Digital Technologies Enabling Smart Circular Waste Management: A Systematic Literature Review

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***Abstract*—This study aims to identify and classify the technologies used across the waste-management lifecycle, qualitatively synthesize the types of operational and circularity-related outcomes reported in the literature, and examine the technical challenges and research gaps that must be addressed to develop interoperable, scalable, secure, and empirically validated systems. The study used a systematic literature review and bibliometric analysis in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 framework. The study identified Internet of Things (IoT), Artificial Intelligence (AI), machine learning, blockchain, cloud and edge computing, digital twins, big-data analytics, Radio-Frequency Identification (RFID), Global Positioning System (GPS), and additive manufacturing as the primary enabling technologies. These technologies enable sensing, monitoring, waste classification, forecasting, route optimization, traceability, simulation, automated sorting, and resource recovery. Across the included studies, the most frequently reported outcome categories included reduced bin overflow, improved collection and route efficiency, lower operational costs and vehicle-related emissions, enhanced waste segregation and recycling, and greater material-flow transparency. Because the studies used heterogeneous technologies, settings, scales, and evaluation metrics, these outcomes were synthesized qualitatively rather than pooled into a single quantitative estimate. Smart circular waste management depends on an integrated digital eco-system and is not dependent on individual technologies.**

Keywords*—Artificial Intelligence (AI); circular economy; digital technology; Internet of Things (IoT); smart waste management

I. Introduction

Rapid urbanization, increasing populations, and changing consumption habits have increased the volume and complexity of municipal waste. Municipal waste management is often based upon traditional practices of fixed collection routes, manual tracking, fragmented data, and minimal waste separation. This inefficiency contributes to higher collection costs for municipalities, lower material recovery rates, and less awareness of waste flows. A Circular Economy approach provides an alternative to the linear "extract-produce-consume-dispose" model by keeping resources viable through reduced, reused, recycled, recovered, or regenerated [1, 2].

Circular Waste Management is a holistic application of the circular economy through the entire lifecycle of waste management - from waste avoidance to waste collection, sorting, re-use, recycling, recovery and reintroduction of recycled materials back into production. This will be supported by there needs to be adequate and timely information on the quantity, quality, location, how it was created, and how much it has been moved. Digital technology will allow us to connect our physical waste processing with sensors, communications, analysis, and decision-making software. Internet of Things (IoT) devices enable real-time monitoring of waste volumes and the current state of collections. Artificial Intelligence (AI) will help classify waste, predict waste generation, and optimize routes. Blockchain can improve the traceability of material flows, whereas cloud computing, edge computing, and digital twins can support data integration, simulation, and operational decision-making [3-6].

The combination of these technologies has contributed to the development of smart circular waste management, in which data are used to improve collection efficiency, automated sorting, material recovery, transparency, and circular resource flows. However, the effectiveness of such systems depends not only on individual technologies but also on their ability to exchange data and operate as an integrated system. IoT sensors, for example, provide operational data, but analytical models are required to transform that data into predictions and decisions. Similarly, blockchain can preserve the integrity of transaction records, but its effectiveness depends on the reliability of the data generated outside the blockchain.

Although they offer many advantages for managing waste, there are also significant barriers to implementing new technologies for digital waste. For example, differences in hardware and software (e.g., different types of devices) and variations in how these devices communicate with one another could make it difficult to get all of them to work together seamlessly; sensor inaccuracies, missing data, unreliable connectivity, cyber security risks, issues related to customer/team member privacy, excessive power consumption by devices and/or networks, and high costs associated with developing/implementing systems are examples of other ways that reliability and scalability may be limited [6-7]. Consequently, despite the contributions of prior reviews, there remains a need for a systematic synthesis that specifically compares multiple digital technologies across the circular waste-management lifecycle, based on their functional roles, supported processes, reported operational and circularity-related outcomes, evaluation approaches, and technical limitations. The distinctions between the present study and the most closely

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related prior reviews are discussed in the following section. This study addresses that need through a Systematic Literature Review of digital technologies enabling smart circular waste management using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 framework. This study aims to identify and classify the technologies used across the waste-management lifecycle, synthesize their reported operational and circularity-related outcomes, and examine the technical challenges and research gaps that must be addressed to develop interoperable, scalable, secure, and empirically validated systems.

II. Related Work and Positioning of the Present Review

Prior studies have examined the intersection of digital technologies, circular-economy strategies, and waste management from several perspectives. At the broader circular-economy level, Bressanelli et al. [3] examined how digital technologies support usage-oriented circular business models, while Kristoffersen et al. [4] proposed a digitally enabled circular-strategies framework for manufacturing companies. These studies established that digitalization can facilitate information exchange, resource optimization, product-life extension, and circular value creation. However, their primary focus was on business models and manufacturing strategies rather than on the full waste-management lifecycle.

Cagno et al. [5] extended this stream of research through a systematic literature review of the role of digital technologies in operationalizing the circular-economy transition. Their study connected digital technologies with broad circular strategies and provided a cross-sectoral account of how digitalization can support circular practices. Nevertheless, its scope was not specifically organized around waste generation, collection, sorting, reuse, recycling, recovery, valorization, and the reintegration of secondary materials into production. It also did not systematically compare digital technologies by their functional roles, report waste-management outcomes, or identify implementation limitations.

