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Digital Technologies in E-Waste Management: A Systematic Literature Review

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Abstract

The fast growth of electronic waste or e-waste is considered one of the serious economic and environmental concerns in the world. Traditional e-waste management (EMW) is unable to deal with the increased volume and complexity of this waste. This issue makes digitalization to be considered as a new solution. Digital technologies such as Artificial Intelligence (AI), Internet of Things (IoT), Blockchain, Big Data, Cloud Computing, Cyber-Physical Systems (CPS), Edge Computing, Robotics, and Digital Twins have great potential to improve the efficiency, traceability, and sustainability of EWM. This study presents a systematic literature review (SLR) to examine how these technologies are adapted in different e-waste processes and what challenges there are in their implementation. The aim of this review is to present a structured classification of digital technologies based on their function in e-waste processes. By taking a comprehensive approach, this study helps clarify how digital tools are used in e-waste management and suggests directions for future research and policymaking.

Keywords

Electronic Waste Management, Digital Technologies, Systematic Literature Review

1. Introduction

The electrical and electronics industries are trying to attract customers and maximize their profits by expanding their product ranges and continuously updating them. This strategy has changed people's lifestyle and encouraged them to consumerism so that individuals are willing to throw away their not-so-old products for newer models (Quinto et al. 2025). The worldwide desire for electrical and electronic devices has grown much more than before, so that their production increases around 2.5 million tonnes yearly (Kavil et al. 2025; Forti et al. 2020). Electronic waste, or e-waste, includes large household equipment and small electronic devices that are no longer usable after completing their useful life. For instance, these items can be: computers, cellular phones, laptops, televisions, washing machines, refrigerators, dishwashers, generators, batteries, printed circuit boards, and other similar devices that are discarded for any reason (Ming et al. 2025; Bhoi 2024). The unchecked growth of e-waste has turned into a critical global issue. Currently, the electronic waste industry is experiencing an annual growth rate of about 2 million tons (Mt) and is estimated to rise to 74.4 Mt by 2030 (Shabur et al. 2024). E-waste includes mercury, cadmium, arsenic, lead, chromium, and other dangerous substances (Brindhadevi et al. 2023). When e-waste is mismanaged, these toxic materials can cause pollution in soil, water, and air, being harmful to public health and the natural environment. In addition to hazardous materials, e-waste holds precious metals like gold, silver, copper, and palladium, which offer opportunities for recovery and reuse. It means less digging for new materials and better use of resources (Islam et al. 2024).

E-waste management consists of several processes, including predicting e-waste generation, segregating components, collecting and transporting discarded devices, and recycling (Baralla et al. 2023; Mousavi et al. 2023). Waste generation refers to the creation of solid waste from daily human activities and is mainly produced by homes, businesses, and public institutions, not by special or rare events (Mor and Ravindra 2023). Waste collection involves moving waste from where it is generated to a place where it can be properly disposed of. Some materials that are not actually waste can also be collected separately to be recycled as part of a city's plan to reduce landfill use (Kannan et al. 2024). Segregation, also known as sorting, refers to separating different types of waste, which takes place either at the initial waste generation place, such as homes and offices, or at recycling centers to improve recycling efficiency (Lu and Chen 2022; Christensen and Matsufuji 2011). Waste transportation is the subsequent stage. In smart waste management systems, the bins are connected to a network that can detect the level of fullness (Kannan et al. 2024). Recycling is the reusing of waste products into goods or raw materials once again and conserving natural resources as well as reducing environmental pollution (Lee et al. 2024). These processes require precise coordination, transparency, and efficiency to minimize environmental and human health impacts while maximizing resource recovery (Murthy and Ramakrishna 2022).

