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A Framework for Leveraging Digital Technologies in Reverse Logistics Actions: A Systematic Literature Review

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Abstract: *Background*: The global climate crisis has intensified the demand for sustainable solutions, positioning Reverse Logistics (RL) as a critical strategy for minimizing environmental impacts. Simultaneously, Industry 4.0 technologies are transforming RL operations by enhancing their collection, transportation, storage, sorting, remanufacturing, recycling, and disposal processes. Understanding the roles of these technologies is essential for improving efficiency and sustainability. *Methods*: This study employs a systematic literature review, following the PRISMA methodology, to identify key Industry 4.0 technologies applicable to RL. Publications from Scopus and Web of Science were analyzed, leading to the development of a theoretical framework linking these technologies to RL activities. *Results*: The findings highlight the fact that technologies like the Internet of Things (IoT), Artificial Intelligence (AI), Big Data Analytics, Cloud Computing, and Blockchain enhance RL by improving traceability, automation, and sustainability. Their application optimizes execution time, reduces operational costs, and mitigates environmental impacts. *Conclusions*: For the transportation and manufacturing sectors, integrating Industry 4.0 technologies into RL can streamline supply chains, enhance decision-making, and improve resource utilization. Smart tracking, predictive maintenance, and automated sorting systems reduce waste and improve operational resilience, reinforcing the transition toward a circular economy. By adopting these innovations, stakeholders can achieve economic and environmental benefits while ensuring regulatory compliance and long-term competitiveness.

Keywords: sustainable operations; waste management; smart logistics; decision support systems; sustainable supply chain; lifecycle assesment; circular economy

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1. Introduction

Recently, climate change has become a central topic in global debates, especially concerning the emissions of greenhouse gases (GHG) from industrial activities. The advancement of industrialization, combined with the increasing demand for industrial goods, has significantly contributed to the higher levels of release of atmospheric gases, such as carbon dioxide (CO_2), negatively impacting the environment and public health. As highlighted by [1], the continuous growth of industrial activities and global economic development have increased energy demand. Consequently, this has led to higher levels of emissions of pollutant gases, particularly CO_2, which intensifies the greenhouse effect and directly contributes to global warming. According to [2], climate change, glacier melting, rising sea levels, flooding, depletion of water resources, reduced rainfall, and desertification,

among other phenomena, result from excessive consumption, modernization, technological advancement, and industrial progress. Furthermore, the generation and inadequate management of solid waste (SW) have worsened climate change, as GHG are emitted during decomposition.

The current climate emergency and its vast impacts on society have influenced the private sector and its leaders, who are now more attentive to local and national legislation. In the United States, solid waste management is regulated by the Environmental Protection Agency (EPA), which is responsible for setting national standards and ensuring that states comply with these regulations [3]. In emerging countries like Brazil, the responsibility for solid waste management lies with the Ministry of the Environment, as established by Law No. 12.305/2010. According to this law, which institutes the National Solid Waste Policy (PNRS), waste management involves direct and indirect activities. These activities encompass the collection, transportation, treatment, and final disposal of waste, ensuring that everything is accomplished in an environmentally appropriate manner, including waste disposal [4]. The United Nations (UN) has raised concerns about the amount of SW generated, warning that global waste volume reached 2.3 billion tons in 2023 and could increase to 3.8 billion tons by 2050, causing significant impacts on climate, health, and the economy [5]. There is an urgent need to develop strategies to mitigate or eliminate waste generation by adopting measures to reduce waste and preserve natural resources, with the aim of decreasing the amount of waste generated by processes and products, thereby reducing pollutant emissions into the air, soil, and water.

The increasing global demand for sustainability has intensified the need for efficient waste management and circular-economy strategies. Reverse Logistics (RL) plays a crucial role in addressing these challenges by enabling materials collection, sorting, recycling, and remanufacturing, in addition to reducing the vulnerability of supply chains [6]. However, traditional RL systems often suffer from inefficiencies, high operational costs, and limited traceability, which hinder their effectiveness in achieving sustainability goals. Despite advancements in RL practices, significant gaps remain in the integration of digital technologies with the aim of optimizing these processes. In this context, Reverse Logistics (RL) has been continually developed as an effective tool to improve waste collection and return processes, returning materials to the production sector. This process allows these materials to be reincorporated into the production cycle, ensuring their final disposal in an environmentally appropriate manner [4]. According to [7], efficient waste management is a key element in environmental preservation and public health protection. Given this scenario, there is a potential to enhance RL actions with the help of Industry 4.0 technologies, linking these technologies with RL practices through a comprehensive approach to addressing the inherent challenges.

Industry 4.0, or the Fourth Industrial Revolution, is characterized by integrating advanced technologies in the industrial sector. As highlighted by [8], this approach combines information and communication technologies, leading to significant productivity, flexibility, quality, and management advances. This progress is driving the adoption of new methods, re-evaluation of work practices, and implementation of modern technologies. With the continuous technological evolution, these innovations are transforming manufacturing operations, promoting the concept of "smart factories", in which systems are integrated, adaptable, and highly efficient. As [9] points out, the essence of Industry 4.0 lies in the connection between machines, systems, and assets, enabling companies to create intelligent networks and manage production processes autonomously. This transformation represents a significant shift in current manufacturing, offering a new approach to maximizing productivity and reducing resource consumption [10–12].

Thus, the integration of digital technologies from Industry 4.0 can play a significant role in improving organizational operations. These technologies not only impact manufacturing but also have the potential to advance RL processes. To enable this integration, alternatives involving the adoption and use of digital technologies have been explored; these have proven successful in addressing various challenges, such as reducing input waste, optimizing execution time, controlling operational costs, and improving management processes, resulting in significant gains in productivity and efficiency [13].

Recent studies on RL have explored various approaches to the improvement of waste management, yet a comprehensive framework linking Industry 4.0 technologies to RL applications remains underdeveloped. This study aims to bridge this gap by analyzing the ways in which technologies like the Internet of Things (IoT), Artificial Intelligence (AI), Big Data Analytics, Cloud Computing, and Blockchain can enhance RL efficiency, reduce costs, and improve environmental outcomes. Specifically, we seek to answer the following research question: How can Industry 4.0 technologies enhance Reverse Logistics operations' sustainability and operational efficiency?

While RL encompasses various material flows, this study focuses on solid waste as a representative example to illustrate the transformative potential of digital technologies. The insights gained from this sector can be extended to broader RL applications. By addressing inefficiencies in waste collection, processing, and disposal through smart tracking, automation, and real-time analytics, Industry 4.0 can revolutionize RL practices and drive the transition toward a circular economy.