Other studies and reviews have concentrated on particular technologies or application domains. Antony Jose et al. [18], for example, reviewed recent applications of artificial intelligence in battery recycling, illustrating the value of AI for classification, process optimization, and material recovery within a specific waste stream. The studies by Bello and Maladzhi [16] and Steenmans et al. [23] investigated, respectively, sustainable waste-reduction methods using additive manufacturing and blockchain technology for plastic waste governance and tracking. The study by Meng et al. [24] examined the application of digital twin technology to circular economy concepts in the construction industry. Lastly, Goel et al. [25] conducted a review of the opportunities and risks involved in digitalization toward achieving environmental sustainability.

The present review addresses this fragmentation by combining systematic evidence synthesis and bibliometric analysis to examine multiple digital technologies across the circular waste-management lifecycle. In contrast to Cagno et al. [5], the unit of analysis is specifically smart circular waste management rather than the general operationalization of circular-economy strategies. In contrast to Zyoud and Zyoud [10] and Khan et al. [12], the review is not limited to publication trends, thematic structures, or knowledge networks. It also extends technology-specific reviews, such as those by Ahmed et al. [6] and Antony Jose et al. [18], by comparing IoT, artificial intelligence, machine learning, blockchain, cloud, and edge computing, digital twins, big data analytics, RFID, GPS, and additive manufacturing within a single analytical framework. The above review assesses these technologies on four bases. The first is the technology functions and operational roles for each. Second are the waste management processes that each supports. Third, there are their reportedly measured performance in terms of costs, environmental impacts, and the circular economy. Fourth are the known technical barriers and areas requiring further study that limit the use of such technologies in ways that allow them to be used together.

III. Methodology

This section outlines the research design, research question(s), eligibility criteria, study screening process, and analysis techniques to find and synthesize research about digital technologies for smart circular waste management.

A. Research Design

The research began with a comprehensive literature search following the PRISMA 2020 guidelines [8,9]. Articles were retrieved from two leading academic databases, Scopus and Web of Science, covering publications from 2015 to 2025. Structured Boolean search equations were developed using targeted keywords such as “smart circular economy,” “waste management,” “digital technology,” “AI,” “IoT,” “blockchain,” and “resource recovery.” Bibliometric analysis was conducted using VOSviewer to uncover keyword co-occurrence patterns, thematic clusters, and emerging research trends in the intersection of smart technologies and circular economy within waste management.

B. Research Questions (RQ)

The four questions that guided this study were:

RQ1: Which types of digital technology have enabled smart circular waste management?

RQ2: In what way do the various technologies function as a part of different waste management processes?

RQ3: What reported outcomes related to operation, economy, environment, and circularity resulted from the use of digital waste management technologies?

RQ4: How have limited technical capabilities and a lack of research hindered the implementation, integration, and scale-up of digital waste-management technologies?

C. Eligibility Criteria

Eligible studies included those that were peer-reviewed and published in English; included in either the Scopus or Web of Science databases; published between 2015 and 2025; used a minimum of one digital technology to support waste management or circular resource management practices; and provided information regarding how the technology was implemented, methodologies, results/outcomes, as well as any obstacles/challenges encountered using the technology. Studies that did not report on the technology's implementation were therefore excluded from this review. Editorials, non-academic reports, unpublished manuscripts, inaccessible full-texts, and studies without a meaningful digital-technology component were excluded. Additionally, articles focused solely on chemical treatment, material characterization, pollution, or waste-processing reactions, and that did not include a relevant computational or informational technology aspect, would also be excluded. The review articles were used to provide additional background and references for reviewing purposes only and were not used as primary data sources.

D. Study Screening

The study screening process followed PRISMA 2020 guidelines to ensure methodological rigor and transparency in identification, screening, and inclusion (Fig. 1).

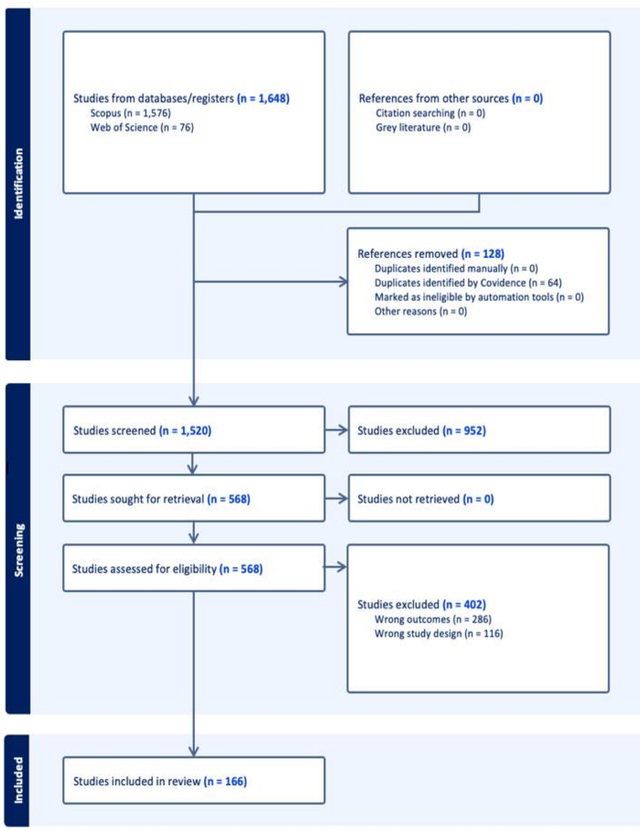

Fig. 1. PRISMA protocol.

