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Industry 4.0 for sustainable reverse waste collection: A systematic literature review

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Background: Despite ongoing efforts to improve resource recovery, waste continues to end up in landfills. Companies are increasingly pressured to address sustainability, particularly under the extended producer responsibility (EPR) frameworks.

Objectives: This article examines how Industry 4.0 technologies can enhance the sustainability of waste collection within reverse logistics systems. By exploring the link among waste management, reverse logistics and Industry 4.0, the study identifies opportunities to improve resource use, reduce environmental impact and boost operational efficiency.

Method: A systematic literature review was conducted using ScienceDirect and Web of Science database, two major databases, Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)-guided mapping study clearly, illustrated inclusion and exclusion steps. Keywords were structured using the PEO (Population, Exposure, Outcome) approach, resulting in 47 articles analysed and categorised into five themes.

Results: The review identifies five key thematic areas in the integration of Industry 4.0 technologies with reverse logistics: collection system design and optimisation, application of core Industry 4.0; stakeholder engagement and consumer participation, policy frameworks and governance and barriers to efficient collection. While Industry 4.0 tools improve routing, traceability and efficiency, their impact increases when aligned with supportive policies and user engagement. Decentralised models, EPR schemes and incentive-driven systems significantly enhance return rates and environmental outcomes.

Conclusion: The synergy between technological innovation, infrastructure planning and behavioural incentives is vital for effective reverse logistics. The review highlights limited empirical validation and calls for research on aligning technology adoption with local policy and informal sector realities.

Contribution: This review introduces a conceptual framework integrating five interdependent dimensions, offering a unified framework for sector-wide sustainable reverse logistics.

Keywords: Industry 4.0; reverse logistics; sustainability; supply chain management; waste collection; circular economy; systematic literature review.

Introduction

As global supply chains face increasing pressure to reduce waste and operate sustainably, reverse logistics has emerged as a strategic imperative for both industry and policymakers. Far from being merely an afterthought in the product lifecycle, the process of returning used, defective or end-of-life products to manufacturers for reuse, recycling or disposal now plays a central role in achieving circular economy goals. Efficient reverse logistics systems not only reduce environmental burdens but also unlock economic value through cost savings, resource recovery and enhanced customer satisfaction (Prahinski & Kocabasoglu 2006; Tukker et al. 2016). In particular, sectors like e-commerce have demonstrated that structured reverse logistics frameworks can significantly minimise post-consumer waste (Nanayakkara et al. 2022). To support this transition, businesses are increasingly adopting Industry 4.0 technologies, such as artificial intelligence (AI), Internet of Things (IoT) and data analytics, that play a role in optimising the return flow of products. These innovations are transforming traditional reverse logistics into smart, sustainable systems, reinforcing their importance as a cornerstone of future-ready supply chains (Arroyo et al. 2023).

For example, integrating the radio frequency identification technology (RFID) into collection operations enables firms to track products throughout the reverse logistics chain, enhancing

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visibility and reducing the risk of loss or misplacement (Pallathadka, Pallathadka & Singh 2022). Also, predictive analytics contributes by helping companies anticipate return patterns and address potential issues in advance and, as a consequence, reducing dependency on reverse logistics operations (Sun, Yu & Solvang 2022). Together, by combining these technologies with sustainable practices, businesses can increase efficiency, reduce waste and boost circular economy principles, resulting in mutual gains for both the environment and corporate performance.

Industry 4.0, which is commonly known as the Fourth Industrial Revolution (4IR), refers to the integration of advanced technologies such as the IoT, big data analytics and AI into production environments (Balasingham 2016). This technological convergence brings a high level of automation and digital connectivity, which contributes to increasing efficiency, adaptability and overall productivity in manufacturing operations (Wollschlaeger, Sauter & Jasperneite 2017). It has also led to the rise of smart factories, where systems are interconnected and capable of responding dynamically to market shifts (Lee, Bagheri & Kao 2015). Evidence from research indicates that adopting Industry 4.0 tools can yield substantial advantages, including cost reduction, quality improvements and heightened innovation capacity (Singh & Singh 2023). Nonetheless, there are challenges to adoption, such as the demand for new skill sets and potential job displacement concerns (Brynjolfsson & McAfee 2014). Indeed, Industry 4.0 marks a pivotal change in manufacturing, reshaping how goods are designed, manufactured and distributed.

The application of Industry 4.0 technologies in the field of reverse logistics can have significant impacts on economic and environmental sustainability (Govindan, Soleimani & Kannan 2015). Advanced sensors and data analysis, for instance, can enable 'real-time' tracing and monitoring of the supply chain in terms of the involved products and materials and optimise resource utilisation and reduce waste (Bhandal et al. 2022). The waste collection process has also been considerably optimised through real-time monitoring with sensors, IoT and geographic location (Prata, Simões & Simoes 2023). The application of Blockchain technology can further optimise transparency and traceability in the operations of reverse logistics by using unique digital codes and smart contracts to record waste type, time and location (Almelhem, Süle & Buics 2023). This creates a secure chain of information from collection to processing, which helps reduce the carbon footprint through better planning and enhances environmental accountability by ensuring all actions are visible and verifiable (Lei et al. 2022). Furthermore, the use of AI and machine learning (ML) algorithms could help optimise routing and transportation, leading to reduced fuel consumption and emissions (Agnusdei et al. 2022). These technological advancements can also ensure cost-effectiveness, revenue increases and increased levels of satisfaction and loyalty among customers (Kovačić 2023).

The implementation of Industry 4.0 technologies also presents challenges, such as the need for infrastructure investment, workforce training and data protection measures (Narula et al. 2020). Nevertheless, these technologies have demonstrated strong potential to enhance both environmental and economic sustainability in reverse logistics systems. Historically, waste management was treated as a standalone municipal or governmental responsibility, largely disconnected from supply chain design. Today, there is a paradigm shift towards integrating waste flows into corporate logistics systems through mechanisms like extended producer responsibility (EPR), which require manufacturers to reclaim their products at end-of-life to promote circularity (Mayanti & Helo 2024; Tseng et al. 2023). In response to this shift, this article conducts a systematic literature review (SLR) to investigate how Industry 4.0 technologies are being applied in reverse waste collection systems. Beyond synthesising existing studies, the review aims to develop a novel conceptual framework that maps the interconnection between technological enablers, governance mechanisms, stakeholder behaviour and sustainability outcomes, thereby offering a strategic framework to guide future research and practice.

The research questions that the article intends to answer are:

- **Research question (RQ) 1:** How does the integration of waste collection methods and reverse logistics operations contribute to economic and environmental sustainability within supply chains?
- **Research question (RQ) 2:** In what ways can the implementation of Industry 4.0 technologies enhance the economic and environmental sustainability in the integrated system of waste collection and reverse logistics operations?

The article conducts an SLR, using the ScienceDirect and Web of Science databases, with a narrative summary, giving an overview of the content of the selected articles and answering the research questions. This study contributes to the identification and synthesis of five core themes, namely waste collection system design, Industry 4.0 in reverse logistics, stakeholder participation, policy and governance and circular economy integration, providing a conceptual framework for future research. This thematic map enables scholars to classify existing studies and identify underexplored intersections, particularly where technology, governance and consumer behaviour overlap.