Since these operations are large and complicated, traditional manual methods are no longer helpful. In response, digitalization is a promising solution. Digital technologies like AI, IoT, Blockchain, Big Data, Robotics, Cloud Computing, CPS, Edge Computing, and Digital Twins are being used to make waste management systems more efficient, secure, automated, and easier to track and manage (Singh et al. 2025). AI means doing tasks with computers that normally require human thinking, such as learning, understanding language, or recognizing images (Hariyani et al. 2025; Zhang and Lu 2021). IoT is defined as a group of joined devices that can gather and exchange data through the internet (Hariyani et al. 2025; Li et al. 2015). By sending real-time information, IoT helps use resources better, decrease waste, and make systems work more effectively (Hariyani et al. 2025; Maksimovic 2017). Blockchain is a digital system that stores records of transactions using a network of many computers, making the information safe, clear, and unalterable (Hariyani et al. 2025; Habib et al. 2022). Big data analytics includes collecting and analyzing large datasets to identify useful patterns, trends, or connections. It helps organizations make better decisions and improve their functions (Hariyani et al. 2025; Vassakis et al. 2017). Cloud computing makes it possible to use and save data or programs through the internet instead of a personal computer. It provides users with access to resources such as storage, software, and computing power whenever needed (Hariyani et al., 2025; Buyya et al., 2011). CPS are modern frameworks that combine physical devices with computer-based control. They work together to gather and share data from different parts of a system and help monitor or manage operations in real time (Patil et al. 2022; Oks et al., 2019; Rawat et al. 2015). Digital twin technology creates a digital copy of a real system, item, or operation. This digital version helps monitor, simulate, and improve how the real one works in real time (Abdessadak et al. 2025).

These technologies are used in different e-waste management operations. For instance, AI-based models are used for predicting e-waste generation and automating classification (Olawade et al. 2024); IoT enables real-time monitoring of waste bins and transport (Lakhouit 2025; Mohsin et al. 2025); Blockchain secures traceability and transparency in the recycling chain and supports incentivized e-waste collection (Du et al. 2025; Alarood et al. 2023); and Big Data helps to make better decisions by spotting patterns and making predictions (Bhoi et al. 2024). Although achieving more attention, several challenges prevent digital technologies from being completely efficient in e-waste management. They include technical limitations, inadequate infrastructure, data privacy, large capital outlay, and inadequate regulation (Govindan et al. 2024). Previous studies usually focus on just one technology or a specific part of e-waste management. They do not look at how different digital tools work together across the whole e-waste value chain (Wang et al. 2022). There is not enough integrated information available about which digital technologies are most typically used in which management stages, so it is difficult to establish the most suitable solutions (Iqbal et al. 2024).

The purpose of this research is to address the digitalization of e-waste management in depth, to bridge current gaps in the literature. Therefore, a systematic literature review has been done to seek answers to these questions as follows: **RQ1:** What are the digital technologies applied in e-waste management? **RQ2:** What are the challenges of adapting these digital technologies in e-waste management systems? Also, A table is shown to compare how different digital technologies are used in steps like collecting, moving, sorting, and recycling materials. This helps identify the technologies that are used most often. The following parts of this paper are organized into five sections. Section 2 provides a review of digital innovations in e-waste management. Then, Section 3 describes the review methodology, and Section 4 covers the results and related discussion. Section 5 presents the conclusion.

2. Review of Digital Innovations in E-Waste Management

Exponential growth in electronic waste has been ranked as one of the most urgent global sustainability challenges. While decreasing technology life cycles and rising consumer demand for electronic devices, the conventional waste management infrastructure is revealed to be unable to meet the volume, complexity, and toxicity associated with e-waste. Digital technology like AI, IoT, Blockchain, Robotics, Big Data, Cloud computing, CPS, and Edge Computing is starting to be seen as a real way to change EWM. The main goals of digital transformation in this field are to improve sorting accuracy, reduce human risk in disassembling operations, allow for real-time monitoring, and enable intelligent decision-making (Bründl et al. 2024; Bhar et al. 2023; Serpe et al. 2025). Even with these potential benefits, digital technologies face significant barriers in being effectively implemented in EWM, particularly in developing economies. Serious drawbacks include inadequate regulatory systems, insufficient data infrastructure, illegal recycling, and a lack of awareness among consumers and local authorities (Moossa et al. 2024; Shittu et al. 2025; Islam et al. 2025). For example, Sofian et al. (2025) and Erdiaw-Kwasie et al. (2024) explain that the main problems for data-driven waste management are the lack of standard monitoring systems and the use of different reporting methods. To solve these problems, recent studies suggest using new Industry 4.0 (I4.0) methods that combine automation, smart sensors, and predictive tools in waste systems. Bründl et al. (2024) describe automation methods for disassembling e-waste, like using robots and AI to recognize objects, which helps make the process safer and more efficient. Similarly, Sofian et al. (2025) demonstrate how AI and IoT can improve lithium-ion battery (LIB) recycling through real-time monitoring and predictive maintenance to reduce environmental risks. Bhar et al. (2023) further show that despite potential automated and modularity-based solutions, recycled LIBs only contribute up to 3%, which highlights a huge need for coupled digital and mechanical solutions to improve processes such as discharging, mechanical separation, and black mass recovery. Advanced digital solutions have also been proposed to improve weak regulations. Serpe et al. (2025) suggest using blockchain and AI to help close the gap between e-waste laws and how they are enforced in 81 countries, where only a small amount of e-waste is officially recycled.