A total of 1,648 records were retrieved from two databases: Scopus (n = 1,576) and Web of Science (n = 72) using structured Boolean searches. After removing 128 duplicates, 1,520 records remained for title and abstract screening. Strict inclusion and exclusion criteria were applied, resulting in 952 exclusions for irrelevance. The remaining 568 articles underwent full-text assessment, with all full texts retrieved. Of these, 402 were excluded: 286 for lacking relevant outcomes and 116 for unsuitable study design. Finally, 166 studies met all criteria and were included for bibliometric analysis and expert validation. This represents 10.1% of the initial records, underscoring the value of a rigorous multi-phase screening process. The selection process is summarized in the PRISMA 2020 flow diagram.

IV. RESULTS

This Section Present Results of the Systematic Literature Review and Bibliometric Analysis Conducted to Examine Digital Technologies that Enable in Smart Circular Economy and Waste Management. First, the Bibliometric Analysis that Identifies the Conceptual Structure, domain keywords, and themes from the Literature. The Section Further Synthesizes the Evidence According to the Four Research Questions, Covering the Enabling Digital Technologies, Their Roles in Supporting Waste-management Processes, the Reported Operational and Sustainability Outcomes, and the Remaining Technical Limitations and Research Gaps. Overall, This Section Demonstrates the Transition of Waste-management Research from Conventional Recycling-oriented Approaches Toward Integrated, Technology-enabled, and Circular Waste-management Ecosystems.

A. Bibliometric Analysis

The bibliometric analysis offers a detailed view of research trends and thematic developments in Smart Circular Economy (SCE) and waste management. Using VOSviewer, co-occurrence maps and keyword heatmaps were generated from 166 articles, revealing conceptual structures and emerging topics (Fig. 2). The co-occurrence network shows “circular economy” as the most frequent and central term, closely linked to “waste management,” “recycling,” “sustainability,” and “environmental impact” (Fig. 2a). Three thematic clusters emerge. The first centers on technological enablers, with keywords such as machine learning, artificial intelligence, digital twin, and IoT, showing the integration of smart technologies in circular systems. The second focuses on material innovation and resource recovery, featuring terms like plastic waste, 3D printing, additive manufacturing, and life cycle assessment, highlighting closed-loop production and material efficiency. The third addresses policy and systems thinking, with terms including urban mining, blockchain, stakeholder engagement, and supply chains, reflecting interest in governance and socio-economic integration.

Keyword co-occurrence over time shows a shift in thematic focus (Fig. 2b). Terms such as blockchain, digital twin, urban mining, and machine learning appear in yellow, indicating recent growth, especially after 2022. In contrast, waste management and recycling appear in green and blue, marking earlier emergence and continued relevance. The keyword density heatmap confirms the centrality of circular economy, recycling, and waste management, which appear in bright yellow, reflecting high frequency and strong connectivity (Fig. 2c). Keywords like life cycle, environmental impact, and resource efficiency bridge technological innovations and sustainability outcomes across both network and heatmap views. Overall, the results show a transition from traditional recycling themes toward integrated, data-driven, and systems-based approaches. The visualizations also indicate a field that remains rooted in sustainability while expanding into digital innovation.

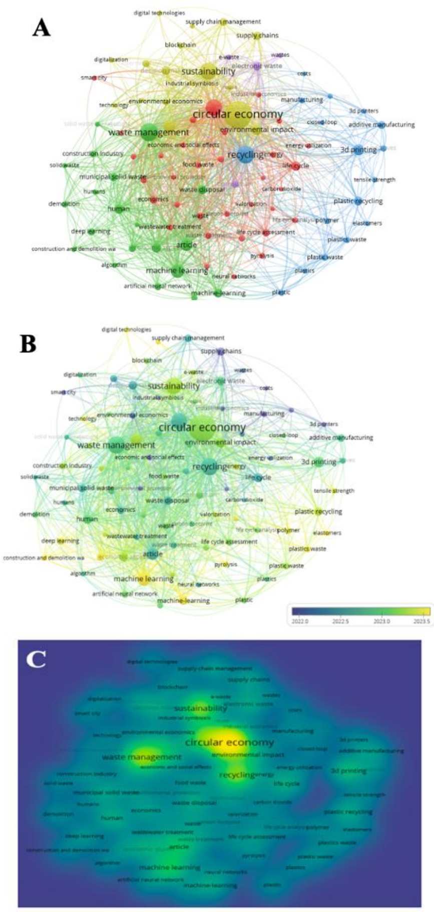

Fig. 2. Keyword co-occurrence map of research.

B. Scientific Performance and Production

Scholarly research in sustainable innovation is strongly anchored in circular economy principles, which account for 15% (n = 685) of the examined discourse (Fig. 3). This dominance reflects a shift from linear consumption toward regenerative systems emphasizing resource efficiency and lifecycle extension [10]. Waste management (6%, n = 288) and recycling (6%, n = 277) follow as key operational constructs, demonstrating circular principles in industrial and urban contexts. Sustainable development (5%, n = 225) and sustainability (5%, n = 222) further align environmental stewardship with economic resilience. Together, these themes reveal an integrated systems-thinking approach essential for addressing global resource constraints. Technological themes are also prominent. Machine learning (4%, n = 165), artificial intelligence (2%, n = 111), and 3D printing (5%, n $\approx$ 272) represent a growing nexus of smart tools embedded in sustainable strategies. These enable resource flow optimization, predictive analytics, and decentralized manufacturing, reducing carbon footprints and logistical demands. Specialized topics such as environmental impact (2%, n = 83), decision-making (2%, n = 82), and life cycle assessment (2%, n = 67) provide evaluation frameworks for system-wide sustainability. Supply chains (2%, n = 70) and economic aspects (2%, n = 69) highlight the importance of integration across production and distribution stages [11,12].

