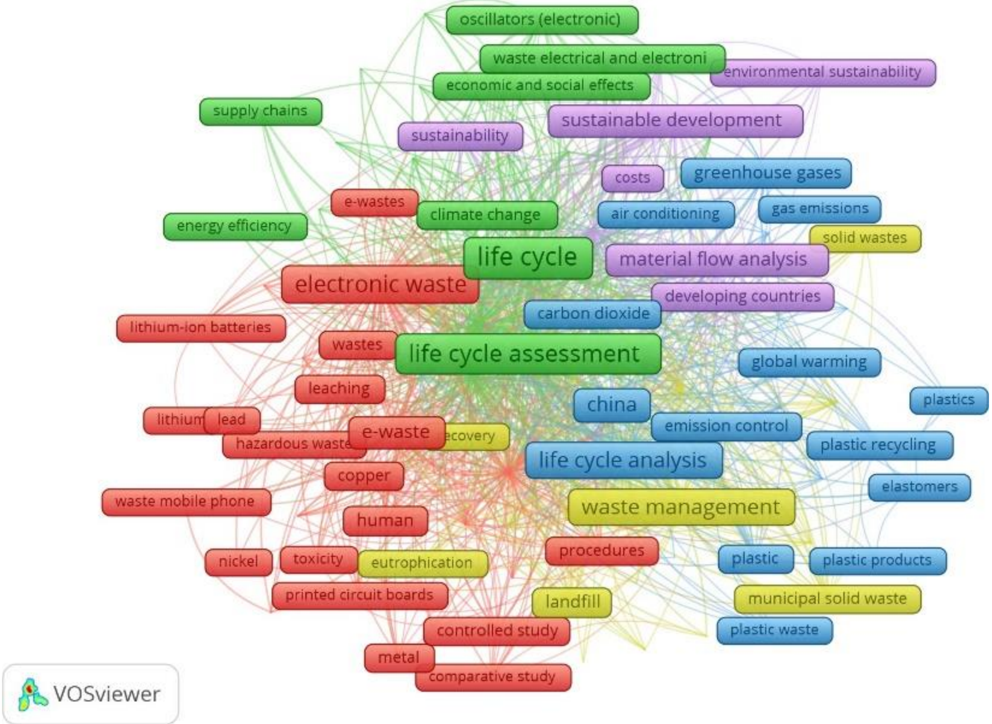
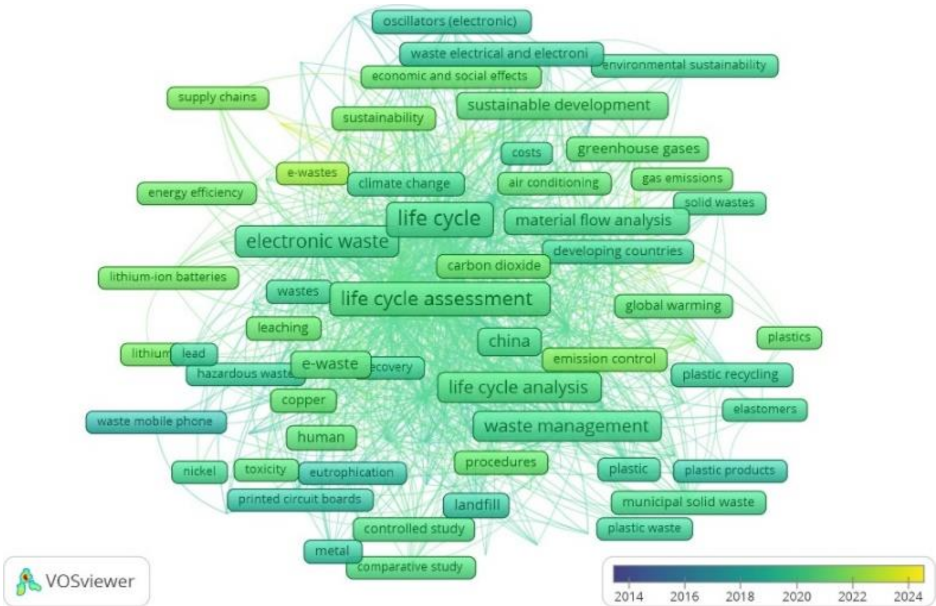


Figure 2. Co-authorship networks based on country affiliations: Overlay visualization (a) and network visualization (b).