Studies like Kim et al. (2024) highlight the potential of microbial bioleaching for recovering rare metals and propose machine learning-based optimization of biological parameters to make the process more viable for real-world applications. As more people worry about urban mining and resource loss, several scholars explore system-level digital strategies. Erdiaw-Kwasie et al. (2024) propose an urban mining model that combines real-time data collection, traceability, and collaboration between formal and informal sectors. Firmansyah et al. (2025) assess Indonesia's urban mining capacity, recommending investment in biohydrometallurgy, public education, and digital infrastructure to boost sustainable metal recovery. Also, Lahane et al. (2025) examine the role of AI and Multi-Criteria Decision-Making (MCDM) tools in building circular supply chains for electronic products, emphasizing how digitalization boosts traceability, forecasting, and material efficiency across reverse logistics networks. Preet and Smith (2025) focus on end-of-life management for photovoltaic (PV) panels, revealing the digital gap in delamination techniques and material separation. Their work advocates for AI-assisted simulation environments to test separation technologies before scaling them industrially. Pan et al. (2024) also add to this by listing ten circular economy strategies, ranging from refuse to recover, and stress the importance of digital tools for optimizing reverse logistics, assessing consumer behavior, and operationalizing sustainable e-waste recovery models.

All these efforts are valuable, but the latest research emphasizes some important gaps that have not been fully addressed. Most studies are islanded, focusing on individual technologies (e.g., AI, IoT), waste categories (e.g., batteries, semiconductors), or geographic locations. Few studies address overarching frameworks that tease out digital technologies from each phase of EWM—generation, collection, segregation, recycling, and disposal. Also, there is not much collaboration across fields of digital innovation, environmental regulation, and circular economy principles (Kumar et al. 2025; Shittu et al. 2025). New types of waste, like old IoT gadgets, solar panels, and smart fabrics, have not been looked at much yet. Because of that, a worldwide effort is needed to set common rules for tracking this stuff, create better policies, and help new technologies grow everywhere.

In addition, there has not been much progress in studying both the environmental and economic sides of e-waste recycling together. Lee et al. (2024), in a review of 159 studies, found that although e-waste contains valuable materials like rare earth elements, up to 75% of it still goes unrecycled, even in well-regulated areas like the EU. Their findings indicate that environmental analyses often ignore climate and energy effects unless life cycle assessment is applied. Also, economic studies neglect broader costs and side effects. The review suggests stronger rule enforcement, setting up official collection systems, giving financial support, and improving technology. Lee et al. (2024) strongly propose using a combined social, technical, and economic approach to make recycling systems more sustainable and effective in the long run. They point out that the circular economy will only work well if both environmental and economic goals are considered at the same time, especially in areas where informal recycling is common. Finally, Kumar et al. (2025) point out the challenge of semiconductor waste that has been paid less attention to. While semiconductors are essential to all modern electronic devices, their manufacturing processes need many resources and often produce pollution. The authors suggest that materials like silicon, GaAs, and CIGS can be recovered using sensors and special recycling methods.

3. Review Methodology

While conducting this research, a systematic literature review approach was applied to examine the role of digital technologies in contributing to e-waste management and the most critical challenges of their implementation. The selection process followed the PRISMA method to keep it clear and easy to repeat. Figure 1 shows the PRISMA diagram, which explains the steps of finding, screening, checking, and selecting the articles in a clear and organized way.