In addition, emerging themes- blockchain (1%, n = 33), polymer (1%, n = 33), and environmental economics (1%)- signal interdisciplinary expansion. They link digital trust mechanisms, material innovation, and economic modelling to enhance transparency and accountability in circular systems. Overall, the thematic structure reflects a technically diverse yet holistically aligned research ecosystem. Foundational topics coexist with advanced tools and methods, indicating a maturing field that adapts to ecological, technological, and socio-economic challenges [13-15]. Building on this base, temporal analysis can reveal how priorities shift over time and how technological innovations are increasingly embedded in sustainable waste management discourse.

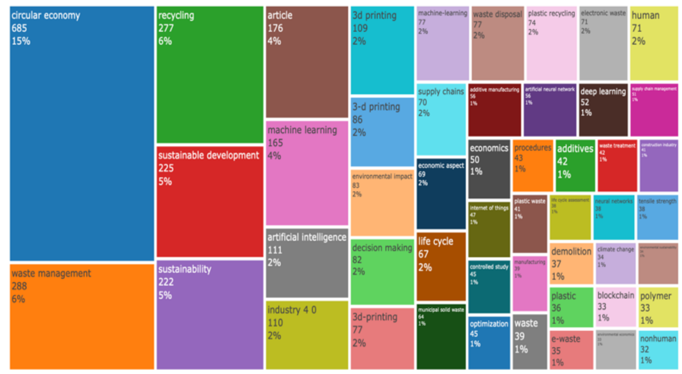

Fig. 3. Treemap of the most frequent terms in smart circular waste management studies.

The temporal distribution of emerging terms in sustainable waste management research shows a steady evolution in thematic focus and technological integration over the past decade. “Circular economy” remains the most dominant and persistent term, appearing consistently from 2020 to 2025 with high research intensity (Fig. 4).

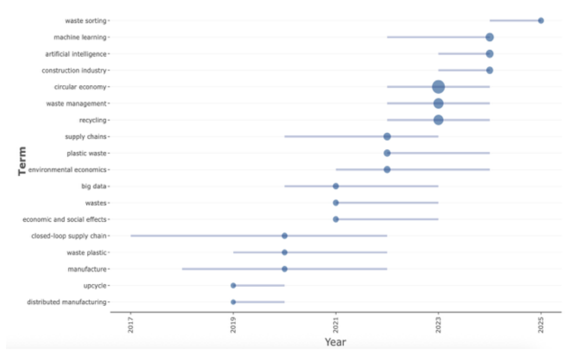

Fig. 4. The temporal distribution.

Its prominence reflects sustained academic and policy commitment to shifting from linear to regenerative systems centered on material reuse, systemic efficiency, and ecological balance. “Waste management” and “recycling” gained prominence in the same period, serving as operational frameworks for implementing circular economy principles. Their strong co-occurrence and longevity underline their foundational role across engineering, environmental science, and public policy [16]. In addition, technological integration has intensified since 2021, with increasing mentions of “machine learning," "artificial intelligence," and "big data." These trends point to growing adoption of data-driven approaches for waste flow optimization, consumption prediction, and responsive infrastructure design. The emergence of "waste sorting" in 2025, alongside AI themes, signals a shift toward automated, real-time material recovery. "Supply chains" and "plastic waste" have maintained steady attention since 2020, highlighting concerns over material accountability and polymer pollution. Mentions of "environmental economics" and "economic and social effects" reflect efforts to align market mechanisms with ecological outcomes. Earlier themes such as "distributed manufacturing," "upcycle," and "closed-loop supply chain" emerged in 2017–2018 but later declined in visibility, likely absorbed into broader frameworks or deprioritized for scalable practices. Overall, the timeline shows a deliberate integration of AI, economic analysis, and systemic efficiency into circular economy strategies, marking a transition toward actionable, technology-enabled solutions [17-19].

C. Addressing RQ1: Which Types of Digital Technology Have Enabled Smart Circular Waste Management?

The reviewed studies identified several digital technologies that support smart circular waste management. The major technologies include: the Internet of Things (IoT), Artificial Intelligence (AI) and machine learning, blockchain, cloud computing, edge computing, digital twins, big data analytics, Radio Frequency Identification (RFID), and GPS. Additionally, the keyword map and tree map suggest that there has been an increase in the connections between machine learning, AI, Industry 4.0, the circular economy, and research into recycling and waste management. The following are the technologies for IoT: smart bin systems with ultrasonic sensors, weight sensors, environmental sensors, RFID tags, and vehicle tracking systems. This technology provides real-time information on waste amount, quality, position, and movement [6,10]. In addition, AI and machine learning are being utilized for classification of waste types, prediction of waste amounts, optimization of waste collection routes, automation of decision-making processes [18,19], and also for improving material tracking capabilities, transaction reliability, and transparency within the waste and recycling chain through the use of blockchain [4,5]. Digital twins and cloud-based platforms support data integration, simulation, and scenario evaluation, while additive manufacturing and 3D printing connect recovered materials with circular production processes [12,16]. The findings indicate that no single technology independently enables smart circular waste management. Instead, the reviewed systems rely on combinations of sensing, communication, analytical, traceability, and operational technologies. This convergence reflects a transition from isolated waste-management applications toward integrated digital ecosystems.