The main contribution of this study lies in developing a theoretical framework that systematically links Industry 4.0 solutions to RL activities, providing practical insights for industries seeking to enhance their sustainability initiatives. The remainder of this paper is structured as follows: Section 2 reviews the literature on RL and Industry 4.0; Section 3 details the methodology employed; Section 4 presents the proposed framework; Section 5 discusses key findings and industrial applications; and Section 6 states the conclusions of the study, along with implications for future research and practice.

2. Theoretical Background

This section presents the theoretical foundations of the study, focusing on solid waste management, Reverse Logistics, and the role of Industry 4.0 in optimizing these processes. The objective is to comprehensively understand how digital technologies can enhance decision-making at operational, tactical, and strategic levels. The discussion is structured as follows: first, we examine the principles of solid waste management, by-products, and Reverse Logistics. Then, we explore the key Industry 4.0 technologies and their impact on RL activities. Finally, we analyze the applications of these technologies in decision-making across different levels, providing a basis for the theoretical framework.

2.1. Solid Waste, By-Products, and Reverse Logistics

Industrial solid waste refers to materials in a solid or semi-solid state that result from manufacturing, transformation, or use in industrial activities and no longer have utility in their original context. Improper management of these wastes can lead to soil and water contamination and the emission of atmospheric pollutants, contributing to environmental degradation and health problems in surrounding communities [14]. By-products, often considered waste, represent an opportunity for resource recovery and reintegration into production cycles. RL practices can transform these materials into secondary raw materials, reducing dependency on newly acquired resources and fostering industrial symbiosis. However, the complexity of RL processes demands advanced technological solutions to optimize decision-making and ensure economic viability.

Managing industrial solid waste involves a set of practices and procedures used to handle these materials in an environmentally appropriate way, from generation to final disposal. This includes source reduction, reuse, recycling, treatment, and safe final disposal. Effective management seeks to minimize environmental impacts and promote sustainability, aligning with current environmental regulations and best industrial practices [15]. The authors of [16] highlight serious issues associated with waste management, noting that waste discarded in inappropriate locations can cause odors and facilitate the spread of pests. Additionally, waste that is incorrectly burned releases toxic gases into the atmosphere. These waste management problems are characteristic of developing countries.

In contrast, [17] argues that returning waste to the production chain as an alternative to raw materials brings numerous environmental, social, and economic benefits. The increasing generation of solid waste has raised concerns regarding environmental sustainability, economic efficiency, and resource optimization. Traditional waste management systems, often based on linear models, have demonstrated inefficiencies in material recovery, cost reduction, and environmental impact mitigation. Reverse Logistics (RL) emerges as a strategic approach able to address these shortcomings, shifting from a disposal-oriented perspective to a resource recovery and reintegration model. When coupled with Industry 4.0 technologies, RL enhances waste management processes' traceability, automation, and efficiency, promoting a circular economy.

Reverse Logistics (RL) originated in customer service, where consumers returned defective or warranty-covered products to suppliers [18]. Initially a reactive process, RL began to gain new significance with the rise of environmental concerns. Issues such as recycling, reuse, and proper disposal have become fundamental in reducing environmental impacts and are essential for the sustainable development of products [19]. Increasing globalization and the shortening of product lifecycles have heightened corporate concerns about sustainability, making Reverse Logistics a critical factor for organizations [20,21].

According to [22], RL involves planning, execution, and the control of materials and products that have already been used, aiming to recover their value and ensure proper disposal. Reverse Logistics (RL) is often viewed as the inverse of traditional logistics. In contrast to RL, traditional logistics follows a linear flow from producer to consumer, while RL manages the return of products to the production cycle [23]. Moreover, a product's lifecycle extends beyond its delivery to the consumer, encompassing post-use stages in which the product requires return for repair, reuse, or proper disposal [24].

Nowadays, Reverse Logistics has gained even more relevance due to growing ecological awareness, limited natural resources, and legal requirements regarding waste management [24]. Companies are under increasing pressure to adopt more sustainable practices and are faced with the responsibility of managing the final dispositions of products after they are delivered to the final consumer. In the United States, for example, the Resource Conservation and Recovery Act (RCRA) established strict policies on solid waste, requiring recycling and the safe disposal of hazardous waste [3]. In this context, RL, divided into its various actions, is a central element in efficient waste management and environmental preservation, one with an increasing focus on returning products to the production cycle for reuse and reducing environmental impacts [25]. RL involves a set of actions aimed at managing the return and reintegration of materials and products into the production cycle, as well as their proper disposal in the environment [25]. Figure 1 illustrates the main actions of RL.

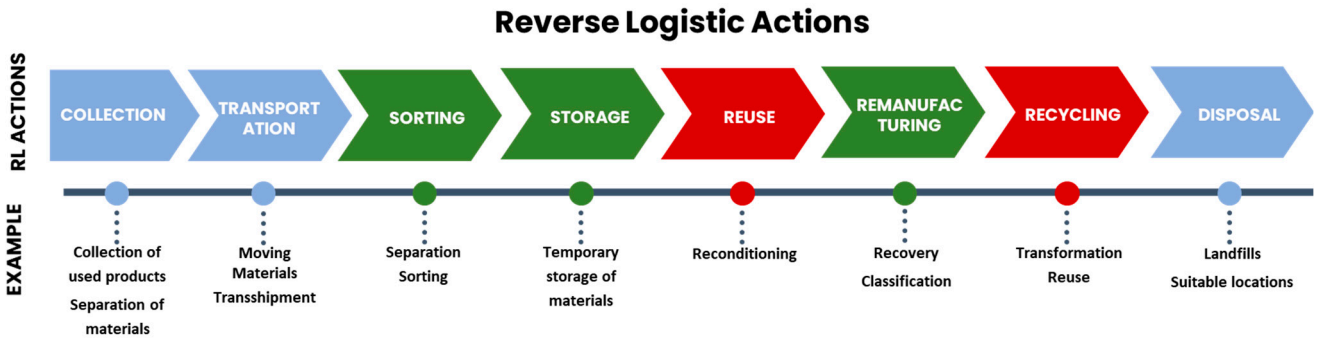

Figure 1. Reverse Logistics actions.

