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Literature Review

Applications of digital technologies for overcoming challenges in municipal solid waste reverse logistics: a systematic literature review

Aplicações de tecnologias digitais para superação de desafios da logística reversa de resíduos sólidos urbanos: uma revisão sistemática da literatura

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ABSTRACT

The aim of this study was to identify in the literature the digital technologies and their methods of application relevant to the functioning of reverse logistics (RL) for municipal solid waste. The method adopted was a systematic literature review using the PRISMA method with five stages, conducted over 9 months (from April to December 2023) and consulting the Scopus and Web of Science databases. The database is composed of 58 articles valid for the research objective, 16 digital technologies, and 61 practical applications to the context of RL of municipal solid waste (MSW) presented under three classifications. It presents a compilation of digital technologies applicable to MSW management and their various applications in the execution of RL of MSW. Until now, the applications of these digital technologies in MSW RL only existed in a scattered manner in the literature. In this way, it contributes to theoretical advancement by providing a solid foundation for future research and developments in this area. Furthermore, we provide a classification for these technologies, according to the pattern identified in this systematic review: individualized use such as blockchain, AI, Big Data, and IoT stand out as the technologies with the most applications, single-use such as tracking sensor, GPS, and RFID, and combined use with other technologies such as BIM+IoT+IA+Big Data. The study provides digital technologies and their various applications so that stakeholders can select them to overcome challenges in the reverse chain of MSW.

Keywords: digital technologies; municipal solid waste; reverse logistics challenges; municipal solid waste management.

RESUMO

Identificar na literatura as tecnologias digitais e seus métodos de aplicação relevantes para o funcionamento da logística reversa de resíduos sólidos urbanos. O método adotado foi uma revisão sistemática da literatura utilizando o método PRISMA em cinco etapas, conduzida ao longo de 9 meses (de abril a dezembro de 2023), e consultando as bases de dados Scopus e Web of Science. A base de dados é composta de 58 artigos válidos para o objetivo da pesquisa, 16 tecnologias digitais e 61 aplicações práticas no contexto da logística reversa (LR) de resíduos sólidos urbanos (RSU), apresentadas em três classificações. O estudo apresenta uma compilação de tecnologias digitais aplicáveis à gestão de resíduos sólidos urbanos (GRSU) e suas diversas aplicações na execução da Logística Reversa (LR) de resíduos sólidos urbanos (RSU). Até o momento, as aplicações dessas tecnologias digitais na LR de RSU existiam de maneira dispersa na literatura. Dessa forma, contribui para o avanço teórico ao fornecer uma base sólida para pesquisas e desenvolvimentos futuros nessa área. Além disso, fornecemos uma classificação dessas tecnologias, de acordo com o padrão identificado nesta revisão sistemática: uso individualizado como *Blockchain*, IA, Big Data e IoT se destacam como as tecnologias com mais aplicações; uso único, como sensores de rastreamento, GPS e RFID; e uso combinado com outras tecnologias, como BIM+IoT+IA+Big Data. O estudo fornece tecnologias digitais e suas várias aplicações para que as partes interessadas possam selecioná-las para superar desafios na cadeia reversa de RSU.

Palavras-chave: tecnologias digitais; resíduos sólidos urbanos; desafios da logística reversa; gestão de resíduos sólidos urbanos..

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INTRODUCTION

The challenges faced in municipal solid waste management (MSWM) involve all stakeholders, including generators, government, sorting units, waste recovery units, and disposal facilities, as they are interconnected within the reverse chain and share responsibility for the proper recovery and disposal of municipal solid waste (MSW). Reverse logistics (RL) of MSW is a set of actions undertaken by interested parties to facilitate the collection and return of solid waste to the production cycle to reuse or properly dispose of this waste. RL of MSW includes the activities of collection, transshipment, transportation, sorting for reuse or recycling, treatment, including composting, and final disposal of household waste, waste originating from commercial, industrial, and service activities, and waste from public urban cleaning services. If properly implemented, it is an instrument to address the challenges in the reverse MSW channel.

The challenge of the heterogeneous composition of waste, which complicates its recovery, is a consequence of poorly designed MSW sorting processes, low public awareness and enthusiasm for participation in this process (lack of waste separation at the generating source), and excessively detailed waste classification standards (Xiao *et al*., 2020). The authors also pointed out that having an inefficient waste collection and transfer network that mixes wet and dry waste and has inadequate treatment capacity due to the high proportion of food waste reinforces this challenge. Carmen-Niño *et al*. (2023) identified the lack of social inclusion as a challenge, as involving the locality in activities related to MSWM requires active community participation to implement initiatives that provide solutions to MSW problems. Waste separation at the source is one such activity, requiring continuous community involvement. Lunag, Elauria, and Burguillos (2021) identified a lack of knowledge about the process and noted that user involvement at the initial stage is the key element for adopting the composting method, increasing compliance and segregation efficiency.