Research design and methodology

An SLR involves a structured process of identifying, selecting and thoroughly analysing existing studies to respond to a clearly defined research question. This type of review conducts a comprehensive search to locate relevant research on a specific subject, followed by evaluation and synthesis using a transparent and predefined methodology. The aim of this systematic review is to synthesise existing studies and develop a conceptual framework linking Industry 4.0, reverse waste collection and sustainability by filling a gap in integrated models. It applies clearly defined and methodical procedures designed to reduce bias, thereby enhancing the reliability of the findings and supporting informed conclusions and decision-making (Briner & Denyer 2012; Denyer & Tranfield 2009). In alignment with this approach, the present study adopted the steps as illustrated in Figure 1.

The process of creating the mapping study was based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) 2020 framework. It was employed to guide the SLR process and enhance its transparency, replicability and methodological rigour. This framework provides a structured flow diagram and checklist to document the identification, screening, eligibility and inclusion of relevant studies. By following PRISMA guidelines, the review ensures a comprehensive and unbiased selection of literature, clearly outlining the rationale behind study inclusion and exclusion throughout the research synthesis process (PRISMA Executive 2021).

During the keyword identification process, careful attention was given to selecting the most relevant terms associated with the topic under investigation, particularly 'reverse logistics' and 'sustainability'. The term 'Industry 4.0' was deliberately kept broad without narrowing it down, to ensure a more inclusive exploration of the subject. Based on this strategy, the selected keywords used in the review were: reverse logistics, waste collection, Industry 4.0, environmental sustainability, economic sustainability, circular economy and closed loop supply chain.

To enhance the precision of search results, the PEO (Population, Exposure, Outcome) framework was adopted for organising keywords into three core categories, as illustrated in Table 1. Both PICO and PEO are valuable tools for structuring research questions and optimising keyword organisation; however, PICO is more suited for quantitative analysis, while PEO aligns better with qualitative approaches, which this study focuses on (Bettany-Saltikov 2016; Metzler & Metz 2010). The PEO framework considers three primary aspects to guide keyword grouping:

- **Population (P):** Who is being examined?
- **Exposure (E):** What are they being exposed to?
- **Outcome (O):** What is the result of that exposure?

The keywords combination used to search the databases was ('reverse logistics' AND 'waste collection') AND ('Industry 4.0') AND ('environmental sustainability' OR 'economic sustainability' OR 'circular economy' OR 'closed loop supply chain'). For a detailed explanation of the key constructs and their definitions used in this review, please refer to Appendix 1.

During the preparation of the SLR, the following inclusion and exclusion criteria were formulated:

- The document type should be Scientific Research articles or Review articles from the selected databases.
- The period of time for the published papers has to be between 2011 and 2025. This period was selected to capture the most relevant and recent developments in the integration of Industry 4.0 technologies with waste collection and reverse logistics. Industry 4.0 itself began gaining widespread attention around 2011, marking a turning point in how digital technologies such as IoT, AI and big data were applied in industrial and environmental systems (Jeff Winter 2022).
- The papers have to be written in English.
- The papers should be available on ScienceDirect or Web of Science databases.
- Papers must be directly relevant or provide insights into at least one of the research questions. To ensure relevance and rigour, each paper was assessed through a two-stage screening process. Firstly, titles and abstracts were reviewed to check for alignment with the research questions. Secondly, full-text analysis was conducted to confirm that the paper explicitly addressed at least one of the two core themes: (1) the integration of waste collection and reverse logistics or (2) the role of Industry 4.0 technologies in enhancing sustainability. Studies were included only if they provided empirical evidence, conceptual frameworks or practical insights that contributed meaningfully to answering either research question. This approach ensured that the selected literature directly informed the study's objectives.

TABLE 1: Keywords categorised based on population, exposure and outcomes.

Population	Exposure	Outcomes
Reverse logistics	Industry 4.0	Environmental sustainability
Waste collection	-	Economic sustainability
-	-	Circular economy
-	-	Closed-loop supply chain

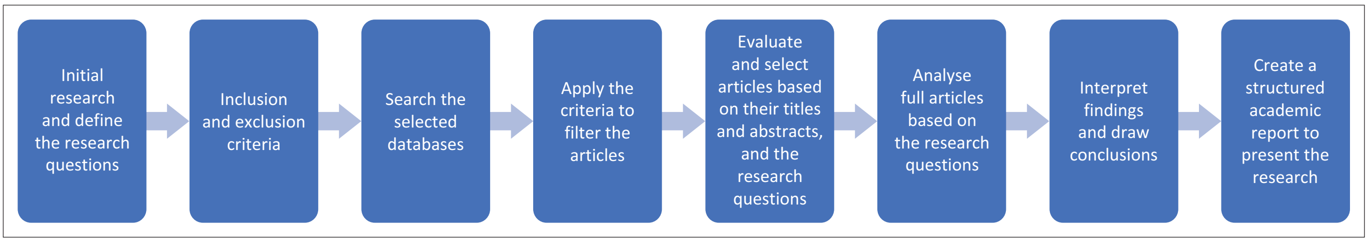
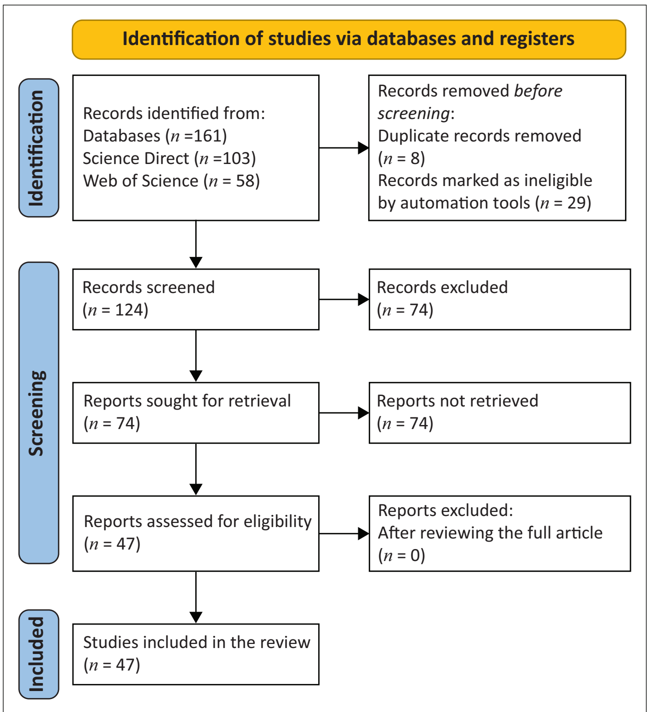


FIGURE 1: Literature review process steps.

Results of the mapping study

By using the PRISMA 2020 flow diagram to illustrate the previously mentioned keywords combination, the ScienceDirect and Web of Science databases were specifically chosen because of their comprehensive coverage of peer-reviewed literature in environmental science, engineering and technology, ensuring access to high-quality, multidisciplinary research relevant to waste management, reverse logistics and Industry 4.0 applications. The authors identified a total of 161 articles, 103 and 58 articles from ScienceDirect and Web of Science databases, respectively. After applying the filters, on each database (language, year, type of document), the number of excluded articles was 29. Then, 8 duplicate articles were excluded, leaving 124 articles to be screened. At this stage, the authors took 4 rounds of reviewing the titles and abstracts, starting with the first author, second author, third author and fourth author and ending with mutual agreement on excluding 74 articles that didn't provide related information for the study. This led to remaining 47 articles to be included in the narrative summary of the discussion part of this study (Figure 2).