According to Figure 4 (b), four clusters can be identified from the VOS clustering. The red and green clusters represent the environmental impact of e-waste, with terms such as greenhouse gases, humans, heavy metals, environmental impact, carbon dioxide, and ecotoxicity. The blue cluster represents the treatment of e-waste with words such as plastic recycling, municipal solid waste, and emission control. The yellow cluster suggests that environmental regulation, technology, and performance are integral to waste management.



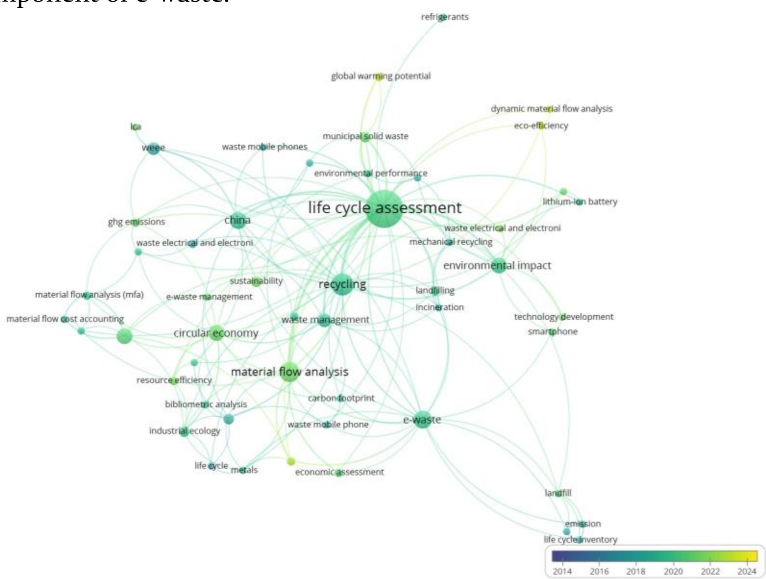
(a)



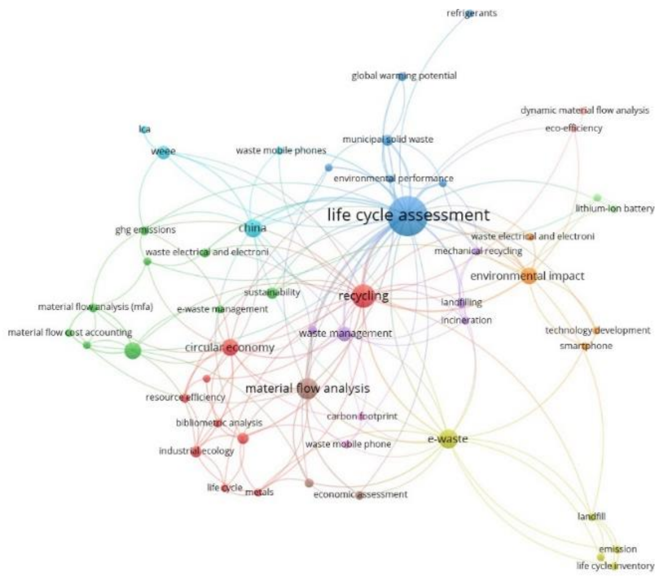
(b)

Figure 3. Co-occurrence keywords: Overlay visualization (a) and network visualization (b)

