Smart waste management 4.0

The transition from a systematic review to an integrated framework

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Smart waste management 4.0: The transition from a systematic review to an integrated framework

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A R T I C L E I N F O

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Smart Factory
Smart Business
Smart People
Smart City

A B S T R A C T

Smart Waste Management (SWM) discusses the waste management process for different types of waste while introducing an intelligent approach to controlling the amount of waste. This paper introduces SWM4.0, which applies Industry4.0 (I4.0) technologies in various related events. First, the paper presents a systematic literature review on the role of I4.0 technologies in SWM activities regarding waste types, waste management processes, and 5R strategies. Then, existing solutions supporting SWM4.0 are extracted to develop a framework for exploring the use of I4.0 technologies. This framework includes sharing the four main pillars that contribute to the success of SWM4.0, namely smart people, smart cities, smart enterprises, and smart factories. Furthermore, this review suggests the possibility of unifying and extending existing solutions and identifying the necessary links and interfaces for researchers. For managerial implications, the framework identifies future strategies to fulfill specific SWM tasks and to foster new technological solutions for future research.

1. Introduction

Waste management is an important current issue for societies. Sectors as varied as cities, manufacturing, and service industries face waste management challenges, and the issue has intensified due to significant population growth, urbanization, and consumerism (Zhang et al., 2019; Paul and Ghosh, 2022). Concurrent with the increase in waste management challenges, smart waste management (SWM) strategies are being developed through the application of intelligent and novel technological tools (Sharma et al., 2020a; Lin et al., 2022).

Recently, with the evolution of technology, industry, and social processes, the fourth industrial revolution or Industry 4.0 (I4.0) has been created to increase interconnectivity and intelligent automation. I4.0 aims to transform industrial value chains, related business models, and manufacturing value chains by combining embedded manufacturing systems with intelligent production systems (Govindan, 2022a; Govindan and Arampatzis, 2023; Govindan, 2023). Undoubtedly, many technologies such as the Internet of Things (IoT), mobile technologies, blockchain, artificial intelligence (AI), big data and analytics, cloud, and cyberphysical systems (CPS) are working together to realize the full potential of the I4.0 movement (Ghobakhloo et al., 2021; Kumar et al., 2019; Govindan, 2022b,c). Also, the impact of the drivers and technologies underlying I4.0 have been studied from the perspective of different sectors, which has led to more "4.0″ terms. Therefore, this paper aims to introduce SWM4.0 with a focus on the role of I4.0 technologies in achieving SWM goals.

Moreover, to study the academic researches and understand their practical achievements, an important approach is the study review, which has extracted a classified information based on a consensus of the mentioned ideas and innovations (Xiao & Watson, 2019). In the field of SWM, (Esmaeilian et al., 2018) proposed a conceptual framework for centralized SWM based on IoT, and Alidoosti et al., (2023) proposed a multi-objective possibilistic mixed-integer non-linear programming model for the sustainable municipal solid waste network. Towards a circular economy, (Lu & Chen, 2022) focused on computer vision-enabled municipal solid waste sorting. Also, (Sarc et al., 2019) studied

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intelligent robots and digitalization in waste management in four segments: waste treatment plants and machines, collection and logistics, business models, and data tools. In addition, (Lin et al., 2022) reviewed deep learning applications for waste collection, transportation, and final disposal. The search string that identified the reviews is shown in Table 1, with each review focusing on the use of only one of the tools, specifically IoT or AI.

No literature review supports the role of I4.0 technologies towards SWM goals, despite a diversity of researchers dedicated to this field. Moreover, each review article only studies a part of waste management directly or indirectly; no comprehensive study exists that leads to the SWM goals in a new era with an emphasis on the function of the whole I4.0 technologies. Therefore, the gap of previous literature reviews clearly reveals the need for this literature review.

In this study, a Systematic Literature Review (SLR) is presented to discover I4.0 technologies in aspects of waste types, waste management processes, and 5R strategies. Also, this study provides a framework to understand the role of I4.0 technologies from the SLR that can accelerate SWM activities. This review selects a sample of articles from key advanced technologies in I4.0 related to SWM for descriptive and thematic analysis. Furthermore, this study identifies four main pillars for successful SWM implementation: people, businesses, cities, and factories. Consequently, the SWM4.0 framework integrates the roles of smart people, smart businesses, smart cities, and smart factories to apply I4.0 technologies to different waste management goals, which has been validated with existing studies and expert analysis. Accordingly, the results of the framework could be considered by academics and practitioners to improve the application of innovative and novel technologies for SWM activities.

The paper is organized as follows. Section 2 explains the research methodology. Section 3 reviews the literature on types, processes, and stages of waste management, respectively. Section 4 presents an integrated framework for implementing SWM4.0. Section 5 suggests the scope for future research and, finally, Section 6 concludes the paper.