D. Addressing RQ2: In What Ways Do Digital Technologies Support Different Waste-Management Processes?

Digital technologies support different but interconnected functions across the waste-management lifecycle. IoT sensors and identification technologies serve as the sensing component and collect a variety of data, including bin levels, total waste generated, temperature, humidity, vehicle location, etc. The communication systems then send this collected data to an application (cloud, edge, or local) that stores it, processes it, and provides analytics. These functions allow the city/organization to monitor in real time the flow of materials, prevent bin overflows, schedule collections, and improve visibility into where waste is coming from [6,10]. AI and Machine Learning algorithms take the raw data and turn it into predictive actions/recommendations. Some examples of their use include classifying waste using images, predicting future waste generation, optimizing garbage truck routes, detecting anomalies in waste patterns, and automatically sorting waste. Blockchain provides a traceability function by recording waste transfers, recycling activities, and material transactions. Digital twins and decision-support systems allow alternative collection, treatment, and resource-recovery scenarios to be evaluated before implementation [4,5].

The functional relationship among these technologies can be represented in Fig. 5. Circular actions include waste collection, sorting, recycling, reuse, recovery, valorization, and the reintegration of secondary materials into production. The findings therefore show that digital technologies contribute not only to waste monitoring but also to the coordination of physical and information flows throughout the circular waste-management system.

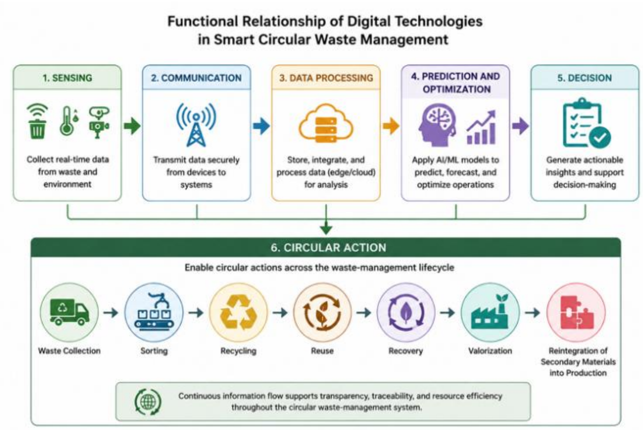

Fig. 5. Functional relationship of digital technologies in smart circular waste management.

E. Comparative Technology Suitability

The evaluated technologies differ from each other in terms of maturity, deployment effort, computational demand, and use case. IoT, RFID, and GPS are applicable as sensors for detection/identification and for localization. AI and Machine Learning can be used to classify, predict, optimize routes, and automatically sort products when sufficient training data and computational power are available. For storing and analyzing large amounts of data centrally, cloud computing is best. Edge Computing is typically used for real-time applications that require fast local processing. For tracing products throughout the supply chain (e.g., through certification), blockchain is an interesting solution. However, due to high computational demands and communication efforts, it does not make sense for simple monitoring. Digital Twins are best used for simulations, facility planning, or scenario evaluation. However, the value of digital twins depends heavily on their ability to be synchronized reliably with the corresponding physical assets. Thus, no technology is suitable for all cases. The appropriate technology depends on the specific operational goals, the relevant infrastructure, the maximum allowed time to react, the amount of available data, costs, and legal obligations.

F. Addressing RQ3: What Operational, Economic, Environmental, and Circularity-Related Outcomes Have Been Reported?

The reviewed literature reports several operational advantages that can be derived from the application of Digital Waste Management (DWM) systems. These consist of: Real-Time Monitoring, Bin Overflow Reduction, Improved Waste Classification, Dynamic Scheduling of Collections, Reduced Length of Collection Routes, Optimized Vehicle Utilization, and Faster Operational Decision Making [10,11], as well as AI-supported forecasting and optimization, allowing waste managers to prioritize locations with the highest demand for services and avoid collecting from non-high-demand locations where possible. In addition to operational advantages, DWM systems provide economic advantages, such as reduced Fuel Use and transportation costs, reduced manual monitoring requirements, and an optimized Allocation of Vehicles, personnel, and Processing Capacity. However, the extent to which each study identifies economic advantages varies due to differences in System Scale, Infrastructure, Type of Waste being managed, and Evaluation Methodology. Some studies identify Economic Advantages based on Cost Reductions and Route Distances, whilst others base their identification on the Accuracy of Classification, Time to Process Materials, and Resource Productivity.

Additionally, there are Environmental Advantages associated with the use of DWM Systems, including Reduced Emissions from Collection Vehicles, Less Dependence on Landfills, Enhanced Segregation of waste, and Greater Efficiency in Recovering Recyclables. There are also Circular Economy Advantages associated with the use of DWM Systems, including Increased Recycling Rates, resource recovery from Waste, Valorization of Waste Streams, and Traceability of Materials throughout Supply Chains. Furthermore, Closed Loop Production and Additive Manufacturing using Recovered Materials are facilitated by DWM systems' ability to track the movement of materials and the activities related to recycling [16-18]. Additionally, the Accountability provided by Blockchain and Digital Tracking Technologies allows for documentation of Material Movements and Recycling Activities.

G. Addressing RQ4: How Do Technical Limitations and Research Gaps Hinder the Implementation, Integration, and Scaling of Digital Waste-Management Technologies?