Kazuva and Zhang (2019) highlighted major challenges for MSWM, including the lack of necessary treatment infrastructure, monitoring capacity to deal with waste disposed of in improper areas, and specialized knowledge for identifying and separating waste types, segregation tools, transportation routes, and final disposal methods. Zhang *et al.* (2024) pointed out the lack of measures to incentivize waste recovery by citizens and the lack of policies and technologies for MSW. Behrooznia, Sharifi, and Hosseinzadeh-Bandbafha (2020) supported these challenges including lack of policies and technologies in a study comparing composting and biogas production. Adequate urban planning and infrastructure for the construction and modernization of waste treatment facilities, and the improvement of selective collections are also challenges affecting MSWM (Shen *et al*., 2015).

The potential to implement digital technologies in MSW appears promising compared to conventional technologies, especially in addressing the challenges of the MSW reverse chain. The use of technologies such as IoT and Big Data can significantly impact city design and management, modifying infrastructure and impacting MSW chain management (Presley; Meade; Sarkis, 2007). Examples of applying these technologies in the MSW of RL include the use of artificial intelligence (AI) for waste classification (Maiurova *et al*., 2022) and sensor systems in trash cans that monitor the amount of contained MSW and notify a central system to optimize the collection process (Kurniawan *et al*., 2023). Another application is implementing blockchain for waste management with significant benefits and potential to be explored further (Bhubalan *et al*., 2022). Considering the context of urban waste management, the following question arises: What would be the applications of digital technologies for implementing the MSW RL? What digital technologies are already available, and in which applications are they being used to enable the MSW RL?

Recent literature reviews have focused on leveraging digitalization in the waste recycling industry (Kurniawan *et al*., 2023); how Smart Cities can be employed for greener practices by integrating them into the supply chain (Franchina *et al*., 2021); how digital technologies can empower future cities to establish a unique structure to become smart, resilient, and sustainable tourist destinations (Vardopoulos *et al.*, 2023); how cities can explore the intersection between the circular economy, sustainable urban development, and city digitalization (D'Amico *et al*., 2021); and how digital technologies impact waste in the fashion industry (Akram *et al*., 2022). More specifically focused on an industry like construction, reviews have identified Industry 4.0 technologies used in the design phase to reduce construction waste (Talla; McIlwaine, 2024) and research and development for adopting digital technologies or platforms to assist in deconstruction planning, deconstruction waste, and construction waste (Jin *et al*., 2021).

Regarding specific technologies such as blockchain, literature reviews have focused much on addressing blockchain technology and plastic redesign to effectively leverage circular economy initiatives (Bhubalan *et al*., 2022); reviewing innovations, uses, and challenges of blockchain technology in solid waste management (Jiang *et al*., 2023); and examining the critical success factors for implementing blockchain-based circular supply chains (Kayikci *et al*., 2022). With more focused research objectives on digital technologies and MSW, reviews have discussed the importance of digitalization in promoting municipal circularity, analyzed the role of digital technologies in efficiently managing urban processes and operations (D'Amico *et al*., 2022), and analyzed the use of digital technologies such as blockchain, IoT, and AI for the circular economy in construction (Elghaish *et al*., 2022). However, none of these reviews focus on identifying digital technologies and their applications in the context of MSW RL. Therefore, to address the research question and fill this identified gap in the literature, this study aims to identify digital technologies and their applications in the context of MSW RL through a systematic literature review.

METHOD

A systematic literature review was conducted to answer the research questions: what digital technologies are already available, and in what applications are they being used to enable RL of MSW? The work was developed following the PRISMA method recommendations (Galvão; Pansani; Harrad, 2015), over nine months (April to December 2023). The research steps are described in the following sections.

Identification

The first step involved searching for articles in two research databases: Web of Science (WOS) and Scopus, conducted in May 2023. The search terms selected for use in the databases were "digital technologies," "emerging technologies," "reverse logistics," "circular economy," "municipal solid waste," "urban solid waste," and "solid waste." After this step, 221 and 280 results were found in WOS and Scopus, respectively. Subsequently, analysis, identification, and elimination of duplicates were performed, resulting in 171 articles for the study base.

Selection

The second step conducted between May and June 2023 involved filtering the databases by reading the titles and abstracts of the articles and classifying them as irrelevant, low relevance, medium relevance, and high relevance. Articles that did not meet the research criteria (works on the theme of digital technologies applied to RL for MSW) were classified as irrelevant; those of low relevance were articles that presented points related to digital technologies or reverse logistics but not focused on municipal solid waste; those of medium relevance were articles that presented points related to digital technologies and reverse logistics but not related to municipal solid waste; and those of high relevance were articles that presented all the highlighted points for the research focus.

This stage resulted in 32 articles considered irrelevant, 42 articles considered of low relevance, 60 articles of medium relevance, and 37 articles of high relevance. Articles of low and no relevance were excluded from the base, leaving those of medium and high relevance, totaling 97 articles.

Eligibility

The 97 articles from the selection stage were read in full, and during this stage, six more articles were added to the base, totaling 103 articles. In this step, 45 articles were excluded because they were not accessible or because the article did not address the theme of this study, resulting in 58 articles for the next stage. This step was conducted between October and November 2023.

Inclusion

For this stage, a spreadsheet was created with the help of Microsoft Excel software to collect the main information contained in the articles, answering the questions: Where was the research conducted? What was the research question? What was the research objective? What methods were employed? What were the results? What types of MSW were addressed? All 58 articles were considered for the next stage.

