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APPLICABILITY OF DIGITAL TECHNOLOGIES TO THE REVERSE LOGISTICS OF MUNICIPAL SOLID WASTE: LAWSHE ANALYSIS FOR THE BRAZILIAN CONTEXT

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Introdução
Municipal Solid Waste(MSW) management involves household and urban cleaning waste, the generation of which puts pressure on municipal MSW management systems, requiring more robust arrangements(Kurniawan et al.,2024).In this context,reverse logistics(RL) is a key instrument for organizing the return of materials to the production cycle through selective collection,drop-off points, sorting,and revaluation,connecting stakeholders and contributing to the circular economy(CE)(Schilling & Seuring,2024). Digital technologies(DT) focused on process optimization have accelerated the transition to CE

Problema de Pesquisa e Objetivo
The literature has explored the application of DTs in MSW RL through various methodologies.Some approaches include:Structural Equation Modeling(Tao&Chao, 2024),MCDM(Narula et al.,2024),TOPSIS(Tanveer et al.,2023),DEMATEL(Quayson et al.,2023),and BWM(Mondal et al.,2023).Despite these applications,there is a lack of research that systematically and quantitatively validates the relevance of these technologies based on expert judgment.Therefore,the aim is to present a framework with DTs and their applications in the RL of MSW and validate them for the Brazilian context,using the Lawshe method(1975

Fundamentação Teórica
The transition to CE has been accelerated by DTs.The IoT,for example,establishes the basis for smarter waste management,using sensors to collect real-time data on the quantity and type of discarded material,which allows for the optimization of collection logistics (Ngoc et al.,2024).This information is processed using Big Data,the analysis of waste flows identifies trends and improves system efficiency(Carlos,de Souza&Mattos,2024).With this data,AI predicts waste generation patterns,dynamically adjusting processes to allocate resources(Onur et al.,2024).

Metodologia
The study employed two methods:a systematic literature review and a structured survey,combined with Lawshe analysis.The review followed the PRISMA method in four stages:identification,selection,eligibility,and inclusion.Searches were conducted in the Web of Science and Scopus databases,with a time frame of 2023–2024.A total of 148 articles were considered.The final analysis resulted in 25 DTs applicable to the RL of MSW.The questionnaire was structured in Google Forms.Respondents were selected based on seven predefined profiles and prospected through LinkedIn.Data were analyzed using Lawshe.

Análise e Discussão dos Resultados
20 DTs were not validated,meaning they are not considered essential in the Brazilian context.Furthermore,five technologies achieved a positive CVR and are considered essential,but not validated by the Lawshe method.Additive manufacturing,although intended to convert plastic waste into valuable products,faces barriers such as high acquisition and maintenance costs,a lack of technical training,and limited infrastructure (HOSSAIN;SAHAJWALLA,2024).These restrictions explain the low prioritization given to it by Brazilian experts.

Considerações Finais
The study offers three contributions:a theoretical framework with 25 DTs and functionalities;a methodological framework with the application of the Lawshe method as an alternative for quantitative validation by a specialized panel;and a practical framework with an indication of the possible incompatibility of national infrastructure as factors impeding immediate adoption.Limitations include the impossibility of generalizing the results.It is recommended to expand the sample of technology developers and further study the feasibility of implementation in developing country contexts.

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Palavras Chave
Digitalization in MSW management, Reverse chain of municipal solid waste, Circularity of resources

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1 INTRODUCTION

The municipal solid waste (MSW) management involves household and cleaning waste, whose growing generation puts pressure on the municipal systems of collection, screening and final disposal and requires institutional and operational arrangements (BRASIL, 2010; Kurniawan et al., 2024; Oyinlola et al., 2024). In this context, reverse logistics becomes an essential instrument for organizing the material's return to the productive cycle - by selective collection, delivery points, screening and valorization - combining public and private actors and contributing to the circular economy (BRASIL, 2010; Schilling & Seuring, 2024; Carlos; de Souza; Mattos, 2024; Leal et al.,2024). Recent literature has highlighted that, when well structured, those systems mitigate environmental impacts, improve operational efficiency, and generate economic value from discarded materials (Hossain et al., 2024; Onur et al., 2024). The management of MSW faces challenges such as the heterogeneous composition of the waste (XIAO et al., 2024). The lack of specialized knowledge and segregation technologies (Kazuva & Zhang, 2019). The transition to a circular economy has been boosted by digital technologies set focused on process optimization through data intelligence.