2. Methods

In this paper, the SLR method, with its three essential steps of planning, conducting, and reporting the review, is used (Xiao & Watson, 2019). Fig. 1 shows the SLR phases that are expanded in the following sections.

2.1. SLR's planning phase

This phase identifies research questions leading to select the studies, methodology, data extraction and synthesis, and reports, and determines the review protocol. According to the role of I4.0 technologies in SWM, some questions arise, including:

RQ1: Which waste types have been managed by I4.0 technologies?

Table 1
Scope of recent review papers on SWM.

Recent review papers	Scope
(Esmaeilian et al., 2018)	IoT-enabled waste management
(Sarc et al., 2019)	Smart technologies and digitalization in waste management
(Lee & Lu, 2020)	Role of data analytics in construction waste management
(Guo et al., 2021)	Role of machine learning models in organic solid waste management
(Alam, 2021)	IoT applications based on cloud in smart cities
(Goutam Mukherjee et al., 2021)	Smart technologies to dispose of the different waste management processes
(Vishnu et al., 2022)	Role of RFID, Wireless Sensor Network, and IoT in solid waste management
(Lin et al., 2022)	Deep learning approaches in municipal solid waste management

RQ2: Which processes of waste management have used I4.0 technologies?

RQ3: What steps of waste management (5R) have been impacted by I4.0 technologies?

RQ4: Which I4.0 technologies have been used in SWM?

RQ5: What is the suggested framework for SWM4.0?

This research protocol, conducted on SCOPUS, is defined to reduce research bias. The RQ-related keywords of "smart waste management", "intelligent waste management", "digital waste management", and "waste management 4.0" were searched in the papers' titles, abstracts, and keywords to answer the research questions. These searches are limited to 2015—2022, and only English papers are accounted for. The reason for considering papers after 2015 is that this year, I4.0 was popularized by Klaus Schwab (Philbeck & Davis, 2018). Table 2 presents the selected keywords, number of papers found, and search queries.

This paper pursues the SLR approach by Govindan et al. (2022) to answer the research questions. At the first step of SLR, a review panel is organized with experts in waste management field. The experts' consensus of this panel helps to define research questions. The subsequent discussion sessions identify the keywords essential for responding to defined research questions. The comprehensive search began when the keywords and search terms were identified for the SLR. About 617 papers were found through this protocol of research.

The process of filtering out the searched papers is summarized in Fig. 2. At the first step, 617 papers were identified through the protocols for study. In Step 2, 481 SCOPUS papers were extracted by screening through the titles of these papers. In the next filtering (Step 3), I4.0 orientations of papers were considered, and they were reduced to 417 eligible ones. By reading 417 papers' abstracts, 26 papers were omitted for further focus in Step 4. The total papers which were thereby selected for deep focus in this study total 391.

2.2. SLR's conducting phase

In the conducting phase, selected review studies have been investigated, extracted, analyzed, and synthesized data. This section discusses a comprehensive analysis of screened review papers. The following sections explore, analyze, and synthesize the data.

Investigating the subject area of the screened papers reveals that two areas of engineering and computer science comprise a majority portion among other focus areas. Approximately 23% of papers belong to computer science and 21% to engineering (Fig. 3-a). Environmental Science, Energy, and Decision Sciences were identified in the following ranks. As Fig. 3-a shows, only 4% of studies are in business management and accounting fields. In an overview of the papers published from 2015 to 2022, we find the papers' trends during these years ascending in Fig. 3-b. Note that the keyword "smart waste management" represents the highest frequency among the other keywords.

In 2015, the beginning of research in this realm, 7 papers were indexed in SCOPUS. For example, (Zhang & Atkins, 2015) research is one of the first works which used Computational Intelligence Rule-based Reasoning technology and Radio Frequency Identification (RFID) technology to provide a decision support application in tracking construction waste. Also, (Medvedev et al., 2015) were one of the pioneer researchers in SWM4.0 which studied the role of IoT in smart cities. In general, Zaslavsky, Anagnostopoulos, and Medvedev are the most prolific researchers with about 16, 13, and 9 publications respectively in this field.

In addition, for further analysis of selected papers, the bibliographic data of these papers are presented through the VOS Viewer software. The output of the keyword analysis is shown in Fig. 4. The keywords "waste management", "IoT" and "smart city" and "bin" have the highest frequencies, appearing in 375, 254, 188, and 136 publications, respectively.