Data Analysis: Identification of Digital Technologies Applied to the RL of MSW

In this final stage, all digital technologies mentioned in the articles were identified along with their application/purpose of use. The identified technologies were categorized into three classifications according to the presented standards: (i) digital technologies used individually and with more than one application; (ii) digital technologies with a single application; and (iii) digital technologies combined with other technologies. For each category, a literature review was conducted to extract the applications of each digital technology, examples of these applications, types of waste mentioned, and the location of these applications. Additionally, the relationships between existing challenges in MSW RL and the application of digital technologies as potential solutions were discussed.

RESULTS

The 58 articles that make up this database were published between the years 2018 and 2023. The final database, consisting of the 58 analyzed articles and their respective authors, is included in the supplementary documents.

Sixteen digital technologies with applications promoting significant advancements in MSW LR were identified, as shown in Table 1.

Digital Technologies Used Individually and With More Than One Application

Blockchain, AI, Big Data, IoT, and robotics stand out as the most prominent technologies with more than one application. Below, the main technologies identified in the literature and how they play a fundamental role in implementing MSW LR are discussed. Tables with technologies (IoT, robotics, 3D Printing, Cloud, and building information modeling [BIM]), their applications, and references are included in the supplementary documents, as they were not included in the article.

Blockchain

With nine applications, blockchain was the technology with the highest number of distinct applications, according to Table 1. The most utilized application was with traceability and process transparency, such as automatic tracking of components and integration with products to estimate their lifecycle, and driving sensors for plastic waste tracking (Elghaish *et al.*, 2022). The use of implementing blockchain-based smart contracts accelerates processing, covering tasks from purchase to inventory, improving efficiency in plastic waste management (Elghaish *et al.*, 2022).

Blockchain can enhance resource consumption, including adapting operations to generate the minimum waste possible, being an effective tool for tracking and analyzing data, and making the transparency provided by blockchain usable to optimize operations and reduce waste throughout the supply chain. It also offers excellent horizontal and vertical management and collaboration, facilitating collaboration not only between different entities at the same level but also between different hierarchical levels, promoting direct collaboration between supply chain participants, and thus reducing costs associated with third-party guidance, making management more efficient and economical (Kayikci *et al.*, 2022).

Another applicability is the possibility of providing a secure and transparent platform for information exchange, effective coordination, and establishing reliable connections among various participants along the chain, thus overcoming traditional collaboration challenges such as lack of trust and uneven data sharing (Liu *et al.*, 2022). By employing it in electronic waste, and by providing a transparent and immutable record of all transactions and movements along the supply chain, blockchain can be instrumental in implementing strategies aimed at reducing the amount of waste generated. The provided transparency allows tracking the provenance of electronic products, from production to final disposal, thus facilitating the identification of improper disposal practices (Bressanelli *et al.*, 2022).

Artificial Intelligence

AI was the second technology with the highest number of applications, totaling eight, showing how its use can be vast and in various ways, according to Table 2. AI enables the recycling process to be more efficient and effective than manual sorting. With the help of sophisticated image processing techniques, intelligent classification and segregation of waste allow for more efficient and precise sorting of recyclable materials, facilitating the proper direction for this revaluation alternative (Maiurova *et al.*, 2022).

Furthermore, AI can be integrated with robotics through the AMP Cortex system, which is designed to recognize, classify, select, and process construction and demolition (C&D) waste. With the use of this technology, it is possible

Table 1 – Digital technologies identified and their applications.

Digital technologies	Applications
Blockchain	Improved traceability and transparency in processes related to the circular economy, such as the sharing of goods and services; automation of payments and verification of information reliability; secure information storage, disintermediation and data decentralization solutions, and enhancing the verification of information, validity, and credibility flow in CE networks; increase in trust among stakeholders + support in improving maintenance and update services; standardization of technology; open platform for innovation and co-creation; network collaboration; increase in remanufacturing and recycling to reduce waste generation; automation of material segregation and collection to facilitate tracking of recycled products along the supply chain.
Artificial intelligence	Classification and intelligent segregation of waste + image processing technique; collection, processing, and intelligent data analysis; maintenance/predictive analysis for modeling future scenarios + inventory management; operational data analysis paired with failure data and maintenance records for decision support and enhanced fault diagnosis; assessment of value and functionality of building components; accurate prediction of generated waste and optimization of product demand; deep learning; AI-based automatically guided vehicles.
Big Data	Improvement in the performance of supply chain traceability + integration and management of databases; processing large volumes of data generated by technologies; improvement in product design facilitating recycling; demand forecasting and customer analysis; data pattern analysis; monitoring internal processes; prevention and mitigation of a range of supply chain risks.
IoT	Collection and sharing of real-time information; monitoring and traceability of activities and products, process optimization, resource efficiency improvement, and real-time data updating; integration of devices and systems to create a network of interconnected objects; manufacturing data and supply chain data acquisition.
Robotics	Changes in the production process; more efficient use of raw materials, ability to conduct large-scale environmental monitoring, and improvements in safety; projection and construction; automation of material handling processes.
3D printing	Manufacture of sustainable materials; customized food production and on-demand manufacturing; projects for optimized structures aimed at reducing material usage.
Cloud	Storage, data simulation, and information sharing across the supply chain; increased internal company awareness of performance.
BIM	Building data integration; information sharing and development of a material information database; project modeling aimed at reducing waste.
Tracking sensors	Real-time monitoring.
Enway urban cleaning	Autonomous sweeping vehicle.
GPS	Precise monitoring of urban vehicles and assets.
RFID (radio frequency identification)	Identified and tracked components to facilitate recycling and reuse.
Machine learning	Autonomous waste collection.
Hamburgsystems	AI-based image classification for illegal waste.
AGV (autonomous guided vehicles)	Information transmission in real-time aiming to monitor, optimize, and enhance traceability.
MOBA (mobile automation)	Navigation and route planning.