Based on the author's keywords in Figure 5 (a), several intriguing clusters and keywords were identified. The most recent keywords, including economic assessment, global warming potential, eco-efficiency, and dynamic MFA, highlight the economic influence of e-waste. In contrast, the older keywords discuss Waste Electrical and Electronic Equipment (WEEE), waste mobile phones, life cycles, and refrigerants. As shown in Figure 5 (b), 11 keyword clusters were generated. The most distant cluster group within the blue cluster appeared to discuss the LCA of e-waste. The green cluster pertains to material flow and sustainability of e-waste management. The purple cluster discusses e-waste management techniques such as landfilling, incineration, and mechanical recycling. Red clusters indicate the economic value of e-waste management. The smallest cluster, light-blue-green, suggests that lithium-ion batteries are a component of e-waste.



(a)



(b)

Figure 4. Co-occurrence terms in title and abstract: Overlay visualization (a) and network visualization (b)

3.1.3 Word clouds

Figure 6 displays the word clouds generated from the titles, abstracts, and author keywords of the analyzed publications. These visualizations illustrate the frequency and prominence of terms commonly used in the literature, based on metadata extracted from peer-reviewed journal articles. As shown in Figure 6(a), the most frequently occurring terms in titles and abstracts include *waste* (f = 534), *recycling* (f = 353), *environmental* (f = 347), *assessment* (f = 199), *management* (f = 190), *study* (f = 162), and *impact* (f = 148). Meanwhile, Figure 6(b) highlights the most common author keywords, which are *life* (f = 88), *cycle* (f = 82), *assessment* (f = 75), *waste* (f = 74), *recycling* (f = 38), and *analysis* (f = 30). The high occurrence of terms such as *waste*, *recycling*, and *environment* underscores their relevance as core themes in the reviewed literature. This pattern indicates that the primary focus of LCA in e-waste management centers on strategies for managing waste through reuse and recycling, while maintaining environmental quality and addressing broader sustainability goals.

(a)

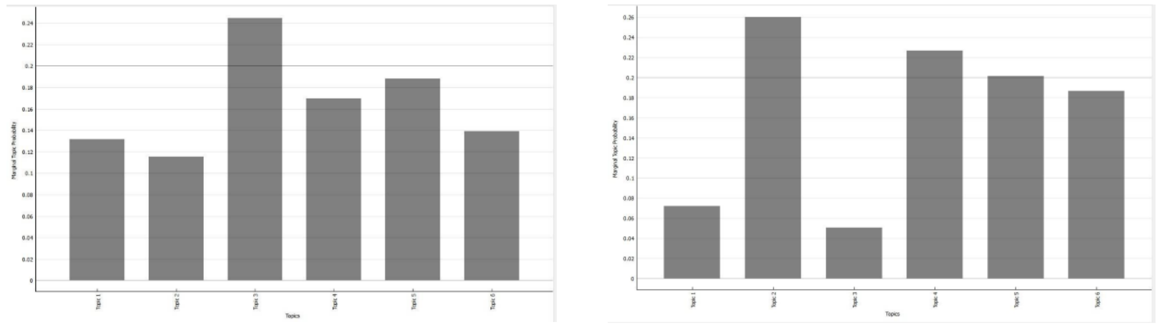
(b)

Figure 5. Word clouds of (a) terms in the title and abstract and (b) author keywords.

3.1.4 Topic Modelling Results

Latent Dirichlet Allocation (LDA) topic modeling is effective for uncovering hidden thematic structures within a given corpus (Bhat et al., 2020). Since LDA may produce overlapping terms across different topics, the initial or most prominent terms were selected to serve as representative keywords for labeling each topic in this study. As illustrated in Table 1, the application of LDA successfully revealed several underlying topics that are not immediately apparent through conventional analysis. For example, topics such as Global Waste Management Strategies (Topic 1), Efficiency and Environmental Impact Assessment in Recycling Processes (Topic 2), Economic and Environmental Perspectives on E-waste Management (Topic 3), Assessment of Environmental Potential: A Study of Waste Management and

Recycling (Topic 4), Environmental Impact Assessment of E-waste Management: Focusing on Battery Recycling (Topic 5), and Analysing Environmental Options in E-waste Recycling: Plastic Waste Management Strategies (Topic 6) were not found in the VOS map. Topic modelling typically uses marginal probability to rank the best candidate topics within a corpus (Allahyari et al., 2017).