- Collection—This refers to the gathering of used products, packaging, and materials. This process involves separating and disposing of recyclable materials, such as plastics, glass, paper, and metals, from various sources like homes, industries, or businesses [26].
- Transportation—Transportation is an important stage in Reverse Logistics, encompassing planning to optimize the collection, storage, and delivery of waste, and ensuring that it is handled safely and in an environmentally appropriate manner [27].
- Sorting—This refers to the separation and classification of the collected products. Sorting is performed at specialized centers, where materials are separated, contributing to the reduction in waste sent to landfills, lowering transportation costs, and enabling the commercialization of recyclable materials [28].
- Storage—Storage is accomplished at centers designed for the temporary deposit of materials, facilitating processes such as sorting, recycling, reuse, and proper disposal [28].
- Reuse—This involves extending the useful lives of goods or materials by means of their reuse in industrial or residential contexts without the need for significant modifications [29].
- Remanufacturing—This is a process that revitalizes products at the end of their lifecycle through stages like recovery, inspection, disassembly, polishing, renewal, and reassembly, resulting in an item that has a condition equivalent to that of a new product [29].
- Recycling—Recycling is the process of transforming solid waste by altering its properties so it can be reused, either as raw material or in the creation of new products [30].
- Disposal—Disposal is the final stage in Reverse Logistics, occurring when a product can no longer be reused or recycled. In this process, waste must be properly disposed of without harming the environment. According to current regulations, waste must be sent to landfills or other appropriate locations in compliance with local laws [30].

Even though these actions are divided, several decision-making problems must be considered in a Reverse Logistics network. According to [31], these decisions can be divided into three levels, namely, strategic, tactical, and operational, depending on the timing of the planning. At the operational level, actions are directly related to practical execution, such as collection, transportation, and disposal. At the tactical level, actions may involve managing and coordinating the processes, including sorting, storage, and remanufacturing. At the strategic level, actions focus on long-term planning and the definition of policies and guidelines for Reverse Logistics, including those involving recycling and reuse. Reverse Logistics covers all necessary stages, including collecting the materials and disassembling them, processing the products, reusing the materials and components, ensuring waste reduction, and minimizing environmental impact [32]. The recovery process relating to these materials begins with the collection, in which products are selected, classified according to their properties, gathered, stored, and transported to specialized facilities for

transformation or reprocessing, with the aim of adding value [33]. Environmental laws hold manufacturers responsible for the disposal of their products and packaging, considering the lifespans of these products. As a result, companies are being pressured to adopt Reverse Logistics actions to promote more sustainable practices, reduce environmental impact, and foster sustainability [34].

2.2. Industry 4.0 and Digital Technologies in Reverse Logistics

Industry 4.0 represented a revolution in business operations management, promoting a more efficient restructuring of production chains and industrial processes [35]. Emerging in Germany in 2011, after the three previous Industrial Revolutions, it brought significant advances in automation, digitization, and the integration of smart technologies, transforming production lines and increasing their efficiency [9]. According to [36], Industry 4.0 goes beyond technological innovations, presenting a vision of smart factories capable of operating autonomously, planning, organizing, and controlling the entire production process. This concept is characterized by the automation of manufacturing systems, and uses advanced information technologies to optimize production with greater precision and safety [37].

According to [38], Industry 4.0 is not just about isolated new technologies but the collaborations between various physical, biological, and digital technologies, an element which sets it apart from previous Industrial Revolutions. The integration of these technologies results in increased production efficiency, the creation of new processes, and the customization of products. Industry 4.0 technologies combine different solutions to provide real-time information more efficiently and integrate advanced technologies within the context of a growing productivity demand driven by more demanding consumers. These technologies allow flexible, decentralized, and customized production while facilitating real-time information exchange. Moreover, Industry 4.0 technologies support and transform modern manufacturing methods, standing out by integrating the physical production world with virtual networks [39]. According to [40], the innovative technologies associated with Industry 4.0 can revolutionize the industrial sector, promoting productivity, cost reduction, process optimization, and greater personalization in manufacturing. These innovations can contribute to sustainability goals and create a more eco-friendly system of production. Several technologies can be used in the context of Industry 4.0 to improve production processes and reduce environmental impacts. Industry 4.0 introduces digital technologies that enhance RL efficiency by improving decision-making, automation, and system integration. Traditional RL systems often have inefficiencies in tracking, sorting, and optimizing reverse flows, leading to high operational costs and suboptimal resource utilization. The main challenges in RL are the lack of real-time visibility and the absence of data-driven decision-making, factors which hinder effective waste recovery and reintegration.

According to [38], the integration of advanced technologies is essential for promoting sustainability and the development of Industry 4.0. The authors highlight 16 key technologies within Industry 4.0 that significantly transform industrial processes and optimize resource use. The technologies mentioned in [38] are presented below, along with a brief explanation of each one:

- Internet of Things (IoT): Connects physical and virtual objects to the internet, enabling communication between products, services, and environments via smart sensors that monitor and control remotely;
- Cyber–Physical Systems (CPS): Integration of physical and digital components, such as software-controlled sensors, that monitor and manage industrial processes in real time, improving automation and logistics efficiency;

- Industrial Internet of Things (IIoT): The application of the IoT in the industrial sector, using industrial devices and sensors to collect, analyze, and share real-time data;
- Machine-to-Machine Communication (M2M) Allows machines to communicate directly, automating processes and eliminating the need for human intervention, aiming to attain greater efficiency [41];
- Artificial Intelligence (AI): Technology that replicates the human ability to control processes and solve problems autonomously, optimizing production and improving efficiency;
- Big Data Analytics (BDA): Techniques used to process large volumes of data generated by industries, turning the data into valuable information for real-time decision-making;
- Cloud Computing (CC): Storing and processing data on remote servers, facilitating access and accruing cost savings for industries;
- System Integration (SI): Connecting machines, processes, and people to ensure efficient communication, increasing productivity and organizing industrial operations;
- Cybersecurity: Protecting data and interconnected systems from breaches and unauthorized access, crucial for ensuring the security and integrity of information in the industrial environment [42];
- Autonomous Robots: Robots that work alongside humans in production, performing high-complexity tasks quickly and precisely [43];
- Smart Sensors: Devices that monitor physical conditions and transmit data, enabling quick and automatic decisions within the industry;
- Mobile Systems and Devices: Tools, like smartphones and tablets, allowing efficient monitoring and control of industrial processes, ensuring access to real-time information [44];
- Digitization and Virtualization: Processes that convert physical elements into digital data and create virtual representations of that data, facilitating production integration and optimization [45];
- Simulation: Using digital models to replicate and analyze industrial systems and processes, aiding in optimization efforts and the anticipation of failures;
- Augmented Reality (AR) and Virtual Reality (VR): Technologies that integrate the physical and digital worlds, supporting activities such as maintenance, training, and real-time process visualization;
- Additive Manufacturing (AM): A manufacturing process in which materials are added layer by layer to create parts, using fewer resources and generating less waste, with applications in prototypes and the production of complex parts;
- Radio-Frequency Identification (RFID): a technology that uses radio waves to identify and track objects, animals, or people by transmitting data from a tag to a reader without physical contact;
- Blockchain (BC): a decentralized digital ledger that records transactions across a network of computers, ensuring immutability and transparency.