The key findings from the review suggest that significant technological work will be required to overcome the technical barriers to implementing an integrated smart waste management system. The majority of current smart waste-management solutions rely on disparate sensors, networks, databases, analytical algorithms, and operational systems. As a result, differences in technology (e.g., sensor type), data format (e.g., binary vs. CSV), and networking architecture (e.g., LAN vs. WAN) can create barriers for data transfer across different systems [5,7]. Another challenge identified in the literature concerns data quality. When sensors fail to operate correctly, measure inaccurately, leave gaps in measurement, do not consistently record timestamps for measured variables, or lack historical data records, it decreases the accuracy of predictive, classification, and optimization models. In addition, AI-based systems used for sorting recyclables into appropriate categories may function poorly with waste mixtures that contain contaminants, are physically broken or otherwise damaged, or consist of items not yet encountered during model training. Therefore, models should be tested across a wide range of "real-world" scenarios rather than only those modeled in controlled experimental settings. Other limitations include cybersecurity and privacy issues associated with connected devices and cloud computing; limited connectivity to remote locations; high power consumption with most types of sensors; and the costs of purchasing, integrating, operating, maintaining, and eventually replacing all required equipment [7].

One area where there is currently a significant knowledge gap concerning long-term field testing is the relative scarcity of large-scale long-term field trials. Most of what has been reported in the literature has come from simulations, laboratory tests, prototype demonstrations, and/or very short-duration pilot projects. While each of these approaches demonstrates the technical feasibility of the proposed solutions, they provide little information about long-term operation and maintenance requirements; the potential scalability of deployed equipment; the potential financial sustainability of the solutions; and the overall impact on environmental performance.

H. Reproducibility and Evidence Strength

The level of reproducibility was variable across the reviews; many implementations documented architectures or performance results but lacked a publicly available dataset, open-source code, all required hardware details, model configuration details, or a standard test environment for benchmarking. The lack of reproducibility is especially relevant for AI/Machine Learning applications, where performance varies based on data content, label accuracy, and the pre-processing performed prior to training. Additionally, there were differences in the amount of evidence supporting each study type. Conceptual and simulation studies demonstrated feasibility; laboratory/prototype studies demonstrated technical validity; and pilot or operational deployment studies demonstrated greater validity with respect to maintenance costs, scalability, and long-term reliability.

V. Discussions

This section will examine how the circular economy (CE) concept is influenced by its convergence with digital technologies as well as the complementary functions of identified digital technologies, the conditions that are necessary for CE to be implemented, and implications for research and practice.

A. Convergence of Circular Economy and Digital Technologies

The findings demonstrate that circular economy, waste management, recycling, sustainability, and sustainable development remain the conceptual foundations of smart circular waste-management research. The dominance of "circular economy" in the term distribution indicates that digital technologies are primarily positioned as mechanisms for extending material lifecycles, improving resource efficiency, and reducing dependence on disposal-based waste systems [1,2]. This result is consistent with studies that describe the smart circular economy as the integration of circular strategies with data acquisition, analytics, and digitally enabled decision-making. The results also reveal a gradual transition from conventional recycling and waste treatment to data-driven, intelligent waste management systems. The increasing use of machine learning, artificial intelligence, the Internet of Things, blockchain, digital twins, and big data-related terms indicates that the field is expanding beyond traditional environmental management. These technologies support the monitoring, classification, prediction, optimization, and traceability of waste and material flows. Machine learning and artificial intelligence are particularly relevant for waste sorting, generation forecasting, operational optimization, and environmental assessment [18,19]. Their increased visibility after 2021 suggests that waste-management research is moving toward more automated, responsive systems. The presence of 3D printing, additive manufacturing, polymers, and plastic recycling also demonstrates the connection between digital waste management and circular production. Additive manufacturing can use recovered materials as production inputs and facilitate decentralized manufacturing, although material quality, energy consumption, and recyclability must still be considered [12,16]. Therefore, digital technology should not be interpreted only as an information-management instrument; it can also reshape the physical processing, recovery, and reuse of secondary materials.

Nevertheless, the term distribution also shows fragmentation in the terminology used by researchers. Terms such as "3D printing," "3-d printing," and "3d-printing" represent the same concept but appear separately in the dataset. Similar normalization may be required for terms such as artificial intelligence, machine learning, Internet of Things, and related abbreviations. Standardizing equivalent terms is important for avoiding the underestimation of technology frequencies and improving the consistency of evidence synthesis.

B. Functional Roles and Integration of Digital Technologies

The reviewed technologies perform different but complementary functions within smart circular waste management. Internet of Things devices and sensors form the primary data-acquisition layer. Smart bins, ultrasonic sensors, weight sensors, cameras, Global Positioning System (GPS) devices, and Radio-Frequency Identification (RFID) tags can collect data on waste volume, composition, location, and movement [20,21]. This collected data will allow for a real-time view of the amount of waste that is being produced, prevent overflows from happening in the future, and optimize vehicle and facility use as part of the process.

The analytical layer of this process would use Artificial Intelligence (AI) and Machine Learning (ML) to take sensor and operational platform data and turn it into classifications, predictions, or recommendations. AI & ML are used in various ways, including image-based waste identification, Waste Generation Forecasting, Route Optimization, Contamination Detection, and Automated Sorting [22]. The reliability of these systems depends upon having representative databases, consistent database labels, appropriate computational resources, and testing under actual working conditions.

Blockchain provides a different function by supporting data integrity, transaction transparency, and material traceability. It can be used to record waste transfers, recycling certificates, extended-producer-responsibility transactions, and the chain of custody of recoverable materials [23]. However, blockchain does not guarantee that the original data are accurate. Incorrect sensor readings or unreliable manual inputs may remain incorrect even after being stored in an immutable ledger. Blockchain should therefore be integrated with reliable sensing, identity management, data-validation procedures, and cybersecurity controls. Digital twins and decision-support systems provide simulation and scenario-analysis capabilities. They can represent waste collection, facility capacity, material recovery, and reverse supply-chain processes in a digital environment [21,24]. These tools allow decision-makers to compare alternative operational scenarios before implementing them in physical systems. Nevertheless, an actual digital twin requires continuous or periodic synchronization between physical assets and their digital representations. Studies using only static simulation should therefore avoid describing their models as digital twins. Cloud computing and edge computing support data storage and processing across these technology layers. Cloud platforms provide scalable storage and centralized analytics, while edge computing can process data close to sensors, collection equipment, or sorting machines. Edge processing may reduce latency and network traffic, but it introduces additional requirements related to device management, security, and computational limitations [25].