2 RESEARCH PROBLEM AND OBJECTIVE

The existing literature has explored the application of digital technologies (DTs) on RL of MSW by many methodologies. Some approaches include: SEM – Structural Equation Modeling (Tao & Chao, 2024), MCDM – Multi-Criteria Decision-Making (e.g., Narula et al., 2024), TOPSIS – Technique for Order of Preference by Similarity to Ideal Solution (e.g., Tanveer et al., 2023), DEMATEL – Decision-Making Trial and Evaluation Laboratory (e.g., Quayson et al., 2023) and BWM – Best-Worst Method (e.g., Mondal et al., 2023).

Despite the application of these methods, a gap remains: the absence of research that carries out systematic and quantitative validation of the relevance of technologies based on expert judgment. Given this fact, this research seeks to answer the following questions: Which DTs are already available and in what applications are they being used to enable the RL of MSW? Which of these DTs would be more adequate to overcome the challenges of RL of MSW?

Therefore, this research aims to presents a framework containing the DTs and their respective applications on RL of MSW and to validate it within the Brazilian context, using the Lawshe Method (1975) to analyze experts' perspectives in the industry, combined with a systematic literature review following the PRISMA method (Preferred Reporting Items for Systematic Reviews and Meta-Analyses).

3 METHODOLOGY

The study used two methods: (i) a systematic literature review and (ii) a structured survey, associated with Lawshe's analysis. The review followed the PRISMA method in four steps – Identification, selection, eligibility, and inclusion – (Galvão, Pansani e Harrad, 2015). The search was conducted in the Web of Science and Scopus databases, considering a time frame of 2023–2024. Initially, 272 registers were identified; after the selection process, 175 articles were selected for integral reading; 148 studies were kept on eligibility. The final

analysis resulted in 25 digital technologies mapped with potential application on RL in MSW in the Brazilian context.

Based on that, the survey was structured using google forms in four sections: Introduction and consent term signature, characterization of the respondent's profile and DTs validation, using the three points scale: (Essential, important, not important). The respondents were selected based on the following profiles: Academic, public sector, waste company or urban planner, environmental engineer, technology developer, NGOs, sustainability consultant. The prospecting was carried out via LinkedIn.

Finally, the data obtained were analyzed based on Lawshe's (1975) statistical method, which aims to measure the level of importance assigned to each identified item according to respondents' judgment.

4 ANALYSIS AND DISCUSSION

4.1 DESCRIPTIVE ANALYSIS OF THE BASE

The search prospected 316 individuals, of whom 52 responded to the survey, resulting in a 16,46% return rate. Regarding the professional profile, the predominance of Consultants and Specialists in Sustainability stood out (26,92%), followed by academics/researchers and environmental engineers or urban planners (19,23% each) and public sector professionals (13,46%). In terms of experience time, 21,15% have up to 5 years, 50% have 5–15 years, 28,85% have over 15 years, suggesting a sample of professionals with highly diverse levels of experience.

4.2 LAWSHE ANALYSIS FOR VALIDATION OF DIGITAL TECHNOLOGIES IN THE RL OF MSW

The statistical parameters necessary to define the minimum CVR that must be achieved for a DT to be validated as essential were calculated. For a sample of 45 respondents, the $CVR_{critical}$ is 0.292, as shown in Table 1.

Table 1 – Parameters of the Lawshe Method

Parameter	Results
Respondents	45
Mean	22,5
Variance	11,25
Standard Deviation	3,354
Critical ne	29,074
$CVR_{critical}$	**0,292**

Source: Authors (2025).