(a) (b)

Figure 6. Marginal topic probability (MTP) of terms in title and abstract (a), author and keywords (b)

As illustrated in Figure 7(a) and Figure 7(b), the highest marginal topic probability (MTP) values derived from both titles and abstracts correspond to Topics 3 and 5. These topics primarily reflect economic and environmental perspectives, along with various approaches to impact assessment within the framework of e-waste management. This finding is further supported by the results of the multidimensional scaling (MDS) analysis, which also showed that only Topics 3 and 5 exhibited significant similarity in both titles and abstracts. The third most prominent topic identified is Topic 4, which relates to studies on waste management and recycling, particularly in assessing environmental outcomes.

A comparison between VOS mapping and MTP results reveals a strong alignment. The VOS analysis highlighted clusters involving LCA in relation to e-waste, while the LDA topic modeling identified similar key themes, reinforcing the consistency between these two analytical approaches. Based on the combined analysis, several topics in the domain of LCA applied to e-waste are attracting growing research interest. These include: (1) the potential applications, options, and environmental implications of LCA in e-waste management; (2) the development of effective and efficient strategies for handling e-waste; and (3) the integration of material flow analysis (MFA) in e-waste recycling practices. These emerging topics will be explored in greater detail in the following subsection through a narrative discussion.

Table 1. List of topics generated by terms in the title, abstract, and author keywords.

Topic Label	Terms in Title - Abstract	Topic Label	Terms from Authors
Topic 1 Global WasteManagement Strategies: A Focus on Environmental Treatment in China	waste, China, global, flow, use, carbon, recycling, environmental, treatment	Topic 1 Environmental Impact Assessment through Life Cycle Analysis of E-waste Management	waste, assessment,life, analysis, cycle,material, flow, environmental, electronic, impact
Topic 2 Efficiency and Environmental Impact Assessment in Recycling Processes: Insights from China	recycling, environmental, process, efficiency, assessment, waste, impacts, China, resource, results	Topic 2 Effective Environmental Management Strategies for E-waste	waste, management, life, assessment, electronic, recycling, environmental

Topic Label	Terms in Title - Abstract	Topic Label	Terms from Authors
Topic 3 Economic and Environmental Perspectives on E-waste Management in China	waste, recycling, environmental, management, assessment, impact, electronic, study, economic, China	Topic 3 Exploring Environmental Impact and Recycling in E-waste through LCA	LCA, environmental, flow, electronic, impact, waste, management, recycling, cycle
Topic 4 Assessing Environmental Potential: A Study ofWaste Managementand Recycling	environmental, impacts, assessment, management, study, LCA, waste, recycling, potential	Topic 4 Assessment of Environmental Impact in E-waste Life Cycle Recycling	life, cycle, recycling, assessment, environmental, impact, waste, analysis, electronic
Topic 5 Environmental Impact Assessment of E-waste Management: Focus on Battery Recycling	waste, environmental, electronic, management, study, batteries, recycling, assessment, resource, impact	Topic 5 LCAof E-waste: Environmental Impact Analysis	life, cycle, assessment, waste, LCA, electronic, environmental, recycling, analysis
Topic 6 Analyzing Environmental Options in E-waste Recycling: Plastic Waste Management Strategies	waste, recycling, plastic, environmental, electronic, plastics, analysis, study, option, tons	Topic 6 MFA in Environmental LCA of Waste Recycling	analysis, flow, material, cycle, life, assessment, recycling,waste, LCA, environmental

3.2 Harnessing LCA and MFA to drive Sustainable E-waste management in Asia

3.2.1 LCA on E-waste

Life Cycle Assessment (LCA) is widely recognized as a methodological approach for assessing the environmental impacts associated with every stage of a product's, process's, or service's lifespan (Xue and Xu, 2017). In the context of e-waste management, the use of LCA is particularly important, as it enables a thorough evaluation of environmental effects throughout the entire life cycle of electronic products, from production to end-of-life disposal. By applying LCA, researchers and policymakers can better understand the potential environmental consequences at each stage of the e-waste stream. This approach is often used in conjunction with other environmental assessment tools, such as Material Flow Analysis (MFA) and multicriteria decision analysis, to produce more comprehensive and informed conclusions.