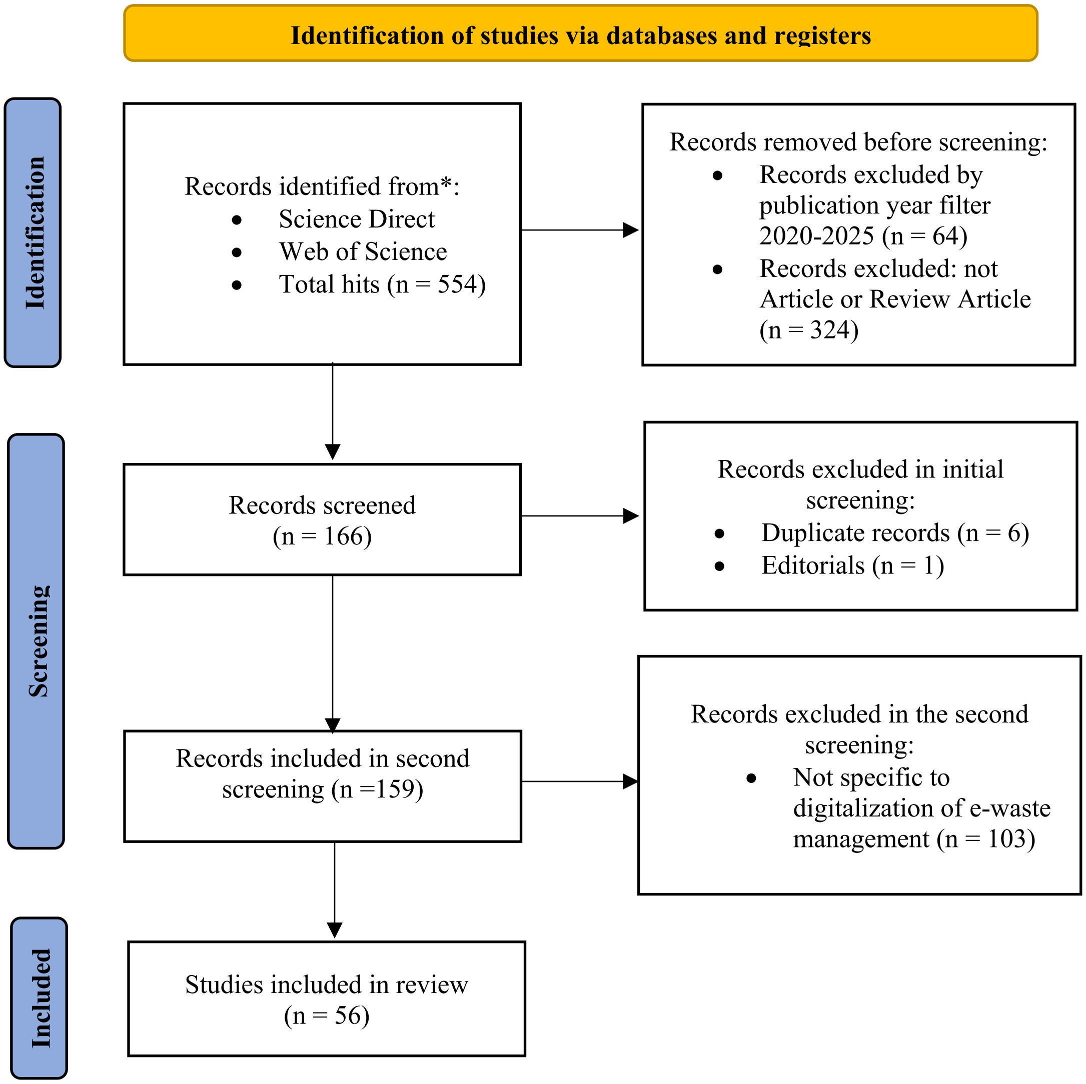

Figure 1. PRISMA flow diagram

The study began with an extensive search of research papers through two leading scholarly databases: ScienceDirect and Web of Science. They were selected since they provide comprehensive coverage of peer-reviewed journals in environmental engineering, technology, and sustainability. The strings and keywords were used to access relevant publications are "*e-waste*", "*electronic waste*", "*digital technologies*", "*Artificial Intelligence (AI)*", "*Internet of Things (IoT)*", "*blockchain*", "*big data*", "*robotics*", "*cloud computing*", "*cyber-physical systems*". The initial search returned 554 papers. Several filtering steps were used to find relevant papers and minimize the dataset. A time filter initially narrowed down the search to papers that were published between 2020 and 2025, resulting in 490 records. Next, to practice academic strictness, only documents that were labeled as "Article" or "Review Article" were retained, reducing the list to 166 items. Then, to maintain research quality, only documents marked as "Article" or "Review Article" were retained, resulting in a reduced list of 166 items. In the first screening, 6 duplicate papers and 1 editorial were removed, leaving a total of 159 papers. In the second screening, the abstracts and, where necessary, the complete texts of the remaining articles were examined to evaluate their close relevance to the research questions. Articles that did not focus on using digital tech in e-waste management or did not address the main challenges were excluded. In the end, 56 articles were chosen that were highly relevant to the research goals.

4. Results and Discussion

4.1 Numerical Results

This part shows the main results from the systematic literature review and explains how different digital technologies are used in the various steps of e-waste management. Table 1 lists how technologies like AI, IoT, Blockchain, Big Data, Cloud Computing, CPS, Robotics, Edge Computing, and Digital Twins are applied across five key stages: generation, collection, segregation, transportation, and recycling. AI, IoT, and Blockchain have the broadest range of applications, being implemented in all five phases. AI and IoT appear multiple times in generation, collection, segregation, transportation, and recycling, which shows how broadly used and integrated they are across different aspects of waste management. This widespread use shows that these technologies are very important for making tasks automatic, helping with predictions, checking processes, and improving how things work. Blockchain is used in all stages too, because it helps keep track of data, protect information, and make everything clearer and more