Next section provides qualitative discussion of the final sample of the included papers (47 articles). The authors followed the same procedure of reviewing the full text on 4 rounds, starting with the first author, second author, third author and fourth author and ending with mutual agreement on the exact information to be included in the discussion section and creating the conceptual model.



Source: PRISMA Executive, 2021, 'The PRISMA 2020 statement: an updated guideline for reporting systematic reviews', *BMJ* 372, n71. https://doi.org/10.1136/bmj.n71

Note: The diagram based on the official PRISMA template, completed with the authors' data.

FIGURE 2: Preferred reporting items for systematic reviews and meta-analyses 2020 flow diagram.

Discussion

Each article from the final sample included in this review was analysed in detail, and the related insights that can answer the research questions or provide valuable information were extracted and listed in this section. The 47 articles were organised into five distinct themes based on their content and focus, and a cross-theme discussion is provided.

Waste collection system design and optimisation

This theme examines the foundational elements of effective waste collection, including the design and implementation of efficient systems, the development of robust infrastructure, the optimisation of collection networks and the tailored approaches required for managing diverse waste streams (Govindan et al. 2024). Such efforts are crucial for the transition to circular economy principles (CEP) and effective natural resource management, as they maximise the collection of solid waste and direct it towards recycling or remanufacturing facilities, thereby re-entering the production process as raw material (Bui et al. 2024). This approach is vital for environmental, resource and economic sustainability, as it captures the value of waste products, avoids landfills and provides alternative raw materials (Iqbal & Kang 2024). A total of 31 articles relate to this theme, emphasising its multifaceted importance in achieving circularity. The literature highlights a complex interplay of infrastructure, logistical strategies and waste-specific considerations that are essential for efficient material recovery.

The review identifies a variety of established collection methods, including drop-off points (e.g., pharmacies for hazardous waste [Sar & Ghadimi 2022], dedicated e-waste centres and general collection points in stores or public spaces), periodic kerb-side collection, mail-in programmes and point-of-sales take-back programmes (Agnusdei et al. 2022). Door-to-door pick-up services are also discussed (Bijos et al. 2022), while hybrid models that combine formal and informal systems are noted for their potential to optimise efficiency and reach, particularly in developing countries (Mallick et al. 2023). Adequate infrastructure is consistently highlighted as essential, including drop-off locations for consumers, scheduled pick-up services and broader systems for transportation, segregation and treatment (Gallego-Schmid et al. 2024). Innovative solutions, such as pneumatic waste collection systems using underground pipes and vacuum technology, are also presented as smart city alternatives (Kuo & Smith 2018; Yildizbasi et al. 2025).

Optimal reverse logistics network design is another key objective, aiming to minimise costs and environmental impacts while maximising take-back rates. Critical factors influencing design include location, product type, population density, transportation and accessibility (Tolio et al. 2017; Xavier, Ottoni & Lepawsky 2021). For example, traditional systems using a single truck to collect all waste types are less effective, while category-based collection simplifies separation (Nascimento et al. 2019). A consistent trend is the recognition that a one-size-fits-all approach is ineffective, requiring tailored strategies for different waste streams. E-waste management is a prominent focus, with challenges in collection infrastructure, separation and recovery often involving informal channels in many regions (Farooque et al. 2019; Ottoni, Dias & Xavier 2020). Hazardous waste collection through pharmacies highlights the need for specifically designed networks (Sar & Ghadimi 2022). In contrast, the United Kingdom (UK) faces gaps in food waste management, where many councils lack dedicated collection services; proposed solutions include local food waste centres with incentives (Rodrigues et al. 2021).

Technological innovations are frequently noted as enablers of efficiency. Pilot projects using smart bottles have traced leakage and collection outcomes (Ponis et al. 2023), while route optimisation algorithms and automated sensors enhance collection processes (Kolade et al. 2022). Innovative packaging, such as polyethylene terephthalate (PET) trays with RFID and consumer incentives, also supports better sorting and recycling (Rossi & Bianchini 2022). Furthermore, challenges in waste batteries were mentioned, particularly in countries lacking specific waste collection policies, where they are often mixed with general household waste, underscoring the need for separate collection systems (Islam et al. 2025). Industry-led voluntary schemes (e.g., 'B-cycle' in Australia) and national deposit refund systems are proposed to enhance collection rates (Islam et al. 2025). Deposit refund systems are especially effective because they offer direct financial incentives that motivate consumers to return end-of-life products, thereby ensuring higher recovery rates and reducing leakage into landfills. Their success depends on broad public engagement, as active citizen participation is essential for returning items and closing material loops within reverse logistics networks. Similar approaches are applied to textile waste, where IoT and robotics support efficient collection and sorting (De Felice et al. 2025; Sarc et al. 2019). Finally, inter-organisational systems, such as footwear collection at designated points, highlight the role of citizen participation in sustaining circular processes (Cafruni Gularte et al. 2024).

The main findings in this theme show that accessible and convenient collection points directly encourage higher consumer participation in waste return programmes, with suggestions that such points should not exceed 0.5 km from consumers to avoid discouraging involvement (Ottoni et al. 2020). Although door-to-door collection is considered the most tedious because of its personnel and time demands, it consistently yields the highest collection efficiency at around 90% and ensures better product condition compared to drop-off systems, which achieve 75% – 80% (Fofou, Jiang & Wang 2021). In contrast, inadequate coverage and accessibility of collection points, especially in rural or remote areas (Mathew et al. 2023), and the persistent low investment in selective collection initiatives are identified as major barriers (Trevisan et al. 2023). The integration of sensors, IoT, AI and cloud computing is reported to enable a transition from fixed-schedule to demand-driven collection, reducing fuel consumption, labour costs and vehicle deployment. Multi-stakeholder collaboration among end-users, councils, retailers, Original Equipment Manufacturers (OEMs), waste management centres and recyclers is also highlighted as essential for reducing costs, minimising environmental impact and improving efficiency (Krstic et al. 2022a; Tolio et al. 2017). At the same time, the informal waste collection sector remains crucial in many developing countries; yet, its informality hampers data tracking and advanced material recovery, making formalisation and inclusion important for enhancing circular practices (Fatimah et al. 2024).

Conflicting issues also emerge in waste collection design. Mallick et al. (2023) note that centralised drop-off points may reduce transportation costs for the overall system but are less convenient for consumers compared to direct pick-up services. In some cases, the frequency of waste collection can even discourage sorting and recycling, showing that more collection is not always better (Gallego-Schmid et al. 2024). Locally organised collection projects, managed by actors who generate, collect or separate waste, can sometimes achieve results beyond what traditional systems deliver, but these initiatives often lack permanence because of limited coordination and commitment from governments and enterprises (Giglio et al. 2024).

Overall, the evidence provides a comprehensive overview of the complexities and recent advances in waste collection systems and waste stream management. The literature draws on diverse geographical contexts and waste types, strengthening the generalisability of the findings. The inclusion of real-world examples, pilot projects and technological applications also enhances practical relevance. Nonetheless, despite the recognition of potential benefits, detailed empirical evidence on long-term impacts, cost-effectiveness and scalability across varied socio-economic contexts remains limited. Many studies rely on conceptual frameworks or pilot initiatives rather than large-scale, sustained implementations.