LCA has become a widely adopted framework in the study of e-waste management (Ismail and Hanafiah, 2019). Its application is especially prevalent in developed European countries, with China being a notable exception among developing nations. In Asia, the relevance of LCA is steadily growing due to the sharp rise in e-waste generation, driven by rapid technological progress and increasing consumer demand. Over a span of three years, a significant increase in e-waste has been observed. In 2019, the total e-waste generated reached 24.9 million metric tons (MMT) (Islam et al., 2024). According to the United Nations Global E-Waste Monitor 2024, this figure rose to 33 MMT by 2022, highlighting the urgent need for sustainable and data-driven e-waste management strategies in the region.

3.3 E-Waste Management

E-waste management refers to the systems involved in proper handling, collection, processing, and disposal of e-waste. In recent years, the rapid worldwide increase in e-waste and the growing difficulties in its management have made waste management procedures significantly complex and challenging. E-waste contains hazardous chemicals such as nickel, lithium, cadmium, copper, and polychlorinated nickel biphenyls (PCBs), and many others which, if not properly managed, can impact the environment and human health (Khatiwada et al., 2023).

3.3.1 Environmental Impacts of E-Waste

Improper recycling practices, non-compliance with e-waste management regulations, and the uncontrolled disposal of electronic waste can significantly degrade environmental quality and pose serious health risks to humans (Islam et al., 2024). Hazardous chemicals, such as cyanide, may leach into water bodies, including surface water and groundwater, contaminating essential sources of drinking and agricultural water. In addition to water pollution, e-waste is a major source of air and soil contamination due to the presence of toxic substances such as gallium, chromium, lead, and other hazardous materials (Ankit et al., 2021).

E-waste is also associated with the release of chemical pollutants like dioxins, polyvinyl chloride, and polycyclic aromatic hydrocarbons, which pose threats to soil quality, plant health, microbial life, and human well-being. Hazardous elements commonly found in landfill-disposed e-waste, such as arsenic (As), mercury (Hg), and lead (Pb), can infiltrate the soil, reducing its fertility and contaminating underlying groundwater. Once groundwater is polluted with heavy metals, these toxins may be absorbed by plants, potentially causing plant diseases and lowering agricultural yields. The degree of soil contamination is influenced by various factors, including temperature, soil type, pH levels, and soil composition.

Moreover, these contaminants can persist in the environment for extended periods, endangering wildlife and animals that depend on natural ecosystems. Heavy metals can eventually spread to nearby water bodies such as rivers, ponds, and lakes, threatening the health of surrounding communities, aquatic life, and terrestrial ecosystems. The continued presence of toxic substances and heavy metals in e-waste may contribute to biodiversity loss, species extinction, and the overall disruption and degradation of ecosystems (Islam et al., 2024).

E-waste poses various environmental threats, as highlighted in previous studies (Amine et al., 2019; Shaikh, 2021; Sheikh et al., 2013). One significant impact is the reduction in plant lifespan, where toxins leaking from improperly managed e-waste decrease soil fertility and adversely affect plant growth. In addition, the disposal of e-waste into or near water sources leads to groundwater contamination, contributing to water pollution. Soil contamination is another critical concern, as hazardous substances from e-waste reduce the nutrient content and productivity of the soil. Air pollution also arises from e-waste management practices, particularly through the release of hydrocarbons and other harmful substances into the atmosphere. Furthermore, the open burning of e-waste contributes to greenhouse gas emissions, intensifying global warming and raising the Earth's average temperature through the release of heat-trapping gases.