According to the keyword analysis in Fig. 4, these cloud papers should be reviewed for gap analysis. As can be seen, the publications

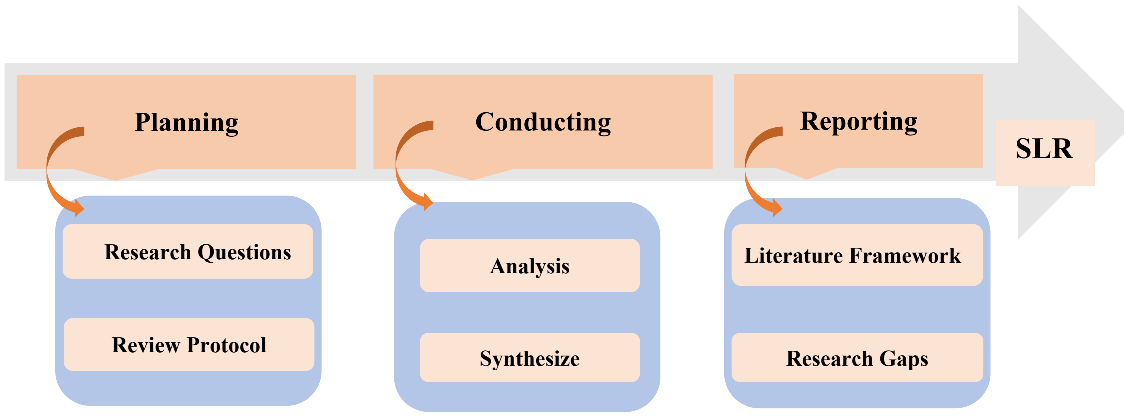

Fig. 1. SLR's phases (retrieved from (Xiao & Watson, 2019)).

focus on different SWM goals: waste types, waste management processes, waste management steps, and different waste applications. Fig. 5-a shows that most of the studies focused on municipal waste management by design of smart bins. Also, an analysis of publications in terms of process categories shows that the most frequent papers worked in the collection of waste (Fig. 5-b). Another analysis in waste management steps shows that 69% of the papers discuss waste reduction (Fig. 5-c). Moreover, investigations of the publications reveal that most papers have examined SWM in smart city applications (Fig. 5-d).

Moreover, Fig. 6 shows the trends of I4.0 tools in the waste management literature during 2015–2018. The IoT is the most well-known tool, and, as expected, it is on the rise. The use of AI in this research ranks second, and the growth of publications using AI in SWM4.0 is significant. Then, the use of sensors, big data analysis, and blockchain are other common I4.0 techniques. An overview of Fig. 6 confirms that SWM4.0 studies accelerated in 2018.

2.3. SLR's reporting phase

This phase consists of results and findings through literature reviews. It also includes the review framework and future directions for further studies. Results in the report phase are pointed out in the rest of the paper.

3. Results

Table 3 provides an overview of the recent relevant papers and their findings, which are reviewed in detail in the following subsections.

3.1. Role of I4.0 in waste types management

Daily, all wastes generated in different urban, rural, industrial, and other sectors can be divided into four types: solid, liquid, gaseous, and hazardous (Barba et al., 2015; Jhariya et al., 2019). Since there are different approaches to deal with them, the role of I4.0 technologies in managing each type of waste is explored.

3.1.1. Solid waste

There are several types of solid waste, but this SLR considers four categories: Construction and Demolition (C&D), e-waste, organic, and municipal waste.

3.1.1.1. Construction and Demolition waste. A number of studies have tried to dedicate I4.0 techniques to the waste management of C&D technical applications. For example, Yang et al. (2022b) employed big data to intelligently recycle construction waste, and Jazzar & Nassereddine (2021) investigated the effect of Construction 4.0 (C4.0) tools on the eight types of lean construction waste. Seruyaningtyas (2019) built a regional construction monitoring model.

3.1.1.2. E-waste. The process of recycling and disposing of electrical and electronic equipment must be safe (Kannan et al., 2016; Sharma et al., 2021). The application of I4.0 in this area facilitates the process of e-waste recycling and management. For instance, Romero et al. (2018) investigated CPS to address the digital waste present in cyberspace due to the lack of use and/or extensive use of new intelligence technologies.

Wanderley and Bonacin (2019) developed a product prototype for e-waste collection using smart recycling bins and mobile technology. Also, through blockchain in the 5G scenario, Dua et al. (2020) proposed solutions to track e-waste produced. Das et al. (2020) proposed a cloud-based framework for storing electronic goods sales data records from e-commerce and offline sales. In addition, Kazancoglu et al. (2020) applied machine learning algorithms for e-waste classification, and Xi et al. (2021) examined electrical materials classification.

3.1.1.3. Organic waste. Other solid waste sources are organic in nature: food, agriculture, and textiles. Researchers have especially focused on food waste because each year, millions of tons of food waste are produced worldwide; thus, researchers have recently considered the I4.0 techniques to reduce food waste. Wang et al. (2019) planned to produce a smart refrigerator. To deal with food losses and waste, de Sousa et al. (2021) suggested a business model for considering the duty of the retail tier based on I4.0 technologies. In addition, mobile technologies offered solutions based on digital platforms for food waste issues (Amaral & Orsato, 2022; Pramana et al., 2021).