Table 1 presents the critical ne, which represents the minimum number of respondents who must indicate that a given functionality is essential for validation to occur. This integer value is 30, which was not reached for any of the functionalities studied, as shown in Table 2.

Table 2 - Validation of Digital Technologies for MSW Reverse Logistics

Digital Technology Functionality	CVR	No. of ESSENTIAL	Validation

1- AI in waste sorting automation	-0,467	12	Not Validated
2- AI for waste demand forecasting	0,022	23	Not Validated
3- IoT in real-time data collection and analysis	-0,067	21	Not Validated
4- IoT in more accurate and data-driven decision-making	-0,289	16	Not Validated
5- IoT in the use of connected sensors	0,022	23	Not Validated
6- BIG DATA for agility in data processing	0,244	28	Not Validated
7- BIG DATA in process optimization	0,200	27	Not Validated
8- BIG DATA for adaptability to specific operational needs	-0,111	20	Not Validated
9- BLOCKCHAIN for traceability and transparency	0,067	24	Not Validated
10- BLOCKCHAIN for security and reliability	-0,022	22	Not Validated
11- BLOCKCHAIN for efficiency in recycling	-0,200	18	Not Validated
12- BLOCKCHAIN for process automation	-0,378	14	Not Validated
13- BLOCKCHAIN in integration with other technologies	-0,289	16	Not Validated
14- 3D PRINTING for transforming waste into new products	-0,511	11	Not Validated
15- 3D PRINTING for product customization	-0,556	10	Not Validated
16- 3D PRINTING in manufacturing from plastic waste	-0,378	14	Not Validated
17- NIR SENSORS for identifying recyclable materials based on chemical composition	-0,111	20	Not Validated
18- NIR SENSORS in integration with waste sorting equipment	-0,111	20	Not Validated
19- MOBILE PLATFORMS in operational efficiency	-0,067	21	Not Validated
20- MOBILE PLATFORMS for digital integration	-0,111	20	Not Validated
21- ROBOTIC SYSTEMS for waste sorting automation	-0,556	10	Not Validated
22- ROBOTIC SYSTEMS for dismantling electronic products	-0,244	17	Not Validated

23- ROBOTIC SYSTEMS for real-time monitoring of recycling processes	-0,244	17	Not Validated
24- DIGITAL TWINS for improved traceability	-0,289	16	Not Validated
25- DIGITAL TWINS for efficiency in maintenance and repair	-0,378	14	Not Validated

Source: Authors (2025).

Table 2 shows that 20 DTs were not validated and presented negative CVR values, indicating that these technologies are not considered essential in the Brazilian context. Nevertheless, five technologies achieved positive CVR values, considered essential, although not validated according to the Lawshe method.

4.3 DISCUSSION OF RESULTS

Table 2 shows that five DTs with positive CVR values, but below the essentiality threshold. This dissonance requires further examination, as literature presents barriers that explain the discrepancy.

For the Internet of Things (IoT), Carlos, de Souza and Mattos (2024) describe applications such as monitoring waste composition and flow tracking. However, adoption faces obstacles: high initial costs, the need for digital infrastructure, and a shortage of technical training, which may have influenced the essentiality evaluation. Similarly, AI for demand forecasting demonstrates optimization potential (Ansari et al., 2024) but depends on adequate digital infrastructure; in less developed regions this limitation compromises the applicability and perception of essentiality (Kurniawan et al., 2024). Dependence on public policies and external investments further delays practical benefits, which justifies respondents' judgment.

Big Data enhances the analysis of large datasets and supports strategic decision-making. Integrated with IoT sensors, geospatial data, and operational histories, it allows route optimization, load balancing, and predictive maintenance (Adewuyi et al., 2024; Menezes, Hemachandra & Isidro, 2024). However, its implementation faces recurring barriers: data quality and completeness, integration of heterogeneous sources, scalability and real-time processing limitations, high upfront costs, shortages of skilled professionals, and governance and privacy requirements. Collaborations with startups are suggested as mitigating factors, but they do not eliminate the inherent complexity and investment required. Blockchain is valued for its immutable traceability and fraud prevention capabilities (Jakubowicz & Yarahmadi, 2024; Hau et al., 2023). However, its application suffers from the lack of a universal model, which hinders interoperability (Jakubowicz & Yarahmadi, 2024), and by complex privacy and regulatory challenges related to data sharing among multiple stakeholders (Carlos, de Souza & Mattos, 2024). This technological immaturity and the need for systemic coordination and regulatory frameworks explain the more cautious evaluation of its immediate relevance.