These relationships indicate that smart circular waste management should be treated as an integrated digital ecosystem rather than as the implementation of a single technology. Its functional sequence can be represented as:

$$\text{Sensing} \rightarrow \text{Communication} \rightarrow \text{Data Processing} \rightarrow \text{Prediction and Optimization} \rightarrow \text{Decision} \rightarrow \text{Circular Action.}$$

Circular actions include collection, sorting, reuse, recycling, recovery, remanufacturing, and waste valorization. Feedback from these processes should return to the sensing and analytical layers, creating a continuous learning and improvement cycle.

C. Key Factors, Technologies, and Implementation Conditions

The literature indicates that technological performance is influenced by technical, organizational, regulatory, and economic conditions. The factors in Table I were synthesized from recurring findings in the reviewed literature. They were not derived from expert ranking or Fuzzy Delphi validation.

TABLE I. KEY FACTORS, TECHNOLOGIES, AND IMPLEMENTATION CONDITIONS IDENTIFIED IN SMART CIRCULAR WASTE MANAGEMENT

Category	Main Factor	Subfactors	Literature	Synthesis of Findings
Drivers	Policy and Regulatory Support	Incentives, digital standards, regulatory enforcement, extended producer responsibility	[21,23]	Regulations and incentives can encourage investment, data sharing, traceability, and the adoption of digital waste-management systems.
	Environmental Pressure	Landfill reduction, emission targets, resource scarcity, pollution control	[1,2,26]	Environmental pressures increase demand for technologies that support recycling, resource recovery, and waste reduction.
	Institutional Readiness	Leadership commitment, government support, organizational coordination	[4,27]	Institutional readiness facilitates technology procurement, data governance, integration, and long-term system operation.
	Economic and Operational Benefits	Cost savings, resource efficiency, route efficiency, improved productivity	[3,6,26]	Digital technologies can reduce unnecessary collection activities and improve operational resource allocation.
Barriers	Financial Constraints	Initial investment, maintenance costs, uncertain return on investment	[7,26]	High acquisition and lifecycle costs restrict adoption, particularly in resource-constrained municipalities.
	Digital Infrastructure Limitations	Limited connectivity, insufficient sensors, inadequate computing capacity	[6,7,21]	Weak communication and computing infrastructure reduce system reliability and scalability.
	Data Quality and Availability	Missing data, inconsistent formats, inaccurate sensor readings, limited historical records	[6,19,22]	Poor data quality decreases the reliability of classification, forecasting, optimization, and decision support.
	Cybersecurity and Privacy	Insecure devices, unauthorized access, sensitive location and operational data	[7,23,25]	Connected waste systems require authentication, encryption, access control, and privacy-preserving data management.
Challenges	System Interoperability	Heterogeneous devices, incompatible protocols, isolated databases	[4,5]	Interoperability is required to integrate sensing, communication, analytics, traceability, and operational platforms.
	Scalability and Field Validation	Prototype-to-city-scale transition, high data volume, network congestion, limited long-term testing	[6,7,20]	Many proposed systems remain limited to simulations, laboratory tests, or small-scale pilots.
	Technology–Policy Alignment	Rapid technological change, unclear data ownership, outdated regulation	[21], [23], [24], [27]	Adoption may be delayed when policies do not adequately address data sharing, automation, and digital transactions.
Success Factors	Stakeholder Collaboration	Public–private partnerships, citizen participation, cross-sector data sharing	[2]	Collaboration provides access to infrastructure, expertise, funding, operational data, and public acceptance.
	Digital Ecosystem Readiness	Integrated platforms, standards, reliable networks, data-governance mechanisms	[4,5]	Successful implementation depends on supporting infrastructure and governance rather than isolated technology adoption.
	Technical Capacity Building	Staff training, system maintenance, digital literacy, analytical capability	[7]	Skilled personnel are required to operate devices, maintain platforms, interpret analytics, and manage failures.
Technologies	Internet of Things and Sensors	Smart bins, fill-level sensors, weight sensors, environmental monitoring, vehicle tracking	[6,20,21]	Internet of Things technologies provide real-time data for monitoring, collection scheduling, and overflow prevention.
	Artificial Intelligence and Machine Learning	Classification, forecasting, route optimization, anomaly detection	[11,18,19]	Artificial intelligence converts waste data into classifications, predictions, and operational recommendations.
	Blockchain	Material traceability, recycling records, transaction integrity, certification	[4,23]	Blockchain can improve auditability when it is connected to reliable physical and off-chain data sources.
	Digital Twins and Decision-Support Systems	Simulation, scenario analysis, capacity planning, multi-criteria decisions	[22,24]	These technologies support the evaluation of alternative operational and circular-system configurations.
	Cloud and Edge Computing	Data storage, distributed processing, dashboards, real-time analytics	[6,25]	Cloud platforms support scalable analysis, while edge processing reduces latency and communication requirements.
	Identification and Communication Technologies	RFID, GPS, LoRaWAN, cellular networks, wireless sensor networks	[6,20]	These technologies improve asset identification, data transmission, location monitoring, and collection visibility.
Opportunities	Smart-City Integration	Integration with transportation, energy, logistics, and public-service systems	[10,20]	Shared smart-city infrastructure can improve coordination, data access, and resource utilization.
	Automated Circular Operations	Robotic sorting, intelligent recycling, automated segregation, predictive maintenance	[11,18,22]	Automation can improve sorting consistency, processing efficiency, and material-recovery performance.
	Data-Driven Circular Business Models	Digital marketplaces, product-service systems, material platforms, circular supply chains	[3,5]	Digital platforms can support new economic mechanisms for reuse, recovery, and closed-loop material management.