Table 2 – Applications of artificial intelligence.

Application	References
Classification and intelligent segregation of waste + image processing technique	Bhubalan *et al.* (2022); Çetin, de Wolf, and Bocken (2021); Chauhan *et al.* (2022); Kurniawan *et al.* (2023); Maiurova *et al.* (2022); Setaki and van Timmeren (2022)
Collection, processing, and intelligent data analysis	Çetin, de Wolf, and Bocken (2021); D'Amico *et al.* (2022); Liu *et al.* (2022); Maiurova *et al.* (2022); Wynn and Jones (2022)
Maintenance/predictive analysis for modeling future scenarios + inventory management	Akbari and Hopkins (2022); Schöggl *et al.* (2023)
Operational data analysis paired with failure data and maintenance records for decision support and enhanced fault diagnosis	Agrawal *et al.* (2022); Talla and McIlwaine (2024)
Assessment of value and functionality of building components	Elghaish *et al.* (2023)
Accurate prediction of generated waste and optimization of product demand	Han *et al.* (2023)
Deep learning	Elghaish *et al.* (2022)
AI-based automatically guided vehicles	Liu *et al.* (2023)

to maximize the capacity of recycling facilities and recover tons of materials per hour, dealing with high accuracy and purity levels of material detection (Setaki; van Timmeren, 2022). Autonomous vehicles can be directly guided by an AI-based system to determine which material needs to be segregated, recovered, and recycled directly from bins to production lines (Liu; Song; Liu, 2023). Utilizing online data and facilitating the control of devices like robots over the internet makes AI powerful when integrated with IoT. The AI-based robot uses its lifting arm to locate and separate target residual materials while moving at each collection point. As the waste is placed on its platform, this represents a viable solution for waste collection with minimal human intervention. After collection, the robot returns to driverless trucks and stores them in a separate location (Maiurova *et al*., 2022).

AI can be used to create systems that allow construction professionals to collaborate and share information about asset maintenance, as well as dismantleable and reusable items in new constructions, assessing the value and functionality of building components (Elghaish *et al*., 2023). Furthermore, AI assists companies in accurately predicting the amount of waste generation, thereby optimizing product demand, which improves supply chain management and reduces unnecessary storage and potential shortages, ultimately reducing costs (Han *et al*., 2023).

Moreover, AI has the potential to be used to model future scenarios, reduce risks, and improve waste management overall (Akbari; Hopkins, 2022). IoT sensors can also be integrated with AI, primarily using deep learning models to identify and assess the functionality and validity status of structural, mechanical, and electrical components of a building, helping asset operators make appropriate choices regarding maintenance or replacement of components (Elghaish *et al*., 2022).

Big Data

Among technologies, Big Data ranked third in terms of variety of uses, with seven distinct applications, according to Table 3. The proficiency of the technology in processing and analyzing large datasets has optimized not only the steps and processes of the chain but also enhanced the use of other tools and technologies, allowing companies to efficiently monitor and track the location and status of products throughout their lifecycle. This precise tracking capability is essential for EC-related activities, such as waste reduction and efficient product recycling, thus identifying opportunities to improve operational efficiency, minimize environmental impacts, and promote more sustainable practices in their operations (Liu *et al*., 2022; Wynn; Jones, 2022).

Analysis of the data stored in Big Data also provides valuable insights into consumer interaction with products throughout the lifecycle. This analysis enables continuous adjustments in design, focusing on durability, identification of recyclable components, and optimization of product efficiency. The application of Big Data in the design phase drives the creation of more sustainable products, promoting circularity throughout the product lifecycle (Han *et al*., 2023).

By processing vast datasets, Big Data offers organizations the ability to identify consumption patterns, anticipate changes in market preferences, and adjust production strategies quickly. Furthermore, the predictive capacity of Big Data enables the anticipation of future scenarios, contributing to more sustainable management by precisely aligning product offerings with real demands, thus promoting efficiency in resource utilization and practices aligned with circular economy principles (Hoosain; Paul; Ramakrishna, 2020; Schöggl *et al*., 2023).

Internet of Things

In total, four applications have been identified for the Internet of Things (IoT). It is a fundamental technology for real-time data collection, where interconnected devices, such as smartphones and machines, communicate with each other and with users, forming an interoperable network. This provides a solid foundation for implementing sustainable practices throughout the product life cycle (Liu *et al*., 2023; Wynn; Jones, 2022).