Industry 4.0 technologies in waste and reverse logistics

This theme explores the impact of Industry 4.0 technologies on transforming waste collection within reverse logistics and the circular economy. Information and communication technology (ICT) is identified as a critical success factor, fostering advanced techniques for urban waste collection and processing (Fatimah et al. 2024). By integrating data collection and analysis across supply networks, these technologies enable companies to better understand customer preferences and capture value from waste streams (Julianelli et al. 2020). Smart Waste Management Systems reinforced by information technology (IT) tools and IoT facilities are considered especially crucial for developing and less-developed countries, where such systems are often lacking (Ranjbari et al. 2021). The integration of IoT, AI, augmented reality (AR) or virtual reality (VR), robotics and Blockchain is increasingly seen as essential for achieving circular transitions in different sectors, including textiles (De Felice et al. 2025). Altogether, 31 articles emphasise the role of technological advancements and digitalisation, showing a clear shift towards automated, data-driven and interconnected waste management systems.

Sensors and smart bins are among the most frequently discussed applications. These systems monitor fill levels, temperature and waste classification (Franchina et al. 2021), providing real-time data to optimise collection schedules and routes (Mallick et al. 2023). Advanced smart bins, such as Bigbelly, combine solar-powered compaction, Wi-Fi connectivity and AI sorting (Kerdlap et al. 2019). Other manufacturers, including 'Green Creative' and 'Bin-e', have integrated material detection sensors and AI for improved waste separation (Sarc et al. 2019). In parallel, IoT connects sensors, bins, vehicles and platforms to enable real-time monitoring (Farooque et al. 2019), supports demand-driven collection (Krstić et al., 2022a) and facilitates material traceability, often together with RFID systems (Govindan et al. 2024; Rossi & Bianchini 2022). Tracking projects such as TRACKPLAST reveal infrastructure gaps and collection inefficiencies in different contexts, highlighting risks of marine leakage (Ponis et al. 2023), while Long Range Radio (LoRa)-based solutions trace packaging waste pathways and accumulation zones (Plakas et al. 2020).

Artificial intelligence is applied for decision-making in routing, logistics design and waste classification (Ciano et al. 2025; Krstić et al. 2022c). Machine learning models provide insights into waste volume and composition, supporting planning and control of municipal solid waste collection and recycling (Bijos et al. 2022). Cloud computing is also important, enabling real-time management of waste types and collection sites while reducing hardware requirements (Nascimento et al. 2019). Blockchain contributes to traceability through digital badges and smart contracts that regulate collection by time, type and volume (Jiang et al. 2023; Krstić et al. 2022c). Together, these technologies support route optimisation, reducing unnecessary trips, fuel use and labour costs (Kerdlap et al. 2019; Kolade et al. 2022).

Robotics and automation expand these opportunities. Projects like DustBot in Europe and ROARy in Sweden tested autonomous robots for waste collection and transport, supported by drones for bin detection (Sarc et al. 2019; Krstić et al. 2022c). Automated guided vehicles and electric autonomous vehicles have also been proposed for sensitive applications such as healthcare waste, reducing risks of contamination (Govindan et al. 2024). Digital platforms and mobile applications further improve efficiency by connecting consumers with collectors, optimising routes and providing recycling information (Mallick et al. 2023; Nascimento et al. 2019).

At the system level, advanced infrastructures such as pneumatic waste collection networks offer smart city alternatives to door-to-door services (Kuo & Smith 2018; Yildizbasi et al. 2025). Deposit refund systems (DRS) also feature prominently, using reverse vending machines and small financial incentives to rapidly increase recycling rates. Deposit refund systems require supply-chain integration through take-back programmes and have shown benefits for resource conservation and environmental sustainability (Zorpas 2024).

Despite strong enthusiasm for these innovations, studies acknowledge limitations. Sole reliance on infrastructure and logistics is insufficient without strong information management systems and improved recycling facilities (Mathew et al. 2023). Moreover, widespread application of Industry 4.0 does not automatically guarantee the most effective outcomes, as costs and stakeholder compromises must also be considered (Krstić et al. 2022b). The coexistence of formal and informal waste collection further complicates integration, particularly in developing countries, where informality obstructs tracking and data systems (Bijos et al. 2022). Resistance to adopting new technologies also stems from limited awareness of their benefits among collectors and recyclers (Gaur et al. 2025).

Overall, the reviewed articles strongly support the transformative potential of digitalisation in waste collection, with robust evidence from real-world projects such as TRACKPLAST, DustBot, ROARy and Bigbelly. However, important gaps remain: empirical data on long-term impacts, cost-effectiveness, and scalability is limited, with most studies relying on pilot projects or conceptual frameworks. Infrastructure deficiencies and informality in waste sectors are not deeply addressed, restricting implementation in resource-constrained contexts (Trevisan et al. 2023). While consumer participation is recognised as critical, its relationship with technology adoption requires further investigation (Mallick et al. 2023). There is also a need to assess the environmental impacts of the technologies themselves within circular economy models (Ciano et al. 2025). Finally, the lack of consistent waste data highlights the need for predictive tools and standardised collection protocols (Afshari, Gurtu & Jaber 2024:4). A more advanced and inclusive approach to data-driven collection would significantly reduce the barriers faced in sorting and recovering end-of-life products (Fofou et al. 2021).

Stakeholder engagement and consumer participation

This theme underscores the irreplaceable role of various stakeholders, including consumers, informal sectors, local authorities, industry and producers, in the successful implementation and scaling of waste collection initiatives. Effective engagement, coupled with robust public participation, is not merely a supplementary aspect but a fundamental driver for achieving efficient material recovery and fostering a truly circular economy. It ensures proper waste segregation, increases return rates and facilitates the integration of diverse collection channels (Islam et al. 2025). The waste sector, often dealing with valuable resources, also necessitates stakeholder engagement to mitigate risks such as crime and ensure transparent management systems (D'Adamo et al. 2022).

A total of 20 articles emphasise the critical importance of stakeholder engagement and public participation in waste collection for reverse logistics and the circular economy. The literature consistently highlights that human behaviour (Ponis et al. 2023), collaboration (Islam et al. 2025) and incentive structures (Iqbal & Kang 2024) are as crucial as technological and policy frameworks for effective waste collection (Darzi 2025). Consumer involvement is consistently identified as critical for efficient waste volume management, ensuring proper waste segregation and disposal and actively returning items to designated collection points (Cafruni Gularte et al. 2024). The convenience and accessibility of collection methods are key drivers for encouraging higher participation rates. For that, campaigns are vital for improving collection rates by informing citizens about collection points, accepted waste types and proper recycling practices (Islam et al. 2025). Conversely, a lack of consumer awareness regarding disposal methods or the benefits of waste management is frequently cited as a significant challenge (Xavier et al. 2021). Also, financial incentives play a substantial role in encouraging consumer returns. Deposit refund systems for items like batteries or PET bottles, or direct fees paid to consumers for returning packaging, have demonstrated profound impacts on increasing recycling rates (Zorpas 2024). Paying consumers and retailers for returning expired food items also proves effective (Iqbal & Kang 2024).

The literature emphasises that cooperation among diverse independent stakeholders, including end users, local councils, retailers, OEMs, waste management centres and recyclers, is imperative to reduce costs, minimise environmental footprint and increase collection efficiency (Tolio et al. 2017). This collective approach involves frameworks such as collective work among city halls, malls for installing e-waste collection points and partnerships with warehouse owners to operate cooperatives (Giglio et al. 2024).