3.3.2 Efficient Strategies in E-Waste Management

Several ways to manage e-waste include can be seen in the following discussion.

a. Collection

The initial stage in managing electronic waste (e-waste) is the collection process, where discarded items from households and offices are gathered before moving on to pretreatment. According to Mir and Chang (2024), e-waste collection can be categorized into four main types: (1) the official take-back system, (2) mixed residual waste, (3) collection outside the official system in countries with advanced waste management, and (4) similar unofficial collection practices in countries with less-developed systems. In the first category, e-waste is collected by authorized bodies such as municipal councils or manufacturers in compliance with national regulations. This method usually includes pre-treatment processes before transferring the waste to modern treatment facilities for material recovery. The second category involves users discarding e-waste together with general household or office waste, resulting in low recovery rates since the waste is rarely separated and often ends up incinerated or landfilled. The third category refers to e-waste collected by licensed individual dealers or companies that operate independently of the official system and typically resell the waste to recycling firms. The fourth category applies to countries with limited or no e-waste legislation, such as Bangladesh, where informal sectors manage e-waste without centralized coordination. In many developing countries, particularly in Southeast Asia, the absence of formal e-waste policies means data on e-waste generation and handling is scarce. Governments in these regions often depend on low-income, independent collectors who work informally. These individuals gather e-waste door-to-door, sort the materials manually, and sell usable or repairable components to urban traders for recycling or refurbishment.

b. Pre-treatment

The second phase of e-waste management is pretreatment, which plays a crucial role in ensuring the efficient recovery of valuable materials and the safe handling of hazardous components. At this stage, e-waste is carefully analyzed and sorted based on its material composition. The main objective is to separate items into two categories: recyclable components and those requiring further treatment through advanced technologies. This process not only facilitates the extraction of valuable materials that can be reintegrated into production cycles, supporting the principles of a circular economy, but also ensures that harmful substances are appropriately managed to minimize environmental and health risks.

Pretreatment methods can generally be classified into three types: manual disassembly, mechanical dismantling and separation, and a hybrid approach that combines both. Manual disassembly is typically used to extract high-value or hazardous components, such as batteries, printed circuit boards (PCBs), and monitor housings. While effective, this method tends to be labor-intensive and costly. Mechanical pretreatment, on the other hand, involves processes such as crushing, shredding, and separation of metals from non-metals, making it suitable for bulk processing. A combined manual and mechanical approach is often considered the most efficient, especially when dealing with mixed and complex e-waste items.

In industrialized countries, pretreatment processes are usually semi-automated and integrated with advanced recovery systems. In contrast, developing countries often rely on small-scale workshops where manual labor dominates metal recovery operations. Common techniques include low-intensity magnetic drums for separating ferrous metals, and conductivity-based systems for isolating non-ferrous metals. Additional processes such as sieving, air classification, and water-flow tables are also used to enhance material separation.

Following pretreatment, the separated metals are subjected to recovery processes, primarily through pyrometallurgy and hydrometallurgy. Pyrometallurgy employs high-temperature techniques such as smelting and incineration to recover and purify ferrous metals. Hydrometallurgy, in contrast, uses aqueous chemical solutions to extract non-ferrous metals like copper, lead, and zinc from complex mixtures. Together, these techniques contribute to a more sustainable and responsible approach to managing e-waste, ensuring both resource efficiency and environmental protection.

c. Reuse and refurbishing

The redistribution and reuse of old electronic items to new owners is intended to reduce the volume of e-waste, provided the items are still in usable condition. Various organizations and communities have been established to facilitate this process, often offering cash in exchange for used gadgets that they will refurbish and resell (Islam et al., 2024). The extraction and reuse of resources is a recycling process that can also generate waste, whereas refurbishment involves only the reuse of functional components in the creation of new products, making refurbishing a more environmentally friendly option (Hong et al., 2015). Refurbishing is feasible when operational components that are still functional can be incorporated into new items.