Companies use IoT sensors to collect data from their production processes, supply chains, and the use and end-of-life phases of products, allowing for more effective resource management. This approach contributes to the optimization of material use, waste reduction, and the identification of opportunities for component recovery and recycling. Furthermore, by integrating IoT with other digital technologies, such as blockchain, companies can transparently track and verify the origin and destination of materials throughout the supply chain, promoting transparency and trust (Schöggl *et al*., 2023).

Robotics

Robotics presented four applications across five different articles. The use of robotics has been associated with a reduction in energy use and greenhouse gas emissions, more efficient use of raw materials, the ability to monitor the environment on a large scale, and safety improvements, resulting in fewer deaths and injuries (Akbari; Hopkins, 2022). The use of robots in the construction industry offers a range of solutions such as precision and automation. They can be used for the manufacturing of construction components and can lead to automated workflows on the construction site that adopt CE with greater precision and accuracy, and reduced production time. Additionally, robots can perform difficult, challenging, or repetitive tasks, such as lifting heavy objects and placing them in a precise position, or working with non-standard materials from waste sources with precision, producing valuable components (Setaki; van Timmeren, 2022).

3D Printing

For 3D printing, three applications were identified. The 3D printing technology can improve on-demand food production and increase the production of

Table 3 – Applications of Big Data.

Application	References
Improvement in the performance of supply chain traceability + integration and management of databases	Rosário and Dias (2022); Rusch *et al.* (2023); Wynn and Jones (2022)
Processing large volumes of data generated by technologies	D'Amico *et al.* (2021; 2022); Liu *et al.* (2022)
Improvement in product design facilitating recycling and providing predictive and preventive maintenance	Han *et al.* (2023); Talla and McIlwaine (2024)
Demand forecasting and customer analysis	Schöggl *et al.* (2023)
Data pattern analysis	Hoosain, Paul, and Ramakrishna (2020)
Monitoring internal processes that constitute sustainable capacity	Akbari and Hopkins (2022)
Prevention and mitigation of a range of supply chain risks	Franchina *et al.* (2021)

personalized foods. Thus, the technology can be useful in enhancing CE by encouraging the recycling and reuse of food (Ada *et al*., 2023). Notably, 3D printing can be used to automate processes in construction, reducing the amount of waste generated. Sustainable 3D-printed steel bridges are an example. Personalization and modularity facilitate reuse, aligning with the circular economy (Talla; McIlwaine, 2024).

Additionally, this technology can help build buildings using local materials, such as soil and organic materials or inorganic waste streams. As it is an additive construction technique, it is possible to create construction processes with minimal waste. This technology can be combined with computational design workflows, using algorithms and optimization methodologies, making it possible to produce parts for optimized performance using minimal material. Furthermore, it is possible to create parts through a single material, which can facilitate disassembly, simplifying the repair and recycling process (Setaki; van Timmeren, 2022).

Cloud Computing

Cloud computing presented two applications in the articles from the database, due to its use with a specific purpose of data storage. It plays a fundamental role in enabling the secure and easily accessible storage of collected data. This technology not only ensures the integrity and confidentiality of information but also efficiently facilitates data sharing among various stakeholders, promoting more dynamic and integrated collaboration (D'Amico *et al*., 2022; Liu; Song; Liu, 2023). It can be used for real-time monitoring and identification of areas for improvement that can guide the optimization of production processes, waste reduction, and better resource management (Neri *et al*., 2023).

Building Information Modeling

With its use directed toward the C&D sectors, BIM has had three applications identified. BIM plays a crucial role in information sharing and the development of a material information database throughout the construction process, with a special emphasis on the preliminary design stage. It is noteworthy that BIM reduces inefficiencies in information exchange, optimizes building design, and contributes to circularity by facilitating end-of-life (EoL) design. Additionally, BIM plugins and tools are employed to predict reusability, recyclability, and EoL performance. It can also be used in the creation of digital material passports (DMPs), using BIM to securely store information about these passports, promoting the tracking and circularity of materials. Furthermore, it is used to predict carbon footprint, resource exploitation, and potential defects during the design phase. In summary, it plays a fundamental role in information management and the development of material data to drive the principles of the circular economy in construction (Khan *et al*., 2023; Setaki; van Timmeren, 2022; Talla; McIlwaine, 2024).

Technologies with Unique Applications

In total, four technologies with unique applications were identified, as shown in Table 4. Tracking sensors, as part of circularity initiatives driven by digitalization, have various practical applications in the municipal context, including waste management. The use of these technological devices in various municipal infrastructures, such as municipal cleaning vehicles, helps to enhance the quality and speed of decision-making processes (D'Amico *et al*., 2022).

The tracking system (GPS) allows real-time monitoring of the location of vehicles and municipal assets. This provides companies with an immediate view of ongoing operations. Furthermore, based on real-time location information, GPS tracking systems help optimize vehicle routes. This can result in time and fuel savings, as well as reduce carbon emissions, contributing to sustainable logistics (D'Amico *et al*., 2022). The municipal cleaning technology from the German company Enwaye uses autonomous vehicles that perform cleaning tasks in public city areas (Maiurova *et al*., 2022). Meanwhile, RFID (radio frequency identification) technology is used to identify and track components, facilitating reuse and recycling (Hoosain; Paul; Ramakrishna, 2020).