In many developing countries, informal collectors handle the majority of e-waste and municipal solid waste, providing a crucial service. However, their informality can pose challenges for data tracking and limit the adoption of advanced material recovery technologies (Trevisan et al. 2023). Government intervention is deemed necessary to regulate and provide guidelines for this sector, and their formalisation and inclusion are crucial for enhancing circular practices and bridging collection gaps (Islam et al. 2025). Here comes the role of the EPR schemes, which shift the physical or financial responsibility for end-of-life products to producers originally handled by governments and municipalities. This scheme considered as a key policy mechanism, necessitates producer commitment and collaboration with other stakeholders for effective take-back systems (Gaur et al. 2025).

The 'B-cycle' scheme for battery collection in Australia is an industry-led voluntary scheme for waste batteries which operates a national collection network with over 5200 drop-off points and conducts 'public awareness campaigns focused on battery safety and proper disposal practices', such as 'Never Bin Your Batteries'. Consumer preferences for collection points (e.g., supermarkets for batteries) are studied using survey. The results show that the success of collection systems relies heavily on citizens actively contributing and being adequately educated on proper practices (Islam et al. 2025). Also, the TRACKPLAST pilot project, while primarily technological, also observed how human behaviour (e.g., waste placement) interacts with collection systems (Ponis et al. 2023). In addition, accessible collection methods and proximity to collection points (e.g., not exceeding 0.5 km from consumers) directly encourage higher participation rates (Ottoni et al. 2020).

Deposit refund systems and direct financial incentives significantly increase return rates and recycling. For example, food waste collection centres are established near consumer markets to ease the collection process, and consumers are incentivised to encourage returning the expired food items, with a specific amount of money paid to consumers and retailers (Iqbal & Kang 2024).

Integrating informal collectors into formal systems improves data quality, enhances material recovery and addresses safety concerns. In many Latin American and Caribbean cities, selective collection of the municipal solid waste is carried out by informal collectors that sort and collect recycled materials individually or organised in associations or cooperatives, sometimes with municipal support (Bijos et al. 2022).

The attitude of senior leadership (e.g., in adopting take-back practices) greatly impacts the successful implementation of e-waste management systems (Darzi 2025). E-waste collectors may resist adopting IoT-based tracking systems because of a fear of disruption to their current traditional processes, highlighting a human-factor barrier to technological integration (Gaur et al. 2025).

Canada's relatively low e-waste collection rate is partly attributed to a complicated collection system divided across geography and e-waste types, making it complex for consumers. The Canadian take-back system faces challenges because of the lack of awareness regarding disposal methods or the unavailability of a drop-off centre, making the system complex for consumers (Xavier et al. 2021).

While local, temporary projects can achieve good collection results, they struggle to establish the long-term interrelation and commitment needed from government and enterprises for permanence. For example, collective work among city halls, malls for installing electronic waste collection points, residential collection companies and partnerships with warehouse owners to operate cooperatives is highlighted as a solution for e-waste collection (Giglio et al. 2024).

The evidence within this theme is robust in highlighting the critical role of human factors and collaboration. The consistent identification of consumer behaviour, public awareness and multi-stakeholder engagement as key drivers or barriers across diverse geographical contexts (Australia, Latin America, UK, Canada) strengthens the generalisability of these findings. The EPR scheme and the DRS provide concrete examples of successful stakeholder integration.

While the importance of awareness, convenience and incentives is well established, the articles generally lack deeper insights into the psychological, cultural or socio-economic nuances that drive or hinder specific consumer behaviours beyond these broad categories. More empirical studies on the effectiveness of different types of educational interventions or incentive designs in varied cultural contexts could be beneficial.

While the need for formalisation of the informal sector is a strong consensus, detailed, actionable strategies for achieving this integration, including specific policy mechanisms, capacity building and financial models that ensure fairness and sustainability for informal workers, are not extensively elaborated in all articles.

The imperative for multi-stakeholder collaboration is clear, but the articles provide limited metrics or methodologies for quantitatively assessing the effectiveness of such collaborations beyond anecdotal success stories or general statements about reduced costs and increased efficiency.

Policy frameworks and governance mechanisms

This theme explores the pivotal role of governmental policies, regulatory frameworks and producer responsibility schemes in shaping and driving efficient waste collection for reverse logistics and the circular economy (Farooque et al. 2019; Fatimah et al. 2024). These mechanisms are fundamental to establishing transparent management systems over collected and processed waste, ensuring accountability and incentivising sustainable practices across the supply chain (D'Adamo et al. 2022). Effective policies are crucial for overcoming challenges such as the cost of recovering value from waste and the lack of adequate infrastructure, thereby enabling the deployment of new business models for circularity (Bui et al. 2024). They provide the necessary legal and financial impetus to shift from linear 'take-make-dispose' models to circular ones, where waste is recognised as a valuable resource (D'Adamo et al. 2022).

A total of 14 articles emphasise the critical importance of policy frameworks, regulations and producer responsibility in advancing waste collection for circularity yet show a lack of focus in the literature from this angle.

The literature consistently highlights that robust policy interventions are foundational to the success of waste collection initiatives, particularly through the widespread adoption of EPR and DRW.

Extended producer responsibility is identified as a globally adopted policy concept where producers bear physical or financial responsibility for end-of-life (EoL) products. This shifts the burden from municipalities to manufacturers, incentivising eco-design and promoting the collection and recycling of materials, especially hazardous and critical ones (Kuo & Smith 2018). Many countries have adopted product take-back schemes based on the concept of EPR, where producers are physically or financially responsible for the collection of EoL electronics and their recovery. The European Union's Waste from Electrical and Electronic Equipment (WEEE) Directive mandates EPR, requiring producers to collect 65% of e-waste, exemplified by Germany's ElektroG Act (Gaur et al. 2025).

Deposit refund systems (are recognised as impactful policy instruments that involve consumers paying a deposit upon purchase and receiving a refund upon returning used items for recycling. These systems have demonstrated profound positive impacts on waste reduction and significantly increased recycling rates over short periods. The DRS have demonstrated profound impacts on waste management, resource conservation and environmental sustainability, to reduce waste and increase recycling rapidly over a short period. For waste batteries, a national deposit refund system is proposed where customers pay a deposit and receive a refund upon return, ensuring high participation. An example from Belgium demonstrated that combining producer responsibility organisations with a deposit system can be cost-effective and significantly improve recycling rates for waste batteries (Islam et al. 2025; Zorpas 2024).

Government intervention is deemed necessary to regulate and provide technical and pollution control guidelines, particularly for the informal waste collection sector. As industries mature, governments are encouraged to gradually reduce direct oversight, allowing e-waste actors to take greater responsibility in accordance with regulatory standards (Darzi 2025).

Mutually consistent policy interventions are crucial for establishing transparent management systems over collected and processed waste, moving towards circular economy models. These policies should be comprehensive, considering factors such as technology levels, subsidies, separate collection systems, existing regulations and political perceptions. The enforcement of producer responsibility regulations is identified as a critical strategy for the recovery and recycling of plastic waste, underscoring the importance of a strong legal framework. Enforcement of producer responsibility regulations to encourage collection of plastic wastes was identified as one of the most critical strategies for the recovery and recycling of plastic solid waste (Detwal et al. 2023; Mwanza, Mbohwa & Telukdarie 2018).