trustworthy during the whole waste management process, especially in collection and transport. Technologies such as Big Data analytics and Cloud Computing are mainly applied in the middle stages (segregation, transportation, and recycling), suggesting their function in data processing, intelligent analytics, and system-level decision-making. CPS, Robotics, and Edge Computing have more specialized applications, mostly in the intermediate and advanced levels. Specifically, CPS and Robotics are largely used in recycling, whose operations are typically complex, unsafe, and require automation. Edge Computing is used in collection and segregation, likely for real-time processing at the edge level and adaptive system adjustment. Digital Twins are only implemented in collection, segregation, and recycling, with no application in the generation or transport phases. This limited implementation may be a function of infrastructure requirements or the maturity level of digital twin solutions for waste management. Overall, segregation and recycling are the most technology-intensive phases, with nearly all digital technologies represented. This trend underlines the technical nature of current operational phases, where efficiency, material recovery, and safety are the most sensitive. Meanwhile, the generation stage shows the least integration, involving only three technologies, and may indicate the existence of a possible research gap in upstream digital (Table 1).

Table 1. DTs and their application in e-waste management

DTs	E-waste Management Process					References
	G	C	S	T	R	
AI	✓	✓	✓	✓	✓	Ada et al. 2024, Quinto et al. 2025, Arun et al. 2024, Simaei et al 2024, Asif et al. 2024, Srivastava and Dhaker 2024, Ravi et al. 2024, Lu et al. 2023, Arun 2025, Iqbal et al. 2024, Nišić et al. 2024, Bhar et al. 2023, Sofian et al. 2025, Bründl et al. 2024, Kim et al. 2025, Pourabbasi and Shokouhyar 2022
IoT	✓	✓	✓	✓	✓	Ada et al. 2024, Mohsin et al. 2025, Quinto et al. 2025, Sahoo et al. 2021, Govindan et al. 2024, Garrido-Hidalgo et al. 2020, Lu et al. 2023, Arun 2025, Ramzan et al. 2021, Iqbal et al. 2024, Islam et al. 2022, Sofian et al. 2025
Blockchain	✓	✓	✓	✓	✓	Alarood et al. 2023, Du et al. 2025, Chen et al. 2021, Salmon et al. 2021, Sahoo et al. 2021, Wang et al. 2022
Big Data		✓	✓		✓	Ada et al. 2024, Ramzan et al. 2021, Pourabbasi and Shokouhyar 2022
Cloud Computing		✓	✓	✓	✓	Ada et al. 2024, Lu et al. 2023, Ramzan et al. 2021
CPS			✓	✓	✓	Lu et al. 2023, Bhoi 2024, Patil et al. 2022
Robotics		✓	✓		✓	Ada et al. 2024, Quinto et al. 2025, Simaei et al. 2024, Asif et al. 2024, Nišić et al. 2024, Bhoi 2024, Bhar et al. 2023, Bründl et al. 2024
Edge Computing		✓	✓			Mohsin et al. 2025
Digital Twins			✓	✓	✓	Lu et al. 2023, Islam et al. 2022