Combined Use Technologies

Combined uses of two or more technologies for specific applications have been identified. For didactic purposes and to enhance understanding, they will be presented in four subtopics: combinations with the IoT, combinations with AI, combinations with the Cloud, and combinations with BIM.

Technologies Combined With the IoT

In total, eight combinations of IoT with other technologies were identified, as shown in Table 5, highlighting the IoT+blockchain combination, which brings three distinct applications.

The combination of IoT and blockchain in the management of waste electrical and electronic equipment (WEEE) can be observed in the creation of a traceable supply chain, as electronic devices can be monitored from manufacturing to disposal, providing complete visibility throughout the entire product lifecycle. This also optimizes logistics, provides useful information for design and maintenance, ensures material traceability and compliance with environmental regulations, and encourages corporate social responsibility. Blockchain, by securely and decentralizedly storing data, and IoT, by collecting real-time information, are presented as complementary tools that extend product life and reduce environmental impacts associated with Magrini et al. (2021). The use of "smart bins," which, through the integration of IoT and blockchain, simplify waste segregation and ensure precise disposal of waste in these smart containers. This not only optimizes recycling operations but also promotes effective resident participation in the waste management process. Additionally, a framework integrates conventional supply chains with technical support for waste management, including segregation, transport, and

Table 4 – Single application technologies.

Technology	Application	References
Tracking sensors	Real-time monitoring	D'Amico *et al.* (2022)
Enway urban cleaning	Autonomous sweeping vehicle	Maiurova *et al.* (2022)
GPS	Precise monitoring of urban vehicles and assets	D'Amico *et al.* (2022); Langley (2022)
RFID (radio frequency identification)	Identified and tracked components to facilitate recycling and reuse	Cherrafi *et al.* (2022); Hoosain, Paul, and Ramakrishna (2020)

disposal, aiming to reduce operational costs in the closed-loop virtual supply chain (Jiang *et al*., 2023).

Rosário and Dias (2022) explored the intersection of IoT, AI, and Big Data, especially in solid waste management, generating significant changes in business models. Accordingly, the integration of these technologies enables companies to make informed decisions about product lifecycles, identifying opportunities to extend their utility and minimize waste.

The combination of IoT with blockchain and Big Data is discussed in the context of the transition to the Smart CE (Bressanelli *et al*., 2018; Bressanelli *et al*., 2022), emphasizing that digitalization enables a systematic redesign of products and supply chains. Practical examples cited include the role of IoT and Big Data in implementing product ecodesign and the use of IoT, blockchain, and Big Data in the professional electronics industry to prevent electronic waste generation and improve supply chain coordination.

The integration of IoT and AI can play an efficient optimization role in construction, monitoring internal spaces, and tracking failures (Talla; McIlwaine, 2024). Smart bins have sensors that classify waste (plastic, bottles, paper, metal, and organic) and inform the level of fullness or emptiness, besides the Cloud, which stores real-time data. The combination of IoT and Cloud computing can illustrate the type of waste and how much of it will be separated or recycled, incinerated, or properly landfilled. An alert message informs waste collectors that materials are ready to be collected once the bins reach a set level (Franchina *et al*., 2021).

Combined Technologies With AI

Three combinations of AI with distinct technologies were identified, as shown in Table 6. The strategic convergence between AI, robotics, and machine learning (ML) in waste management is evidenced after its innovative implementation in Nanning, China. Digitalization has driven the transition from manual waste collection to a robotics-based system, where AI with ML was integrated to control the quality of recyclable materials. Robots, guided by ML algorithms, significantly improved sorting efficiency, achieving 99% accuracy. Additionally, digitalization and ML were applied to optimize collection routes, reducing operational costs and CO_2 emissions (Kurniawan *et al*., 2023).

On the other hand, the integration of robotics with AI in the context of waste management presents significant advancements, such as the use of robots with AI capabilities to autonomously conduct recycling processes, precise identification of materials through advanced algorithms, and the application of IoT technologies to optimize real-time operations. AI-driven automation is emphasized as an effective tool to increase efficiency in waste segregation and recycling, offering innovative solutions like robots that perform the separation of specific materials in C&D waste (Maiurova *et al*., 2022). Hamburgsistems software utilizes AI-based image classification to process images of illegal waste. Residents use their smartphones to capture images of illegal waste, and the software organizes the images and redirects them to the appropriate agents (Maiurova *et al*., 2022).

Combined Technologies With Cloud

Two combinations of Cloud with different technologies and applications were identified, as shown in Table 7. To promote recovery, recycling, and remanufacturing, Cloud computing can be integrated with AGV (autonomous guided vehicle) technology that helps ensure real-time information in the supply chain and aims to monitor, predict, optimize, and increase traceability (Ada *et al*., 2023). Moba (mobile automation) through Cloud computing performs tracking, customer and container management, navigation, and route planning (Maiurova *et al*., 2022).