Methods commonly studied in this theme were case studies, such as the EU's WEEE Directive and Germany's

ElektroG Act, which are also mentioned as examples of EPR mandates (Gaur et al. 2025). Comparative analysis, such as comparisons of e-waste collection systems in countries such as Japan, India and Indonesia, highlights varying levels of formal sector implementation and reliance on informal channels despite regulations (Fatimah et al. 2024). Evidence from policies targeting specific waste streams (e-waste, plastics, and batteries) indicates that regulation must be tailored regulatory needs (Islam et al. 2025; Mwanza et al. 2018).

Major findings are, firstly, EPR is consistently presented as a foundational policy for effective e-waste management and for promoting the collection and recycling of hazardous and critical materials (Farooque et al. 2019). Deposit refund systems are highly effective in rapidly increasing recycling rates and reducing waste, particularly for items like PET bottles and batteries (Zorpas 2024). Secondly, the attitude and strong determination of top executives are critical for the successful implementation of take-back practices and the establishment of effective collection networks (Darzi 2025). Thirdly, a lack of specific policies (e.g., for waste batteries) often leads to improper disposal (e.g., mixing with general household waste), complicating recovery efforts. Inadequate legal conditions and weak dissemination of information are also identified as significant barriers to circular economy deployment (Bui et al. 2024; Mathew et al. 2023).

Although, EPR mandates producer responsibility, manufacturers may struggle to collect e-waste from consumers because of insufficient infrastructural and technological facilities, indicating that policy alone is not enough without adequate support systems (Gaur et al. 2025). Mathew et al. (2023) note that sole dependency on increasing collection points and optimised reverse logistics strategy is not sufficient without a strong information management system and Industry 4.0 assimilation. This suggests that policy, while crucial, must be complemented by other enablers.

The evidence within this theme strongly establishes the indispensable role of policy frameworks and producer responsibility in driving waste collection for a circular economy. The consistent emphasis on EPR and DRS across multiple articles and waste streams (e-waste, plastics, batteries) lends significant robustness to the findings. The use of specific country examples (Germany, Australia, Belgium) provides concrete illustrations of policy implementation and their observed impacts.

However, while policies are described, the articles often lack in-depth analysis of the practical challenges and complexities of policy implementation in diverse socio-economic and political contexts. For instance, the difficulties in enforcing regulations or ensuring compliance, especially in regions with large informal sectors, are noted but not always thoroughly explored with actionable solutions.

While EPR addresses producer financing, the broader financial sustainability required for large-scale investment in waste collection, classification and recycling infrastructure is highlighted as a challenge, but detailed policy mechanisms to ensure this long-term financial viability are not always elaborated.

The necessity of government intervention to regulate and provide guidelines for the informal sector is a consensus, but the specific policy designs that effectively integrate and formalise these workers without disrupting their livelihoods or creating unintended consequences are not deeply detailed.

Most importantly, while some articles provide collection rates (e.g., B-cycle's 15.3% for batteries), comprehensive metrics for evaluating the overall effectiveness and efficiency of different policy interventions across various waste streams and their long-term socio-economic impacts are not consistently presented.

Challenges and barriers to efficient waste collection

This theme presents various obstacles that hinder the effective implementation and enhancement of waste collection systems within reverse logistics and circular economy frameworks. Recognising and understanding these barriers is substantial, as they directly impede the transition to CEP, limit material recovery and undermine efforts towards environmental and economic sustainability. Addressing these challenges is not merely about optimising processes but about overcoming fundamental systemic, economic and behavioural impediments that prevent waste from being effectively collected and reintegrated into the value chain.

A total of 12 articles emphasise the significant challenges and barriers to efficient waste collection. The literature reveals a complex web of interconnected challenges, ranging from tangible infrastructural deficits to intangible issues like a lack of awareness and resistance to change.

Barriers

Inadequate infrastructure: This is a prominent and recurring challenge. It includes insufficient coverage and accessibility of collection points, particularly in rural or remote areas, which hampers convenient disposal and encourages improper practices. A general lack of physical infrastructure for waste pickers' cooperatives, preventing them from sorting complex materials or providing quality data, is also noted. Underdeveloped sorting and collection systems are identified as a significant barrier to achieving a circular economy (Cafruni Gularte et al. 2024; Giglio et al. 2024; Mallick et al. 2023).

High costs and financial sustainability: The cost of recovering value from waste is a major impediment to applying circular economy principles. Investing a large amount into waste collection, classification and recycling infrastructure requires substantial financial sustainability, which is often lacking. While centralised drop-off points may reduce transportation costs, the overall system costs remain a concern (Bui et al. 2024).

Lack of awareness and participation: Gaps in consumer awareness regarding proper disposal methods and low rural participation directly impede collection rates. In addition, a lack of awareness among collectors and recyclers about the contributions of Industry 4.0 technologies to reverse logistics hinders the adoption of these beneficial innovations. Consumers' knowledge, awareness and behaviour, alongside the convenience of the collection process, are identified as primary barriers (Afshari et al. 2024; Gaur et al. 2025; Xavier et al. 2021).

Logistical and geographical constraints: Long distances, low population density rates and low e-waste generation in certain areas pose significant challenges to achieving collection targets. Pilot projects reveal ineffective or inconsistent collection practices and 'blind spots' in the collection system, where waste is not picked up even when bins are nearby or in less visible locations (e.g., hidden street corners, dry streams, mountainside spots) (Ponis et al. 2023).

Informality and regulatory gaps: The informality of certain waste collection sectors, such as waste pickers' cooperatives, hinders the effective use of data technologies for tracking waste. A lack of specific policies for certain waste streams, such as waste batteries, often leads to their mixing with general household waste, complicating recovery efforts. Weak dissemination of information and a deficiency in regulations contribute to inadequate enablers for efficient reverse logistics (Mathew et al. 2023; Trevisan et al. 2023).

Resistance to change: E-waste collectors, for instance, may resist adopting IoT-based tracking systems because of a fear of disruption to their current traditional processes. This highlights a human-factor barrier to technological integration (Gaur et al. 2025).

Many articles implicitly or explicitly suggest that these barriers are not isolated but interconnected, often creating a 'vicious cycle' that hinders progress. For example, low investment in selective collection leads to underdeveloped sorting systems, resulting in lower-quality materials and higher recovery costs, further discouraging investment (Gallego-Schmid et al. 2024).

Even with advanced digital solutions, robust physical infrastructure is a prerequisite for efficient waste management. Digital solutions based on waste management cannot operate efficiently in places with low logistics infrastructure (Trevisan et al. 2023).

Conflicting results are presented in the Latin America and the Caribbean study, where the frequency of waste collection is identified as a negative factor that discourages sorting and recycling, suggesting that more frequent collection is not always better for circularity goals. This contrasts with the general aim of timely collection (Gallego-Schmid et al. 2024). In addition, while Industry 4.0 technologies are seen as beneficial, a lack of awareness about Industry 4.0 contributions among collectors and recyclers can lead to resistance, indicating that the mere availability of technology does not guarantee adoption. Consumer behaviour (a lack of awareness, inconvenience) and collector resistance to new technologies are also significant impediments (Afshari et al. 2024).

This theme identifies a consistent set of challenges that impede efficient waste collection globally. The recurring mention of inadequate infrastructure, high costs and behavioural issues across diverse geographical contexts (developed and developing nations) strengthens the generalisability of these findings.