G - Generation C – Collection S- Segregation T- Transportation R – Recycling

4.2 Graphical Results

A detailed analysis was conducted to examine the focus of research on each digital technology applied in electronic waste management, as illustrated in Figure 2. The results of this analysis show that AI (30%) and IoT (22%) have the largest share among the reviewed articles in terms of researchers' attention. This illustrates the importance of these two technologies in automating processes, real-time monitoring, and predictive analytics throughout the waste management lifecycle. Then, Robotics and Blockchain also have an important share of studies. It reflects a growing interest in the application of intelligent systems in recycling operations and the need for transparency and traceability of information within the waste supply chain. Cloud Computing, Big Data, and CPS hold a moderate position, primarily serving as enabling technologies for data integration, process control, and decision-making in intermediate stages. In contrast, technologies such as Digital Twins and particularly Edge Computing have received less attention, which may be attributed to lower technological maturity or infrastructural challenges. The distribution presented in Figure 2 demonstrates that the current research landscape is largely focused on established and widely used technologies, whereas emerging technologies offer valuable opportunities for future development in the digitalization of waste management.

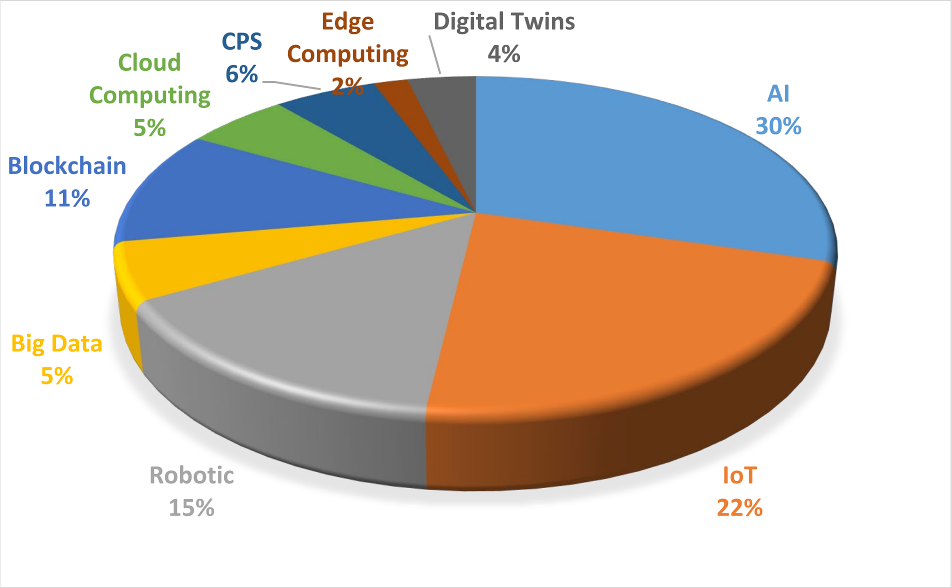

Figure 2. Distribution of articles by digital technology in e-waste management

Figure 3 shows the trend of publications on digital technologies in e-waste management from 2020 to 2025. In the first years, the number of studies increased slowly. Then, the trend stayed almost the same for a short time before dropping slightly. After that, there was a clear rise in interest, but it decreased again in the most recent year. Overall, the trend shows that researchers are paying more attention to this topic over time.