By integrating these technologies, RL systems can address key challenges, such as inefficient waste handling, high costs, and lack of transparency, transforming waste management into a more effective and sustainable process. The proposed theoretical framework highlights how these digital solutions contribute to the optimization of RL operations and the fostering of a more resilient circular economy. Figure 2, adapted from [46], shows how digital technologies can be used in Reverse Logistics actions in a disassembly line for waste from electrical and electronic equipment (WEEE).

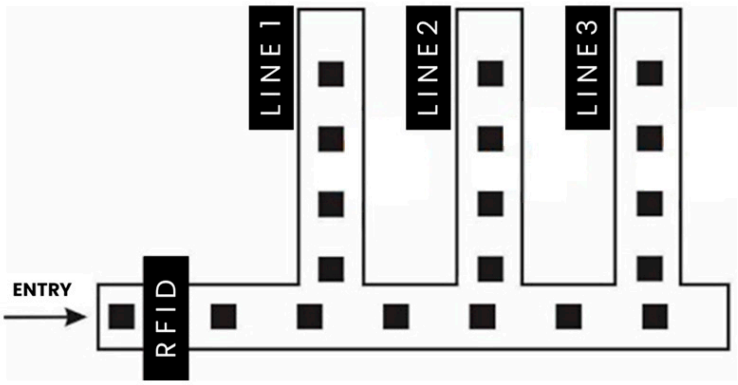

Figure 2. Automation in Waste Electrical and Electronic Equipment lines.

The example in Figure 2 demonstrates the use of RFID at the entry points of the disassembly lines for WEEE (Waste Electrical and Electronic Equipment), identifying the types of equipment being disassembled. Based on this identification, the system automatically directs the product to the most appropriate processing line equipped to handle that specific type of item. This way, the process is optimized, ensuring that each product is sent to the right location, where it will be dismantled or processed properly.

3. Materials and Methods

This study used a systematic literature review, and is properly classified as a secondary study, as it analyzes and synthesizes information from previously published primary studies [47]. This type of research follows a qualitative approach, aiming to interpret and systematically organize existing data in the literature. It is categorized as descriptive research, primarily identifying, structuring, and synthesizing information about digital technologies aligned with Reverse Logistics (RL) practices. Its purpose is theoretical, seeking to consolidate and expand existing knowledge. The review was systematically structured, following a sequential process to ensure methodological rigor and avoid arbitrary or disorganized approaches. As [48] has proposed, Figure 3 presents the steps of the methodology used in this study.

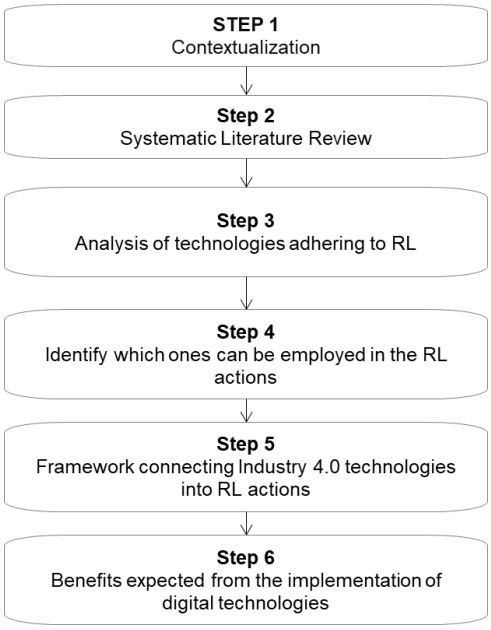

Figure 3. Steps used to conduct this study.

Step 1—Contextualization: In this stage, the research guidelines are presented, which are based on the justification for the study and the above introduction. Related studies were analyzed to provide a foundation that facilitates the implementation of Industry 4.0 technologies in Reverse Logistics (RL) actions.

Step 2—Systematic Literature Review: The literature review was conducted using the Scopus and Web of Science databases due to their extensive coverage of peer-reviewed academic publications. The search focused on studies published between 2011 and 2024, a timeframe chosen to capture the emergence and evolution of Industry 4.0 technologies in RL. This period marks the rapid development and adoption of digital technologies in industrial applications. The search query was designed to ensure precision and comprehensiveness, using the following Boolean logic: ((“Industry 4.0” OR “smart manufacturing” OR “digital technologies”) AND “reverse logistics”), as illustrated in Table 1. This query structure ensures that articles addressing RL within the context of Industry 4.0 and smart manufacturing are included, refining the scope to technological and operational advancements.

Table 1. Searched-for items.

Filters	Scopus	Web of Science
Searched for	Title, abstract, and keywords	Title, abstract, and keywords
Publication year	2011–2024	2011–2024
Area	Engineering	Engineering
Document Type	Article	Article
Language	English	English
Search terms	(“Industry 4.0”) OR (“smart manufacturing”) OR (“Digital Technologies”) AND (“reverse logistics”)	(“Industry 4.0”) OR (“smart manufacturing”) OR (“Digital Technologies”) AND (“reverse logistics”)

The PRISMA method was used to ensure the transparency and integrity of the research when conducting the systematic review [49]. This method organizes the article selection and analysis stages, providing a clear structure for the research’s search elements. As suggested by [49], to define the inclusion and exclusion criteria, the four phases of the PRISMA method were applied: identification, screening, eligibility, and inclusion; these are shown in Figure 4, which presents the detailed flowchart of the systematic review, illustrating each of these phases.