Cross-themes discussion

The various themes identified in this systematic literature review – Industry 4.0 technologies in waste and reverse logistics, waste collection system design and optimisation, policy frameworks and governance mechanisms, stakeholder engagement and consumer participation and challenges and barriers to efficient waste collection – are deeply interconnected and form a dynamic ecosystem crucial for advancing waste collection within reverse logistics and the circular economy. Based on these five themes, this review creates a conceptual framework as illustrated in Figure 3.

At its core, the field is evolving towards a 'Smart Circularity' framework, where technological advancements and digitalisation (theme 2) are not merely supportive tools but fundamental enablers. The integration of Industry 4.0 technologies like IoT, AI and Blockchain generates real-time data on waste levels and types, which is then used to dynamically optimise collection routes and schedules within optimised collection systems and waste

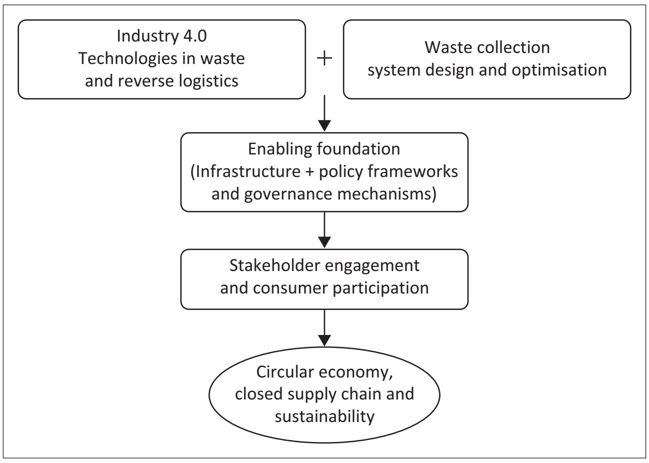


FIGURE 3: Conceptual framework for Integrating Industry 4.0 technologies, waste collection design, governance and stakeholder engagement towards circular economy and sustainability outcomes.

stream management (theme 1). This data-driven approach shifts collection from rigid, fixed schedules to a more responsive, demand-driven model, leading to significant gains in operational efficiency, reduced costs and improved environmental performance. Technologies like RFID also enhance traceability, ensuring better material flow and quality within these systems.

However, the effectiveness of these advanced systems is heavily reliant on robust policy frameworks, regulations and producer responsibility (theme 4). Policies such as EPR and DRS provide the essential regulatory and financial impetus, mandating producer involvement and incentivising desired behaviours across the supply chain. These policies drive the establishment and improvement of optimised collection systems (theme 1), ensuring the necessary physical infrastructure, such as collection points and logistics networks, is in place. Without adequate policy support and enforcement, even the most sophisticated digital solutions can be hampered, highlighting a direct link to challenges and barriers to efficient waste collection (theme 5).

Crucially, the success of any collection initiative hinges on stakeholder engagement and public participation (theme 3). Accessible and convenient optimised collection systems directly encourage higher consumer involvement, as convenience is a key driver for participation (theme 1). Public awareness campaigns and incentive mechanisms, often driven by policy, are vital for ensuring proper waste segregation and increasing return rates. Furthermore, the significant role of the informal waste collection sector, particularly in developing economies, necessitates their formalisation and strategic inclusion. This integration not only improves their working conditions but also enhances data quality, thereby benefiting technological advancements and overall system efficiency (theme 2). Resistance to adopting new technologies among collectors, however, can emerge as a challenge and barrier to progress (theme 5).

Indeed, resistance to adopting new technologies (theme 5) act as common hindrance across all themes. Inadequate infrastructure, high costs, lack of public awareness, logistical constraints and regulatory gaps create a ‘vicious cycle’ that undermines technological adoption, system optimisation, policy effectiveness and stakeholder participation. For instance, low investment in selective collection (a barrier) leads to underdeveloped sorting systems (a challenge to optimised systems), resulting in lower quality materials and higher recovery costs, further discouraging investment. This interconnectedness means that addressing waste collection challenges requires a holistic, multi-faceted strategy rather than gradual solutions.

Finally, the field has evolved to recognise that a one-size-fits-all approach is ineffective, leading to the need for the development of waste stream specific collection approaches that combine all the previously mentioned themes. Policies, technologies, infrastructure and engagement strategies must be tailored to the unique characteristics of different waste types, such as e-waste, hazardous waste, plastics or batteries, ensuring optimal recovery for each. This specialisation reflects the maturation of the field from generic waste disposal to a nuanced, resource-recovery-focused attempt.

Overall, the evolution of the field is marked by a shift from manual, reactive and disposal-oriented practices to automated, proactive and resource-recovery-focused systems. This transition is driven by the increasing sophistication of technology, the strategic implementation of robust policies, the continuous optimisation of physical and logistical systems, and the recognition of the indispensable role of engaged human behaviour, all while navigating and overcoming persistent systemic barriers.

Notably, 26 articles were pure reviews, 12 were quantitative studies and 9 employed a mixed-methods approach, combining qualitative methods (such as focus groups and interviews) with quantitative analysis. This distribution clearly highlights a significant gap in empirical research and underscores the need for more evidence-based studies to support the theoretical frameworks and technological propositions in the field.

Conclusion

This systematic literature review set out to explore two critical research questions: RQ1: How does the integration of waste collection methods and reverse logistics operations contribute to economic and environmental sustainability within supply chains? and RQ2: In what ways can the implementation of Industry 4.0 technologies enhance the economic and environmental sustainability in the integrated system of waste collection and reverse logistics operations? The comprehensive analysis of the literature reveals a dynamic and interconnected landscape where strategic integration and technological innovation are pivotal for achieving circularity.

Regarding RQ1, the integration of diverse waste collection methods and robust reverse logistics operations significantly contributes to both economic and environmental sustainability within supply chains. Economically, optimised collection systems, encompassing various strategies like door-to-door pick-up, drop-off points and hybrid models, are designed to minimise overall costs, including transportation, labour and vehicle deployment, thereby enhancing operational efficiency. The effective recovery of valuable materials from waste, often termed ‘urban mining’, provides alternative raw materials, reducing reliance on virgin resources and generating economic value. Policy frameworks, particularly EPR schemes, shift financial responsibility for EoL products to producers, incentivising eco-design and reducing the financial burden on municipalities. Deposit refund systems further stimulate economic activity by directly incentivising consumer returns, increasing the volume of materials flowing back into the economy. From an environmental perspective, these integrated systems are crucial for diverting waste from landfills, thereby mitigating associated environmental pollution and land degradation. Proper waste segregation at the source, facilitated by accessible collection points and public awareness, improves the quality of collected materials, enhancing recycling and remanufacturing processes and conserving natural resources. Tailored collection approaches for specific waste streams, such as hazardous waste or e-waste, ensure appropriate handling and minimise environmental leakage. Multi-stakeholder collaboration, including the formalisation of informal collection sectors, further streamlines operations, reduces environmental footprint and increases overall collection efficiency.