Table 5 – Technologies combined with the internet of things.

Combinations	Application	References
IoT + blockchain	WEEE Traceability	Magrini *et al.* (2021)
	Facilitates traceability and authenticity of waste logistics data, prevents fraud, protects privacy, and enhances waste management efficiency	Jiang *et al.* (2023)
	Transition to circular economy	Kayikci *et al.* (2022)
IoT + AI + *Big Data*	Identification of opportunities in solid waste management and changes in business models	Rosário and Dias (2022)
IoT + blockchain + *Big Data*	Transition to smart circular economy (CE)	Bressanelli *et al.* (2022)
IoT + *Big Data*	Support for internal CE practices for resource efficiency	Bressanelli *et al.* (2022); Neri *et al.* (2023)
IoT + *Big Data* + robotics	Enables better understanding of the process	Neri *et al.* (2023)
IoT + Nuvem + *Big Data*	Flexible and agile manufacturing processes	Awan *et al.* (2022)
IoT + AI	Monitoring internal spaces and tracking faults	Talla and McIlwaine (2024)
IoT + Cloud	Real-time notification, transmission, and storage of data on waste in bins, waste characteristics, and possible dispatch options such as recycling	Franchina *et al.* (2021)

Table 6 – Technologies combined with artificial intelligence.

Combinations	Application	References
AI + *machine learning* + robotics	Autonomous waste collection	Kurniawan *et al.* (2023)
AI + robotics	Identifies and performs material separation	Cagno *et al.* (2021); Maiurova *et al.* (2022)
AI + Hamburgsystems	AI-based image classification for illegal waste	Maiurova *et al.* (2022)

Combined Technologies With BIM

BIM can be combined with IoT, AI, and Big Data in two possible applications, according to Table 8. It can be utilized in the initial design and planning phase, where digital modeling not only optimizes the construction design but also incorporates plugins and advanced algorithms to predict aspects such as reusability, recyclability, and disassembly (Çetin; de Wolf; Bocken, 2021).

Additionally, during off-site manufacturing, BIM is combined with robotics and 3D printing to efficiently produce module components. In the transportation and logistics stage, IoT sensors and real-time data analysis are integrated with BIM to monitor the integrity of modules during transportation. Finally, during on-site assembly, virtual reality, AI, and other technologies are synergistically employed with BIM to optimize site layout planning, reduce waste, and improve collaboration among stakeholders. This integration demonstrates a holistic approach, harnessing the power of BIM together with other technological innovations to enhance efficiency and sustainability throughout the VMC project lifecycle (Khan *et al*., 2023).

DISCUSSION

Among the presented technologies and their various applications, blockchain, AI, Big Data, and IoT stand out as the technologies with the most applications when used individually, and they are also the most researched technologies. Second, the applications of other technologies such as robotics, 3D printing, Cloud, and BIM were evident, which, despite having fewer applications, carry relevance for the implementation of MSW RL. Both the technologies with more general use and those with a more specific application, such as BIM used in C&D, have their own degree of importance for the implementation of RL.

Focusing on application and utility issues, it is noticeable that the greatest potential manifests when technologies are combined. The integration of IoT with blockchain, Big Data, AI, and robotics, as well as the integration of AI with ML, robotics, and hamburgsistems, opens up great possibilities for use and offers more assertiveness for the implementation of RL in municipal areas, as in cities already experiencing such combinations and their results. For example, waste separation done by robots automates this process that was previously done manually. Additionally, there are applications where city residents can report illegal waste disposal, contributing to the sanitation of the territory and the existing logistics (Maiurova *et al*., 2022). The effective use of these combinations is the automatic collection of waste using robotics, from planning the most efficient collection routes to sorting recyclable waste with a 99% accuracy rate (Kurniawan *et al*., 2023). These applications demonstrate how the use of digital technologies can assist in the implementation of RL in municipal centers as well as help overcome existing barriers to MSWM.

Xiao *et al*. (2020), in a study conducted in Shanghai, identified challenges such as poorly designed MSW sorting processes and an inefficient waste collection and transfer network that mixed wet and dry waste. In response to these barriers, AI proves to be more efficient and effective than manual separation. Using image processing techniques, the intelligent classification and segregation of waste enable more efficient and precise sorting of recyclable materials, facilitating their redirection toward revaluation (Maiurova *et al*., 2022). Integratively, AI and robotics can recognize, classify, select, and process C&D waste, maximizing recycling capacity with high precision and material purity detection (Setaki; van Timmeren, 2022).

Creating an inventory of items used in construction can support the circular life of materials (steel, concrete, windows, and doors) that could be reused if there were incentives to implement this circularity (Arora *et al*., 2021; Brandao *et al*., 2023). AI can be leveraged to create systems that enable construction professionals to collaborate and share information about asset maintenance, as well as dismantling and replacing items that can be reused in new constructions, allowing the assessment of the value and functionality of building components (Elghaish *et al*., 2023).

The use of inappropriate tools and vehicles for RL can lead to additional costs (Melo *et al*., 2022; Oliveira Neto; Correia, 2019; Nobre *et al*., 2022; Nunes *et al*., 2023). The integrated use of digital technologies such as AI, Cloud computing, and IoT facilitates the control of devices like robots, which can locate and separate targeted waste materials while moving through collection points (Maiurova *et al*., 2022).