Table I shows that technical and non-technical factors are closely connected. Although IoT, artificial intelligence, blockchain, digital twins, and cloud platforms provide distinct technological capabilities, their performance depends on data quality, interoperability, infrastructure, cybersecurity, institutional support, and human capacity. Therefore, implementing advanced technology without improving the surrounding digital ecosystem may produce isolated prototypes rather than scalable circular solutions. The table also indicates that policies and stakeholder participation should not be treated as separate from technology implementation. Regulations influence data sharing, procurement, ownership, extended producer responsibility, and reporting requirements. Similarly, cooperation among municipalities, private operators, citizens, recyclers, and technology providers determines whether sufficient data and operational support are available.

D. Waste-Stream and Regional Applicability

Technology fit varies by waste type. Solid municipal waste (household trash) will benefit most from using IoT for monitoring, GPS for collection, routing, and AI for sorting. Most industrial wastes will use process monitoring, material accounting, big data analysis, and digital twin technology. Biomedical and hazardous wastes will require enhanced identity verification, tracing, security, and regulatory compliance. Plastic wastes and electronic wastes will have strong opportunities in AI to classify materials that can be recovered. Construction waste has potential uses as a digital twin, an inventory of materials, and tracking at the project level. Therefore, selecting technology should be based on the properties of the waste being processed (characteristics), the risk of contamination, the dollar value of the materials contained in the waste stream, how sensitive the waste stream is to regulation, and the objective(s) for recovering materials.

Regional conditions also influence the deployment of technologies. Urbanized areas that are highly connected may be able to support cloud-intensive AI-enabled systems as well as integrated systems; however, areas with low connectivity, limited service integration, poor infrastructure, and/or budgetary constraints will likely require less expensive sensors, RFID/GPS, or local edge processing. The feasibility of blockchain-based technologies such as digital traceability and/or advanced analytics is also highly dependent on the level of regulatory maturity in an area, the presence/absence of formal recycling programs and/or institutions that enforce extended producer responsibility policies, and the overall institutional capacity in an area. Results from large-scale funding of "smart city" pilot projects cannot be directly applied to resource-limited municipalities.

E. Implications for Research and Practice

The reviewed literature provides insight into the potential of digital technologies to support sustainable waste management practices. However, it highlights several challenges that will affect whether and how this can happen. These include the lack of standardized systems for collecting and processing data, the absence of established policies and regulatory structures governing the deployment of these technologies in waste collection and disposal systems, and the limited availability of data describing the physical operations of waste collection and processing systems. In addition to addressing these structural challenges, future research should examine not only individual technologies (such as sensors, sorting machines, and mobile apps) but also how they interact and how they can be used by stakeholders who make different types of decisions. For example, what happens when data generated about the composition of municipal solid waste is transmitted to local government agencies? How do those data inform agency decisions regarding where to locate new recycling facilities? What happens at the intersection of waste management and land-use planning? Answering questions like these will require cross-disciplinary research efforts involving experts in information technology, public administration, engineering, materials science, economics, urban planning, and sociology. In terms of specific research topics, there are many possibilities. Some examples might include developing new metrics for measuring success in waste management; designing decision-making tools for use by city officials responsible for managing large-scale recycling programs; identifying ways to reduce the amount of energy required to sort recyclables from non-recyclable trash; and improving methods for estimating the carbon footprint associated with the production of goods made from recycled materials.

VI. Conclusion

This systematic literature review and bibliometric analysis addressed the four research questions on digital technologies in smart circular waste management. For RQ1, the main technologies that enabled the development of intelligent waste management systems included the Internet of Things (IoT), artificial intelligence and machine learning, blockchain, cloud computing and edge computing, digital twins, big data analytics, RFID/GPS, and additive manufacturing. For RQ2, these technologies performed complementary functions across all phases of the waste-management lifecycle, including sensing/monitoring, classification/forecasting, route optimization, traceability, simulation, sorting, recycling, recovery, and material reintegration. For RQ3, the studies reviewed reported operational economic and environmental circularity-related benefits, such as reduced bin overflow, shorter collection routes, lower fuel and labor requirements, fewer collection-related emissions, improved waste segregation, greater material recovery, and stronger material traceability. However, these outcomes were synthesized qualitatively due to differences across studies in the technologies used, the scale of waste, evaluation times, indicators, and units. For RQ4, the primary barriers to adopting these technologies were poor data quality, limited interoperability, unreliable connectivity, cybersecurity/risk, privacy/harm, higher energy/life-cycle costs, and limited technical expertise. The evidence base is also limited by different methods of evaluating performance and by a few large-scale, long-term field-deployment studies. Therefore, future research should emphasize interoperable architectures, standardized performance measures, secure data governance, reproducible implementations, and long-term validation with respect to various waste streams and regions.

Declaration on Generative AI

ChatGPT (OpenAI) was used to assist in the visual development of Fig. 5. The conceptual framework, scientific content, and final design were subsequently reviewed and refined by the authors, who remain fully responsible for the figure's accuracy and integrity.

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