Addressing RQ2, the implementation of Industry 4.0 technologies profoundly enhances both the economic and environmental sustainability of integrated waste collection and reverse logistics systems. Economically, these technologies drive unprecedented efficiencies and cost reductions. Internet of Things sensors in smart bins provide real-time data on fill levels and waste types, enabling dynamic route optimisation and demand-driven collection. This minimises unnecessary trips, reduces fuel consumption, lowers labour costs and optimises vehicle deployment. Artificial intelligence and ML further refine these processes by optimising vehicle routing, network design and decision-making, leading to more cost-effective operations. Blockchain technology enhances material traceability, which can increase trust and value in secondary material markets, while cloud computing reduces the need for extensive hardware and software infrastructure. Environmentally, Industry 4.0 technologies contribute significantly to improving resource conservation and pollution reduction. Enhanced sorting capabilities through AI-based smart bins lead to higher-quality recovered materials, maximising recycling and minimising waste sent to landfills. Reduced fuel consumption from optimised routes directly translates to lower greenhouse gas emissions and air pollution. The use of electric autonomous vehicles for specialised waste streams, such as healthcare waste, further reduces air pollution and contamination risks. Moreover, real-time monitoring prevents bin overflows, improving urban hygiene and preventing environmental contamination. Digital platforms and mobile applications also play a role by encouraging proper waste segregation at the source, which is critical for effective recycling and resource recovery.

Although technological and logistical innovations in waste collection and reverse logistics are widely studied, few works present integrative models that simultaneously combine behavioural, institutional and technological dimensions. Most case studies remain concentrated in high-income countries, leaving a limited understanding of infrastructure and governance adaptability in developing countries. Indicators such as collection efficiency, cost–benefit analysis and environmental impact are not consistently applied, restricting comparability across studies. While many articles highlight the benefits of IoT and AI, few provide cost-based feasibility assessments or scaling strategies suited to resource-constrained settings. Similarly, although consumer participation is recognised as crucial, there is a lack of predictive models or empirical validation of the drivers of sustained engagement. The importance of multi-stakeholder collaboration is also widely acknowledged, yet metrics or methodologies for quantitatively evaluating its effectiveness are rarely provided beyond non-scientific success stories. Furthermore, precise quantification of the economic and environmental impacts of specific barriers remains infrequent, and comprehensive metrics for evaluating the long-term socio-economic effects of different policy interventions across waste streams are still lacking.

Future research should address several critical gaps to advance waste collection for circularity. There is a notable need for more extensive empirical validation and long-term data on the scalability and precise cost-effectiveness of proposed technological solutions and collection strategies across diverse contexts, moving beyond conceptual frameworks and pilot projects. Deeper insights are required into the psychological, cultural and socio-economic factors influencing consumer behaviour, alongside the direct role technology can play in shaping these behaviours and overcoming resistance to new systems among collectors. Furthermore, research should focus on the practical complexities of policy implementation and develop comprehensive metrics for evaluating the long-term effectiveness of various policy interventions. Quantitative analysis of the economic and environmental impacts of specific infrastructure deficits and high costs is also needed, alongside exploration of innovative financing models. Finally, the application of advanced automation such as DRS in reverse logistics, including the optimisation of their auxiliary network design, requires further investigation, as does a thorough assessment of the environmental footprint of Industry 4.0 technologies themselves.

In conclusion, the transition to a truly circular economy hinges on the synergistic integration of sophisticated waste collection methods, efficient reverse logistics and transformative Industry 4.0 technologies. While significant challenges persist, including infrastructural deficits, high costs and behavioural barriers, the evidence overwhelmingly demonstrates that a holistic approach, where robust policies enable smart infrastructure, optimised by technology and supported by engaged stakeholders, is essential. This integrated system not only captures economic value from waste but also delivers substantial environmental benefits, paving the way for more sustainable supply chains globally.

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Competing interests

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Authors' contributions

M.A., L.B. and E.S. conceptualised the study. M.A. and L.B. developed the methodology. M.A. implemented the software and produced the visualisations. Resources were provided by M.A., E.S., and R.S. M.A. prepared the original draft. Writing—review and editing were carried out by M.A., L.B., E.S., and R.S. L.B. and E.S. supervised the research, and L.B. managed the project administration. All authors have read and agreed to the published version of the manuscript.

Ethical considerations

This article followed all ethical standards for research without direct contact with human or animal subjects.

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Data availability

The data presented in this study are available on request from the corresponding author, M.A.

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Appendix 1

Key construct and definitions

- Collection points: Designated physical locations where consumers can return EoL products or waste (Mallick et al., 2023).
- Reverse logistics network design: The strategic planning of facilities and transportation routes to efficiently bring used products and materials back into the supply chain for recovery (Tolio et al. 2017).
- Smart bins: Waste containers equipped with sensors and communication technology to monitor fill levels, waste type and transmit data for optimised collection (Sarc et al. 2019).
- Pneumatic waste collection systems: Underground pipe networks that use vacuum technology to transport waste to central stations, offering a modern alternative to traditional collection (Yildizbasi et al. 2025).
- Selective collection: The practice of separating waste by categories (e.g., plastic, paper, organic) at the source to facilitate recycling and material recovery (Nascimento et al. 2019).
- Urban mining: The process of recovering raw materials from discarded products and waste within urban environments (Fatimah et al. 2024).
- First-mile reverse logistics: The initial stage of the returns and recovery chain, where products are retrieved from end users and transferred into the reverse supply network. It typically relies on three intake channels: home pickup, locker/parcel stations and collection-and-delivery points in retail or public sites (Agnusdei et al. 2022).
- Real-time monitoring: The continuous, immediate collection of data on waste levels, locations and conditions, primarily enabled by IoT and sensors (Ciano et al. 2025).
- Predictive analytics: The use of data (often Big Data) and algorithms to forecast waste levels, product returns and adjust collection logistics proactively (Kerdlap, Low & Ramakrishna 2019).
- Traceability: The ability to track materials or products throughout the reverse logistics pathway, often facilitated by Blockchain and RFID tags, ensuring transparency and quality control (Afshari et al. 2024).
- Automation: The use of technology (robotics, AI) to perform tasks with minimal human intervention, improving efficiency and safety in collection and sorting (Trevisan et al. 2023).
- Consumer participation: The active involvement of individuals in waste segregation, disposal and return processes (Mallick et al. 2023).
- Public awareness: The extent to which citizens are informed about waste management practices, collection points and the benefits of recycling (Islam et al. 2025).
- Incentive mechanisms: Strategies (e.g., financial rewards, convenience) designed to motivate desired behaviours in waste return (Iqbal & Kang 2024).
- Multi-stakeholder collaboration: Cooperative efforts among various independent entities involved in the waste management value chain (Tolio et al. 2017).
- Informal sector formalisation: The process of integrating unofficial waste collectors into regulated systems, providing support and guidelines (Fatimah et al. 2024).
- Extended producer responsibility (EPR): A policy approach under which producers are given a significant responsibility – financial and/or physical – for the treatment or disposal of post-consumer products (Farooque et al. 2019).
- Deposit refund system (DRS): A system where a small charge (deposit) is added to the price of a product, which is refunded to the consumer when the product (or its packaging) is returned for recycling or reuse (Islam et al. 2025).
- Take-back systems (TBS): Systems established where the producer holds responsibility over the product at its EoL, promoting the collection of EoL products for correct destination (Salvador et al. 2021).
- Circular economy principles (CEP): A framework aiming to keep resources in use for as long as possible, extract the maximum value from them while in use, then recover and regenerate products and materials at the end of each service life (Bui et al. 2024).