In summary, the barriers analyzed help to understand the judgment of the responding professionals and provide a consistent explanation for the observed dissonance. CVR values below the essentiality threshold do not indicate rejection of digital technologies but rather reflect respondents' perceptions of the practical, contextual, and economic challenges to their effective adoption in the Brazilian context.

Of the 25 functionalities surveyed, 20 had negative CVRs, showing that less than half of respondents considered them essential corresponding to 80% of the total. The lowest scores were observed for 3D printing for product customization (CVR= −0.556), robotic systems for

sorting automation (CVR = −0.556), and 3D printing for transforming waste into new products (CVR = −0.511).

Additive manufacturing, although considered a method to convert plastic waste into high-value products, faces barriers: high acquisition and maintenance costs for 3D printers, a lack of technical training, and limited infrastructure (HOSSAIN; SAHAJWALLA, 2024). Furthermore, the economic viability of models based on recycled filaments is compromised without subsidies or strategic partnerships (KOLADE et al., 2024). These constraints explain the low priority given to it by Brazilian experts.

Regarding robotic sorting systems, the integration of IoT, computer vision, and robotics can optimize fraction separation and reduce exposure to hazardous materials (KURNIAWAN et al., 2024). However, poor connectivity, high implementation costs, and the need for specialized maintenance teams make large-scale adoption unfeasible, which justifies its cautious evaluation by experts. 3D printing for the creation of new products also requires convergence between government, industry, and academia to establish policies, technical standards, and appropriate logistics networks (ONUR et al., 2024). The need for coordination and joint investment, given regulatory and institutional gaps, limits its national-scale implementation.

Other functionalities with negative CVR, although closer to zero—such as IoT for real-time collection/analysis, mobile platforms, and blockchain for security/reliability—reflect a division among evaluators; negative values close to zero indicate a lack of consensus in the perception of essentiality (LAWSHE, 1975). The literature highlights the potential of IoT for monitoring and integration with big data (MEDAGLIA et al., 2024; JAUHAR et al., 2023), but gaps in governance and network compatibility restrict scalability (OYINLOLA et al., 2024). Mobile platforms can connect collectors and recyclers, but their effectiveness depends on device penetration, network quality, and engagement of informal actors (KOLADE et al., 2024). Blockchain offers immutable records but faces energy and transaction costs and a lack of regulatory frameworks, making its adoption conditional on partnerships and institutional incentives (SHETTY et al., 2024; OYINLOLA et al., 2024; KOLADE et al., 2024).

5 FINAL CONSIDERATIONS

This study validated DTs applicable to the RL of MSW through a literature review and the Lawshe analysis of survey data with Brazilian experts. The findings indicate that none of the 25 technologies is considered essential, highlighting the tension between theoretical potential and practical feasibility due to infrastructural and professional limitations. Despite this, some DTs exhibited positive CVR—notably AI for generation forecasting, IoT for sensor monitoring, Big Data for processing and optimization, and Blockchain for traceability—although they remained below the critical value.

The study addresses three contributions: (i) theoretical — systematization of an analytical framework with 25 technologies and functionalities; (ii) methodological — demonstration of the application of the Lawshe method as a quantitative validation instrument by means of a specialized panel; (iii) practical — indication of the possible incompatibility of national infrastructure as a factor impeding immediate adoption.

Limitations include the impossibility of generalizing the results and the limited participation of technology developers (3.7%). It is recommended to expand the sample of developers and conduct in-depth studies on the feasibility of implementation in developing countries to inform public policies and digitalization strategies in MSW management.

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