In the first phase of the PRISMA method, identification, 159 documents were found, 68 in the Scopus database and 91 in the Web of Science, using the Boolean operators and keywords presented in Table 1. In the second phase, screening, inclusion (studies published in peer-reviewed journals and conference proceedings; research focusing on the application of Industry 4.0 technologies in RL; and studies presenting empirical findings, case studies, or theoretical frameworks linking digital technologies to RL activities) and exclusion (papers unrelated to RL or Industry 4.0; studies lacking sufficient methodological details; and publications focusing solely on forward logistics without reverse flow considerations) filters were applied. In the first filter, which limited the texts considered to research articles, 61 documents were excluded; in the second filter, which included only the articles in English, two papers were discarded; and in the third filter, by focusing on the research area of “engineering”, 50 documents were removed. The engineering-field limitation was applied to ensure a focus on technological and operational aspects, but we acknowledge the need for a broader scope and subsequently reconsidered this limitation. In the third phase, eligibility, 10 duplicate articles were eliminated. Then, 12 papers were discarded due to

their not addressing the proposed topic or for being considered irrelevant to the research. Finally, in the fourth phase, inclusion, 24 articles were selected for their relevance and underwent a detailed analysis.

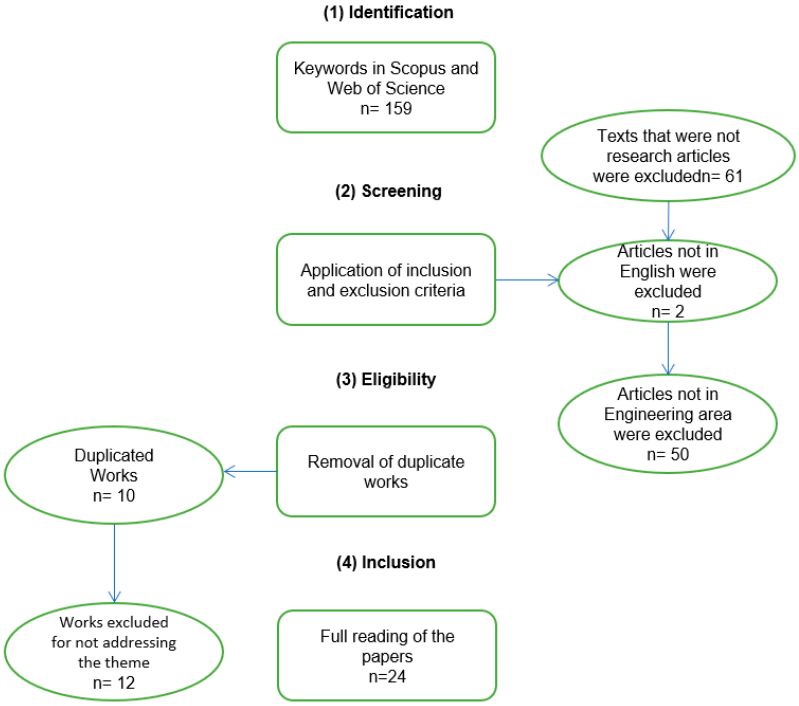

Figure 4. Flowchart of the PRISMA method.

Step 3—In this phase, the technologies that align with Reverse Logistics (RL) actions were analyzed. The analysis included verifying how each technology aligns with RL actions' specific needs and challenges, considering aspects such as efficiency, sustainability, and traceability.

Step 4—The identification of Industry 4.0 technologies currently being used in RL was conducted based on a survey of technologies shaping RL, with a focus on innovation.

Step 5—In this phase, a theoretical framework was developed to establish the relationship between Industry 4.0 technologies and RL actions. This phase included creating a visual representation to facilitate understanding of the interactions between these technologies and RL activities.

Step 6—Finally, in this phase, the expected benefits of implementing these technologies were presented, highlighting improvements in operational efficiency, waste management enhancement, and promotion of sustainable practices.

4. Results

This section presents the main results of the systematic literature review and the collected data.

4.1. Digital Technologies That Contribute to RL Actions

The systematic literature review identified several digital technologies contributing to Reverse Logistics actions. Table 2 was created to organize the selected studies, containing information such as the ID (identification) of the articles, authors, years of publication, and the frequency of citation of the mentioned technologies. To identify the digital technologies most aligned with RL actions, a detailed analysis of the 24 selected articles was conducted. This analysis involved evaluating the studies; identifying and comparing the

technologies mentioned, including examination of their practical application; and verifying their relevance to the objectives of RL. As a result, the 14 most relevant technologies were highlighted, and the information associated with these technologies, including citation frequency, was organized. This approach provides a comprehensive overview of the most cited digital technologies in the reviewed literature.

Table 2. List of the most used technologies in RL.

DIGITAL TECH-NOLOGIES	Internet of Things	Big Data	Cloud Computing	Artificial Intelligence	Blockchain	Additive Manufacturing	Autonomous Robots	Cyber–Physical Systems	RFID	Simulation	Digital Twin	Digitalization	Intelligent Sensors	Augmented and Virtual Reality
Reference														
[50]	x	x	x		x	x		x						
[51]	x			x						x	x	x		
[52]	x			x										
[53]	x	x	x	x	x			x	x		x			x
[54]		x	x			x		x	x					
[55]		x				x				x				
[56]	x		x					x	x					
[57]		x		x										
[58]	x	x		x	x		x		x					
[59]	x	x	x	x	x	x	x							x
[60]			x			x		x						
[61]					x							x		
[62]					x									
[63]	x	x					x					x	x	
[64]	x		x											
[65]	x												x	
[66]	x	x					x			x				
[67]	x	x	x	x			x	x	x					
[68]	x												x	
[69]	x					x	x				x			
[31]										x	x			
[70]				x						x				
[59]	x		x											
[71]	x													
TOTAL	16	10	9	8	6	6	6	6	5	5	4	3	3	2

Each cell marked with an 'x' indicates that the technology was mentioned in that article.

According to the data presented in Table 2, the most cited technologies in the analyzed articles were, in order of frequency, the Internet of Things and Big Data Analytics, followed by Cloud Computing and Artificial Intelligence. However, beyond listing these technologies, it is essential to discuss the levels at which they are applied:

- Operational Level: Technologies such as RFID and the IoT enable real-time tracking and monitoring of returned products, thereby enhancing efficiency in collection and sorting processes.
- Tactical Level: Machine learning and data analytics help in decision-making regarding refurbishment, redistribution, and waste management practices.
- Strategic Level: Blockchain offers transparency and traceability in Reverse Logistics networks, enhancing compliance with environmental regulations and fostering stakeholder trust.

By categorizing these technologies according to their application levels, we provide a clearer understanding of their roles in Reverse Logistics operations. The next section discusses how the identified technologies can be applied to improve Reverse Logistics efficiency, illustrating their integration into key Reverse Logistics processes.