Oliveira Neto and Correia (2019) argued that without advancements in technological processes, it is impossible to minimize the amount of construction waste, and the difficulties in meeting the sector's demands increase significantly. Arguably, 3D printing can be used to automate construction processes, reducing the amount of waste generated, such as 3D-printed sustainable steel bridges (Talla; McIlwaine, 2024). Additionally, this technology can aid in constructing buildings using local materials, such as soil and organic materials, or inorganic waste streams. As an additive construction technique, it enables the creation of building processes with minimal effort (Setaki; van Timmeren, 2022). BIM can be used to minimize construction waste throughout the entire

Table 7 – Technologies combined with the Cloud.

Combinations	Application	References
Cloud + AGV (autonomous guided vehicles)	Information transmission in real-time aiming to monitor, optimize, and enhance traceability	Ada *et al.* (2023)
MOBA (mobile automation) + Cloud	Navigation and route planning	Maiurova *et al.* (2022)

Table 8 – Technologies combined with BIM.

Combinations	Application	References
BIM integrated with IoT + AI + Big Data	Optimizing resource utilization by reducing waste at all points along the chain	Çetin, de Wolf, and Bocken (2021)
	Predicting carbon footprint, resource exploitation, potential defects, and performance criteria for the building	Khan *et al.* (2023)

building process, from the preliminary design to the EoL project (Khan *et al*., 2023; Setaki; van Timmeren, 2022; Talla; McIlwaine, 2024)

Brandao *et al*. (2023) highlighted that small waste generators significantly impact the reverse chain of C&D waste due to the practice of adding these wastes to household garbage, increasing management challenges. The combination of blockchain and IoT enables the implementation of innovative solutions like "smart bins," which simplify waste segregation and ensure the accurate disposal of waste into these containers (Jiang *et al*., 2023).

Construction companies are increasingly hesitant to use recycled construction materials due to concerns about not having enough materials to complete their constructions (Geng *et al*., 2023). Addressing this challenge, Big Data has the capability to identify consumption patterns, anticipate market changes, and swiftly adjust production strategies. It also allows for the anticipation of future scenarios, contributing to more sustainable management by precisely aligning product supply with actual demand (Hoosain; Paul; Ramakrishna, 2020; Schöggl *et al*., 2023). The synergy between these technologies can not only transform waste management but also promote sustainable practices, demonstrating an integrated and effective model for the future of municipal waste management (Kurniawan *et al*., 2023).

In emerging countries such as Brazil, RL credits are beginning to apply blockchain technology to implement smart contracts and ensure traceability and transparency of processes (Elghaish *et al*., 2023), where credits can be traded between companies, such as manufacturers and recyclers, facilitating the secure and transparent transfer of these credits and automating the transfer process based on predefined conditions. It also allows for providing a secure and transparent platform for exchanging information, coordinating effectively, and establishing reliable connections between participants along the chain (Liu *et al*., 2022), as blockchain allows recording all stages of RL, from collection to final destination, where each transaction (such as packaging return) is recorded in blocks, creating an immutable and transparent history. Therefore, it helps to verify the authenticity of credits and track compliance with targets.

Therefore, the advancement of digital technologies presents possibilities for overcoming the challenges in the reverse chains of MSW. Highlighting these technologies enables planning investments by various chain stakeholders to overcome these challenges. Identifying these digital technologies and their applications, as well as relating them to the challenges in MSWM, provides a practical compilation for public and private managers operating in these chains to address actions, policies, and investments for improved chain management.

CONCLUSIONS

This study aimed to identify applicable digital technologies for the operation of RL for MSW. In total, 16 digital technologies and 61 practical applications were identified, from their individual use to their combined use, providing a set of diversified tools that can assist in the implementation of RL as well as applications that can overcome the difficulties of its adoption. It further discussed the relationship between the functionalities of digital technologies and the existing challenges throughout the reverse chain of MSW.

This research contributes by offering a comprehensive view of digital technologies that can be effectively used to implement or improve the operation of RL for MSW. Identifying and understanding these technologies and their applications is crucial for theoretical advancement in the field of MSWM, providing a solid foundation for future research and developments in this area. In practical terms, it contributes by offering already available technologies, being used in municipal environments and their applications, either individually or combined, where they drive better results.

Since the research presented is theoretical in nature, there is a need for future empirical research. Therefore, we suggest conducting an empirical survey to identify the importance of these digital technologies among area specialists, as well as to expand the literature review by considering more databases, considering that digital technologies and their applications should remain on the research radar due to being a current topic with various application possibilities. It is also suggested to survey the economic impact that the implementation of these technologies would have on an MSW chain. Finally, we suggest carrying out a theoretical and empirical survey to identify the existing difficulties in using the aforementioned technologies.

AUTHORS' CONTRIBUTIONS

Leal, AEF: Conceptualization, Formal analysis, Methodology, Validation, Writing – original draft. Costa, VCC: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft. Fernandes, RM: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. Melo, ACS: Formal analysis, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. Nagata, VMN: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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