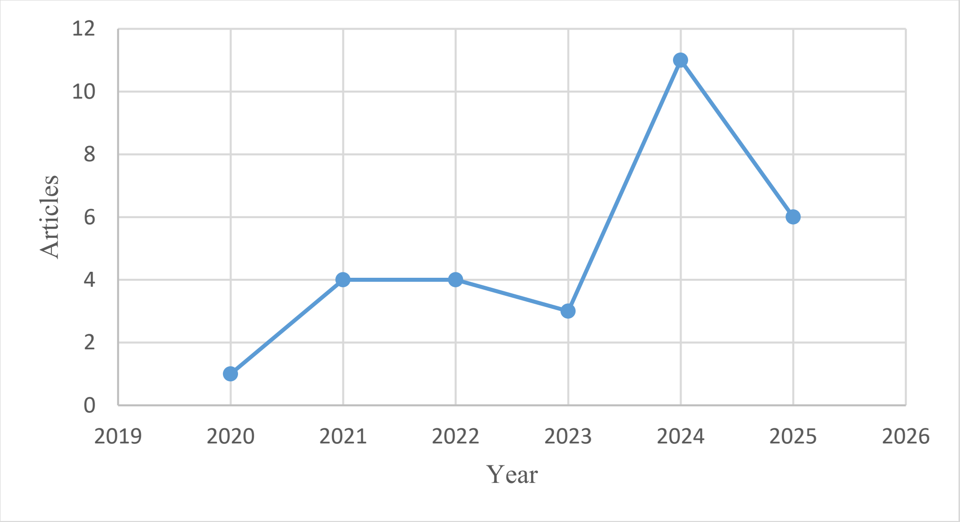

Figure 3. Annual distribution of publications (2020–2025)

In addition, this study highlights the importance of considering data as a strategic asset in the EWM lifecycle. Data generated from collection, segregation, and recycling processes could be systematically fed back into product design and marketing operations. This data feedback loop is a modern business intelligence approach that helps firms not only improve waste management but also support product design and customer relations (Govindan et al. 2024; Iqbal et al. 2024; Sofian et al. 2025). Also, from the reviewed literature, there is a well-founded business case for applying digital technologies in EWM. In addition to environmental benefits, these technologies are capable of creating operating efficiencies, reducing costs, and opening up new sources of revenue, making them highly beneficial for industries as well as policymakers (Lee et al. 2024; Ramzan et al. 2021; Pan et al. 2022).

6. Conclusion

This study conducted a systematic literature review to examine the application of digital technologies in EWM and the most important challenges of their adoption. The study identified AI, IoT, and Blockchain as the most used technologies across all the stages of the e-waste lifecycle, from generation through recycling. Other technologies like Big Data, Cloud Computing, CPS, Robotics, Edge Computing, and Digital Twins are mostly used in the middle or later steps of e-waste management, such as segregation and recycling. The study also shows that even though digitalization seems very promising, there are still many problems, like technical issues, weak laws, poor infrastructure, and high costs, that make it hard to use these technologies widely, especially in developing countries. Also, most existing studies are scattered and don't give a full picture of how digital tools are used across all stages of e-waste management. By showing how each technology is used in different stages, this research gives a new and complete view of how digital tools are used in e-waste management. The results can help policymakers, professionals, and researchers choose the right technologies and match them with specific waste management needs. The chart also shows that AI and IoT have gotten the most attention in the studies, which shows how important they are both in practice and in research. In contrast, Edge Computing and Digital Twins have been used less often, which shows there are still important gaps in the research. Also, segregation and recycling are the processes that use the most technology, but the generation uses very little, showing that more digital innovation is needed in the early steps of e-waste management. Future research areas of focus should cover the disposal stage, new emerging waste flows, and the socio-economic implications of digital change. In addition, the formulation of aligned, cross-industry standards can also supplement the global application of digital technologies towards building a circular and sustainable e-waste system. To continue conducting this research, the identification of the drivers and impediments that influence the application of digital technologies in the management of e-waste will be the focus of future research. Based on such findings, a conceptual framework will be constructed to guide the strategic application of such technologies across different stages of the e-waste life cycle, particularly for developing nations. Lastly, one of the emerging trends is the emergence of prescriptive analytics in waste management infrastructure. Although predictive models assist in predicting e-waste production and recycling performance, prescriptive analytics can take it a step higher by suggesting the best actions given real-time information. Prescriptive analytics integration within the EWM lifecycle would improve decision-making at all stages, from generation to recycling, and could assist in bringing circular economy thinking (Srivastava and Dhaker 2024; Simaei and Rahimifard 2024; Lahane et al. 2020). Subsequent studies should therefore investigate how prescriptive models could be combined with other digital technologies so as to attain the highest efficiency and sustainability in e-waste systems.

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