4.2. Digital Technologies That Can Be Employed in RL Actions

Based on the data analysis from the systematic review, it was possible to identify the ways in which digital technologies are being applied in different RL actions. After analyzing the 24 articles and collecting information about the technologies most employed in RL actions, 12 technologies with greater alignment were identified. These can optimize processes, facilitate a more efficient and sustainable implementation, and promote greater integration among the involved agents. As stated in step 3 of this study, the analysis included verifying that the technologies align with the needs of RL. Thus, technologies such as Digital Twins and Augmented Reality were not considered, as they are more related to more complex cases requiring a high level of digitization and data integration, which is not always feasible in all operations. The 12 technologies aligned with RL are IoT, AI, Big Data Analytics, Cloud Computing, Blockchain, Cyber-Physical Systems, Digitalization, RFID, Sensors, Autonomous Robots, Additive Manufacturing, and Simulation. A framework was then created that links the digital technologies to RL actions, providing a systematic methodology for applying the technologies at different organizational levels. Despite these benefits, several challenges hinder full-scale adoption, including the following:

High Implementation Costs: Many companies struggle to justify the investment required to deploy digital Reverse Logistics solutions.

Data Integration Issues: Ensuring compatibility between different technological systems remains a key barrier.

Regulatory and Compliance Constraints: Legal and environmental regulations often complicate the adoption of new technologies.

Addressing these challenges requires industry collaboration, policy support, and technological advancements that enhance accessibility and affordability.

Impact on Sustainability

Digital technologies significantly contribute to sustainability by enabling more efficient Reverse Logistics processes. Their impact is evident in the following areas:

- Reduction of Waste: AI-driven analytics and IoT-based tracking prevent unnecessary disposal of returned goods by optimizing repair and redistribution processes.
- Enhanced Resource Recovery: Blockchain and RFID facilitate better traceability, ensuring materials are effectively recovered and reintegrated into production cycles.

- Carbon Footprint Reduction: Digital tools help optimize transportation routes for returned goods, minimizing emissions and improving energy efficiency.

Figure 5 summarizes the contributions of each digital technology to Reverse Logistics actions, providing a clear linkage between technological implementation and environmental benefits.

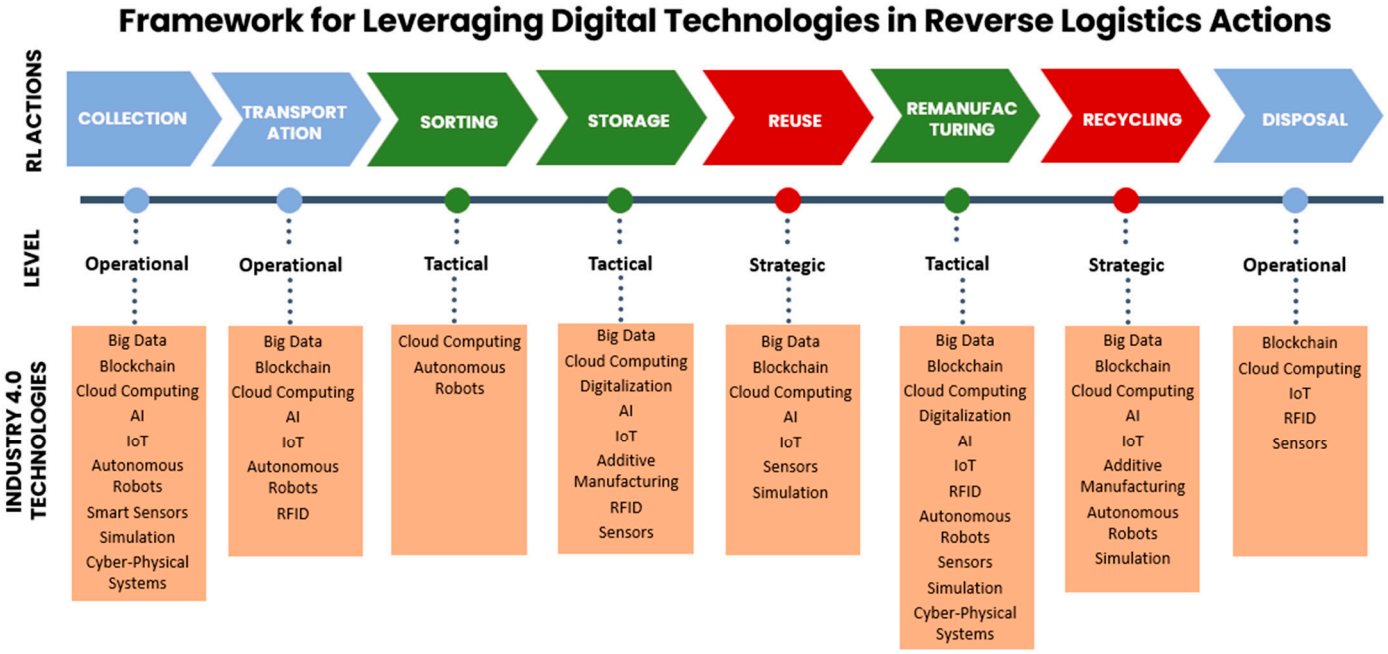

Figure 5. Framework describing the contributions of digital technologies to RL actions.

In addition, various decision problems must be considered in an RL network. According to [72], these decisions can be divided into three levels, namely, strategic, tactical, and operational, depending on the planning time. At the operational level, actions are directly related to practical execution, such as collection, transportation, and disposal. At the tactical level, actions can involve the intermediate management and coordination of processes, including sorting, storage, and remanufacturing. At the strategic level, actions focus on long-term planning and defining policies and guidelines for RL, including recycling and reuse.

4.3. Operational Level

At the operational level, actions are directly related to practical execution, such as collection, transportation, and disposal. Collection can be optimized using Industry 4.0 technologies such as automation, IoT, and Big Data Analytics, which improve communication, tracking, and information processing. Autonomous Robots reduce the need for manual labor and minimize the risk of human error. At the same time, integrating digital technologies, such as the IoT and Sensors, enhances real-time monitoring, aiding decision-making and improving waste management efficiency [63]. Simulation and artificial intelligence (AI) are applied to enhance waste collection through route planning and optimization of the process, resulting in lower operational costs and reduced impact due to waste [70,73]. Blockchain is used to create tracking systems for collection points and route optimization, allowing precise identification of collection locations and ensuring logistical efficiency [62]. Simulation in Reverse Logistics (RL) aims to optimize collection efficiently, meeting demand while considering uncertainties in the process [51]. Additionally, when used together, the IoT and CPS create an intelligent waste collection system, improving

processes and facilitating the tracking and automation of collection operations. In this context, RFID tags can track and identify products [53].