d. Recycle

Recycling e-waste is a crucial factor in reducing e-waste and offers several benefits such as reducing air and water pollution, conserving natural resources, lowering greenhouse gas emissions, and creating job opportunities (Ibrahim Mohammed, 2023). Recycling e-waste can prevent the decomposition of waste in the soil, which contains toxic substances, thus helping reduce global warming, groundwater contamination, and freshwater pollution. In addition, the accumulation of toxins can damage ecosystems and aquatic populations. Recycling e-waste helps reduce or prevent harmful substances from entering water bodies, ensuring that water remains clean and safe for use (Islam et al., 2024).

e. Recovery

The recycling industry presents substantial commercial opportunities through the recovery of valuable metals from electronic waste, particularly precious metals such as gold, palladium, silver, and platinum. Among these, gold stands out as the most significant, representing approximately one-third of the total precious metals recovered from e-waste processing (Vidyadhar, 2016). Extracting these high-value elements is essential for improving the economic feasibility of recycling operations. A range of techniques has been successfully employed for metal recovery, including pyrometallurgy, hydrometallurgy, electrometallurgy, and biological methods such as bioleaching (Dutta et al., 2023).

To facilitate these recovery processes, e-waste separation facilities are typically outfitted with a range of mechanical technologies. These include grinding, crushing, screening, air classification, magnetic separation, electrical conductivity-based systems, and eddy current separation (Islam et al., 2024). Each of these components plays a crucial role in isolating valuable materials from complex waste streams, enabling more effective downstream refining and supporting the overall efficiency and profitability of e-waste recycling operations.

f. Reduce

Most consumers tend to buy new electronic items at high prices and discard their old ones in landfills. Limiting the use of electronic devices, using multifunctional gadgets, and engaging in activities to reduce e-waste can help extend the lifespan of electronic devices. For example, regularly cleaning electronic devices and storing data in the cloud can reduce the need for new hardware. Many consumers have already started returning old items to retailers to reduce e-waste, and several well-known brands are beginning to offer takeback programs for used products.

g. Rethinking

Before purchasing electronic devices, it is essential to consider several factors, including functionality, the materials used in manufacturing, the expected lifespan of the product, and whether it is certified by the Electronic Product Environmental Assessment Tool (EPEAT). Making informed and conscious choices when selecting electronic products can significantly reduce the environmental impact associated with toxic chemicals released from e-waste (Islam et al., 2024).

3.3.3 MFA of E-waste Recycling

Material Flow Analysis (MFA) plays a vital role in managing complex waste streams, such as electronic waste, and has become a widely used tool in research related to recycling and e-waste management. Several Asian countries, including India, Vietnam, and China, have actively conducted MFA-based studies in response to the growing volume of e-waste. In particular, China and India have produced a substantial number of MFA studies, reflecting the scale of their e-waste challenges. While MFA is instrumental in shaping government policies and improving the efficiency of e-waste management systems, it does not directly assess the environmental impacts associated with e-waste (Islam and Huda, 2019; Kiddee et al., 2013; Withanage and Habib, 2021).

To achieve sustainable and environmentally responsible e-waste management, it is essential to enhance technologies for collection, disposal, and recycling. This includes integrating innovative solutions with existing systems to boost performance and effectiveness (Gollakota et al., 2020; Ilyas et al., 2021). Addressing the complex nature of e-waste challenges also requires a comprehensive research framework capable of guiding policy formulation and recycling strategies (Nuwematsiko et al., 2021). Moreover, the implementation of a continuous monitoring, control, and data-archiving system is crucial for managing process variables, ensuring health and safety compliance, tracking pollutants, and overseeing material and waste flows (Ikhlayel, 2018).