Big Data Analytics stands out in transportation actions, enabling route and operation improvements by analyzing large volumes of information [55]. Integrating the IoT and RFID allows for real-time tracking and control of waste during transportation, ensuring better monitoring and safety [58]. Autonomous robots play a crucial role in loading and unloading materials. Big Data Analytics is also used to optimize vehicle route planning, while cloud computing facilitates storing and processing this data in real time [59]. Similarly, Blockchain ensures secure transportation transactions, tracking goods from the collection point to the final destination [50]. In logistics operations, AI complements these technologies by providing predictions and advanced analytics that assist decision-making and identifying patterns for continuous improvements [52].

Five technologies can be effectively applied to disposal actions. Sensors integrated with the IoT enable real-time data monitoring of products, making this activity a crucial factor in RL. RFID allows for the tracking of returned products, and assists in the decision-making regarding the proper disposal of materials [63]. Technologies like the IoT also contribute to the evaluations of the conditions of products at the end of their useful life, enabling more precise disposal decisions [59]. Blockchain is central in ensuring the security, visibility, and tracking of items during disposal [62]. Cloud computing, in turn, centralizes information relating to materials to be discarded [67].

4.4. Tactical Level

At the tactical level, actions involve management and intermediate coordination processes, including sorting, storage, and remanufacturing. Cloud computing can manage and store data related to these items, enabling the storage of returned products. Technologies such as Big Data Analytics, Sensors, and the IoT are applied to manage and track movement and storage, ensuring precise identification of products during the storage process [63]. Additionally, RFID enables detailed tracking of returned products, recording information such as code, description, date, time, and ideal storage location. Digitalization contributes to the dynamic adaptation of the RL network parameters, allowing the system to adjust efficiently to variations in demand and production processes [51]. Additive Manufacturing (AM) facilitates inventory planning by enabling on-demand production of parts and components, reducing the need for large quantities of storage and contributing to a more sustainable system [54]. With the aid of AI, data processing is optimized, facilitating decision-making related to allocation and efficient inventory management.

In sorting, technologies such as cloud computing play a relevant role by anticipating the workload in sorting-center sectors, ensuring better performance in the RL chain, even before the arrival of trucks [60]. Autonomous Robots are employed in sorting to perform tasks such as separating and selecting waste, increasing safety and the efficiency of operations [66].

Remanufacturing is the stage with the greatest potential for technology application; it is focused on restoring and improving the functionality of residual products. Digitalization plays an important role in remanufacturing, transforming the planning and execution of RL networks [51]. IoT-based sensors allow for real-time monitoring, ensuring transparency in remanufacturing processes [68]. AI, especially in image recognition, is a valuable tool in remanufacturing, particularly when detailed product information is unavailable [53]. Technologies such as Big Data Analytics and Simulation can be used to develop flexible structures that facilitate restoration and prolong the product lifecycle [55]. Combining AI and Big Data Analytics provides detailed insights into product lifecycles, helping companies identify components that still hold value and that can be remanufactured [69].

RFID tags added to remanufactured products enable the sending of information to the system for calculating returns and optimizing process management [54]. Integrating cloud computing with IoT creates more flexible and adaptable production systems, enhancing efficiency and quality in remanufacturing [59]. Blockchain ensures traceability, reliability, and transparency in the remanufacturing process, ensuring that remanufactured products meet the required quality standards [61].

4.5. Strategic Level

At the strategic level, actions are focused on long-term planning, a consideration which defines the policies and guidelines that guide RL. Among these actions are the establishment of strategies for recycling and material reuse. Technologies such as AI and Big Data Analytics enhance product reuse and recycling actions based on consumer feedback via the web [57]. AM improves recycling operations by reducing waste, increasing precision, and enhancing material reuse [60]. The reuse and recycling of materials can be optimized by using sensors integrated with the IoT, which enable real-time tracking of reusable and recyclable materials, facilitating their identification and handling during the process. Integrating Big Data Analytics, the IoT, and automation in recycling enables the analysis of large volumes of data, identifying the patterns and best practices in waste management, promoting safety, and reducing human errors. Technologies like AI, Blockchain, Big Data Analytics, and Simulation innovate recycling and material reuse processes. Big Data Analytics helps identify patterns and strategic planning [74]. Blockchain ensures traceability throughout the reverse chain in recycling and reuse processes, monitoring the flow of products [62]. The use of Autonomous Robots optimizes various RL tasks, such as the recycling process, in which they are involved in dismantling products, making the performance of the tasks more agile and safe [63]. Finally, Simulation, used in the optimization RL practices such as product reuse and recycling, offers a virtual environment for modelling and testing the strategies that promote material reuse [31].

5. Discussion and Implications

This section interprets and discusses the findings, emphasizing how Industry 4.0 technologies enhance Reverse Logistics actions while addressing key challenges. Additionally, it explores the broader implications of these findings for industry and as to sustainability.

5.1. Enhancing Reverse Logistics Through Digital Technologies

The results highlight that digital technologies fundamentally optimize Reverse Logistics by improving efficiency, transparency, and sustainability. A broad range of Industry 4.0 technologies contribute to these improvements. RFID enhances real-time tracking and automated sorting, reducing waste and improving process visibility. Blockchain ensures secure and transparent data exchange among stakeholders, strengthening traceability and compliance. Artificial Intelligence (AI) supports predictive analytics for return forecasting and demand planning, enabling more efficient storage, redistribution, and disassembly processes. The Internet of Things (IoT) provides real-time monitoring of returned products, facilitating automated decision-making regarding refurbishment, reuse, or recycling. Big Data Analytics enables pattern recognition and insights into waste generation and product lifecycle optimization. Cloud Computing supports integrated platforms that enhance communication across supply chain stakeholders, improving coordination in Reverse Logistics operations. Meanwhile, Digital Twins allow real-time simulation of Reverse Logistics scenarios, identifying inefficiencies and optimizing resource allocation. While these technologies offer significant advantages, challenges such as high implementation costs, integration complexities, and regulatory barriers must be addressed to facilitate

widespread adoption. This aligns with findings from [75], in which the authors emphasized the significance of adopting appropriate technologies at each stage of the RL process, highlighting the contributions of these technologies to cost reduction, increased efficiency, and improved environmental outcomes. As described in [51], digital technologies significantly impact RL, although the high initial cost still represents a significant barrier to adoption. The study described in [53] expands on this view, identifying additional obstacles such as a lack of understanding of Industry 4.0 concepts, inadequate management practices, financial constraints, and resistance to cultural change. However, [51] emphasizes the need for careful strategic analysis to determine the most suitable technology and the right timing for its implementation, a consideration which can mitigate high costs and maximize benefits.

The organization of RL actions at the strategic, tactical, and operational levels enables more efficient coordination between various operations and decisions, aligning them with the organization's strategic objectives. The relevant literature has already discussed the applicability of these levels in business management, and by adapting them to RL, we can achieve more efficient structuring of activities, from policy definition to practical execution. The study reported in [72] reinforces the importance of integrating these levels, as this integration reduces costs and environmental impacts and makes the process more efficient and sustainable.

Digital technologies such as the IoT and CPS are central in integrating RL processes. These technologies provide interconnectivity between sensors, machines, and devices, optimizing tracking and transportation management through technologies like BDA, CC, and BC. The IoT and cloud computing are crucial in improving the management and operation of reverse supply chains [64], monitoring production, machinery, and component flow [50]. During remanufacturing, digitization enables the development of more flexible solutions with the help of simulations, allowing continuous monitoring of operations [51].

Material monitoring for the purposes of reuse is facilitated by the IoT and Sensors, which enable tracking during stages such as collection and return for reuse [71]. The study reported in [70] demonstrates that combining Simulation and Artificial Intelligence enhances efficiency in electronic waste collection. As to transportation, [58] highlights the importance of Blockchain, which ensures secure and traceable transactions, while RFID optimizes real-time tracking of transportation routes [54].

The IoT is also essential for the safe disposal of materials. As described by [68] Rajput and Singh (2022) highlight that sensors connected to the IoT ensure product tracking and proper disposal, while RFID tags increase process accuracy and reduce accident risks [54]. In product storage, cloud computing can centralize data and optimize stock management. At the same time, Additive Manufacturing (AM) enables on-demand production, avoiding large stock volumes and optimizing material use [54].

Autonomous Robots utilized in recycling and waste separation activities contribute to process automation, increasing safety and operational efficiency [66]. Blockchain, in turn, ensures transparency and traceability throughout the production and disposal chain, being particularly relevant in the automotive industry [62].

5.2. Addressing the Role of Solid Waste in Reverse Logistics

A critical aspect of Reverse Logistics is managing solid waste efficiently. The findings indicate that digital technologies minimize waste generation by improving material recovery and extending product lifecycles. RFID and Blockchain enhance waste traceability, ensuring proper handling and processing. AI and the IoT optimize waste sorting and classification, leading to better recycling and resource recovery. Big Data and Machine Learning algorithms refine waste categorization and disposal strategies, allowing companies to predict material degradation and repurpose resources before disposal is necessary.

Digital Twins contribute by simulating alternative waste treatment methods, ensuring optimal resource allocation and sustainability outcomes. Cloud-based platforms further support data sharing and transparency among Reverse Logistics stakeholders, facilitating regulatory compliance and environmental responsibility. Despite these benefits, industries must overcome infrastructure limitations and invest in scalable solutions to maximize the impact of digital tools on solid waste management.

5.3. Implications for Industry and Sustainability

The study's findings have several implications for industry and sustainability. First, companies can leverage digital technologies to streamline their Reverse Logistics operations, reducing costs and improving operational efficiency. AI-driven predictive analytics and Big Data can enable better decision-making regarding returned goods, while Blockchain and the IoT enhance supply chain visibility and waste traceability. Second, adopting these technologies can improve regulatory compliance and stakeholder collaboration by ensuring transparency and accountability in waste management processes. Digital Twins and Cloud Computing also allow organizations to optimize Reverse Logistics strategies dynamically, reducing inefficiencies and the accumulation of waste. Finally, the integration of Industry 4.0 technologies supports sustainability goals by reducing waste, lowering carbon emissions, and promoting a circular economy through enhanced resource recovery and lifecycle extension. Moving forward, businesses must focus on developing strategies that facilitate the integration of digital solutions while addressing implementation challenges, such as technological adoption barriers, workforce digital skills, and investment costs.

The proposed theoretical framework facilitates the implementation of these technologies, providing a structured foundation for their application, while emphasizing that theoretical frameworks based on a systematic literature review are essential for guiding studies and ensuring a reliable interpretation of results. Finally, when applied correctly, digital technologies positively impact optimizing processes across the Reverse Logistics chain. The study reported in [56] indicates the general benefits of these technologies, while [59] emphasizes the importance of the IoT and cloud computing, highlighting their positive impacts on the development and outcomes of reverse supply chains.

6. Conclusions and Future Research Directions

This final chapter summarizes the study's findings, highlights contributions, and proposes directions for future research. This study demonstrated how Industry 4.0 technologies—such as Artificial Intelligence (AI), Blockchain (BC), Big Data Analytics (BDA), the Internet of Things (IoT), and Digital Twins (DT)—enhance Reverse Logistics by improving efficiency, traceability, and sustainability. (All acronyms have been introduced and referenced in a normalized manner throughout the manuscript to maintain consistency).

A key contribution of this study is the proposed framework, which provides a structured approach to the integration of digital technologies into Reverse Logistics actions. As stated above, this framework addresses existing gaps in the literature by offering a practical and theoretically grounded model to enhance decision-making in Reverse Logistics operations. The framework facilitates waste reduction, improved material recovery, and extended product lifecycles by aligning with circular-economy principles.

In addition to the consideration of Industry 4.0, emerging discussions on Industry 5.0 emphasize human-centric, sustainable, and resilient approaches to industrial systems. Future research should explore how transitioning from Industry 4.0 to Industry 5.0 will shape Reverse Logistics, particularly the possibilities of incorporating collaborative robotics, personalized AI-driven decision-making, and ethical considerations in digital transformation strategies.

The role of public authorities is another crucial factor in adopting these technologies. Government agencies and regulatory bodies should establish policies that incentivize digital technology adoption in Reverse Logistics while enforcing compliance with environmental and sustainability standards. Future studies could investigate the effectiveness of policy frameworks in fostering technological integration.

Regarding research limitations, this study primarily relied on a systematic literature review, which, while comprehensive, may not fully capture all industry-specific challenges and technological advancements in real-world applications. Empirical validation of the proposed framework through case studies, industry collaborations, and quantitative modeling would strengthen its applicability and provide deeper insights into practical implementation.

Future research should address these limitations by conducting empirical studies, exploring cross-industry comparisons, and evaluating digital technologies' economic and environmental impacts in Reverse Logistics. Expanding the research to include perspectives from policymakers, industry leaders, and technology providers would also offer a more holistic understanding of the digital transformation in Reverse Logistics systems.

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