The environmental impact of e-waste management is both substantial and complex. One of the primary concerns is resource depletion, as electronic waste contains valuable materials such as metals and rare earth elements that, if efficiently recovered, can be reintegrated into production cycles. However, in the absence of effective recycling systems and proper management, these resources are often lost, leading to increased reliance on mining and raw material extraction, which in turn places additional pressure on the environment. Pollution and contamination represent another critical dimension of e-waste's environmental footprint. Inadequate practices in the collection, transport, recycling, or disposal of e-waste can result in the release of hazardous substances—including heavy metals and persistent organic pollutants—into the soil, water, and atmosphere, thereby threatening both ecological systems and human health (Ismail and Hanafiah, 2019).

To comprehensively assess these impacts, environmental analyses in e-waste management are typically classified into midpoint and endpoint categories. Midpoint impacts refer to problems that occur at an intermediate stage, such as climate change, ozone depletion, or toxicity levels, while endpoint impacts address broader consequences, including ecosystem degradation, resource scarcity, and damage to human health. Evaluating both types of impacts is essential, as it enables the identification of critical intervention points that can guide the development of more sustainable e-waste management practices. This dual-level analysis plays a vital role in shaping informed policy decisions and strategic planning aimed at mitigating the environmental consequences of e-waste throughout its life cycle (Xue and Xu, 2017).

4. Conclusion

The rapid advancement of technology has been a key driver behind the escalating generation of electronic waste. In the past three years, this trend has become increasingly evident, with a notable rise in e-waste volumes. Insights derived from bibliometric analysis (BA) reveal significant developments in the research landscape, particularly in studies employing life cycle assessment (LCA) to evaluate e-waste. Since 2014, there has been a substantial increase in scholarly publications addressing this topic, with sustained growth continuing through 2024. Earlier research, especially prior to 2018, concentrated on specific e-waste sources, including mobile phones, metals, printed circuit boards, and issues related to landfilling. In contrast, more recent studies have expanded their focus to encompass the broader environmental and economic impacts of e-waste, with growing attention to topics such as climate change and material flow analysis (MFA).

LDA-based topic modeling within this study identified several recurring themes, including life cycle assessment, MFA, circular economy, waste management, sustainability, climate change, and energy efficiency. Among these, topics such as circular economy, energy efficiency, and waste management are gaining increasing attention, especially in their application to LCA-MFA frameworks in e-waste research. The analysis also revealed a notable gap in the literature concerning dynamic MFA, suggesting an area for future investigation. It is important to acknowledge the limitations of this bibliometric analysis. The scope of the study was confined to keyword-based searches in the Scopus database, which may have introduced selection bias and excluded relevant studies not captured by the chosen terms. Although this limitation was mitigated through a complementary narrative review presented in a subsequent section, some hidden research gaps may still remain undetected. Therefore, future research should consider expanding the keyword set and exploring additional databases to achieve a more comprehensive visualization of LCA studies in the context of e-waste.

Life Cycle Assessment (LCA) has emerged as a critical approach for evaluating the environmental impacts of electronic waste throughout its entire life span, from production and use to final disposal. As a management tool, LCA is particularly valuable for identifying environmental "hotspots," or specific stages in the life cycle that contribute the most to environmental degradation. This insight is essential for guiding mitigation efforts aimed at reducing these impacts. The findings from LCA studies also serve as a foundation for informed decision-making, supporting manufacturers in designing more environmentally responsible products and assisting policymakers in formulating regulations that encourage sustainable practices.

In addition to guiding product development and policy, LCA aligns closely with the principles of the circular economy. By examining the full life cycle of e-waste, it becomes possible to pinpoint opportunities for reuse, recycling, and resource recovery, thereby extending the use of materials and minimizing waste generation. LCA also enables comparisons between different e-waste management strategies, helping stakeholders identify the most sustainable and efficient options. In summary, conducting an LCA offers valuable insights into the environmental consequences of e-waste and plays a key role in developing strategies to manage these impacts more effectively. It serves as a comprehensive tool for advancing the sustainability of e-waste management systems.

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