Agriculture produces food by acquiring resources such as nutrients, water, and soil. The smart agriculture concept has emerged to incorporate optimal farming management on water usage and crop production through the IoT and different sensors. Also, to increase the effectiveness of agricultural waste, Yuzhen (2021) applied a system with intelligent monitoring to decrease agricultural waste flow based on big data analytics.

3.1.1.4. Municipal waste. Many studies in waste management emphasize waste's municipal scope and attempt to solve one of the serious problems of urbanization. Most studies, including those of Pargaien et al. (2021) and Roshan & Rishi (2022), presented IoT-based solutions in municipal waste management, which focus on the design of smart waste bins. Some research integrated the IoT technique and mobile technology to alarm the status of smart waste bins (Ghahramani et al., 2022; Jhaveri et al., 2021). Few studies (e.g., Ahmad et al., 2021) examined the possibility of applying the blockchain, and some studies (e.g., Ab Wahab et al., 2022; Kanaga & Jacob, 2021) focused on big data and analytics in SWM.

In addition, Azhaguramyaa et al. (2021) and Rahman et al. (2022) applied some I4.0 technologies such as IoT and AI; Baras et al. (2020)

Table 2
Keywords, number of papers found, and query of search.

Key word	Number of Papers found	Query string
"Smart waste management"	419	TITLE-ABS-KEY (smart AND waste AND management) AND PUBYEAR > 2014 AND PUBYEAR < 2023 AND PUBYEAR > 2014 AND PUBYEAR < 2023 AND (EXCLUDE (SRCTYPE, "p") OR EXCLUDE (SRCTYPE, "d")) AND (EXCLUDE (OA, "publisherhybridgold") OR EXCLUDE (OA, "publisherfree2read") OR EXCLUDE (OA, "repository")) AND (LIMIT-TO (PUBSTAGE, "final")) AND (LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "DECI") OR LIMIT-TO (SUBJAREA, "BUSI")) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "ch") OR LIMIT-TO (DOCTYPE, "re") OR LIMIT-TO (DOCTYPE, "bk")) AND (LIMIT-TO (LANGUAGE, "English"))
"Intelligent waste management"	80	TITLE-ABS-KEY (intelligent AND waste AND management) AND PUBYEAR > 2014 AND PUBYEAR < 2023 AND (EXCLUDE (SRCTYPE, "p") OR EXCLUDE (SRCTYPE, "d")) AND (LIMIT-TO (OA, "publisherfullgold")) AND (LIMIT-TO (PUBSTAGE, "final")) AND (EXCLUDE (DOCTYPE, "cp") OR EXCLUDE (DOCTYPE, "cr") OR EXCLUDE (DOCTYPE, "sh") OR EXCLUDE (DOCTYPE, "Undefined") OR EXCLUDE (DOCTYPE, "le")) AND (LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "BUSI") OR LIMIT-TO (SUBJAREA, "DECI")) AND (LIMIT-TO (LANGUAGE, "English"))
"Digital waste management"	90	TITLE-ABS-KEY (digital AND waste AND management) AND PUBYEAR > 2014 AND PUBYEAR < 2023 AND PUBYEAR > 2015 AND PUBYEAR < 2023 AND (LIMIT-TO (SRCTYPE, "j") OR LIMIT-TO (SRCTYPE, "k") OR LIMIT-TO (SRCTYPE, "b")) AND (LIMIT-TO (OA, "publisherfullgold")) AND (LIMIT-TO (PUBSTAGE, "final")) AND (LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "BUSI") OR LIMIT-TO (SUBJAREA, "DECI")) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re")) AND (LIMIT-TO (LANGUAGE, "English"))
"Waste management 4.0"	28	TITLE-ABS-KEY (waste management 4.0) AND PUBYEAR > 2014 AND PUBYEAR < 2023 AND PUBYEAR > 2014 AND PUBYEAR < 2023 AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "BUSI") OR LIMIT-TO (SUBJAREA, "DECI")) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "bk") OR LIMIT-TO (DOCTYPE, "ch")) AND (LIMIT-TO (PUBSTAGE, "final")) AND (LIMIT-TO (SRCTYPE, "j") OR LIMIT-TO (SRCTYPE, "b") OR LIMIT-TO (SRCTYPE, "k")) AND (LIMIT-TO (OA, "publisherfullgold"))

and Jain et al. (2019) used cloud computing and the IoT; Manikanta et al. (2019) and Pardini et al. (2020) employed mobile applications and IoT to municipal solid waste management.

Monitoring urban waste containers is another exciting issue. For example, Anil et al. (2019) used the IoT, Shetty & Salvi (2020) employed mobile technologies, Tan et al. (2019) integrated IoT and mobile apps, and Atayero et al. (2019) designed the cloud-based IoT to propose a model to provide real-time information on waste fill levels.

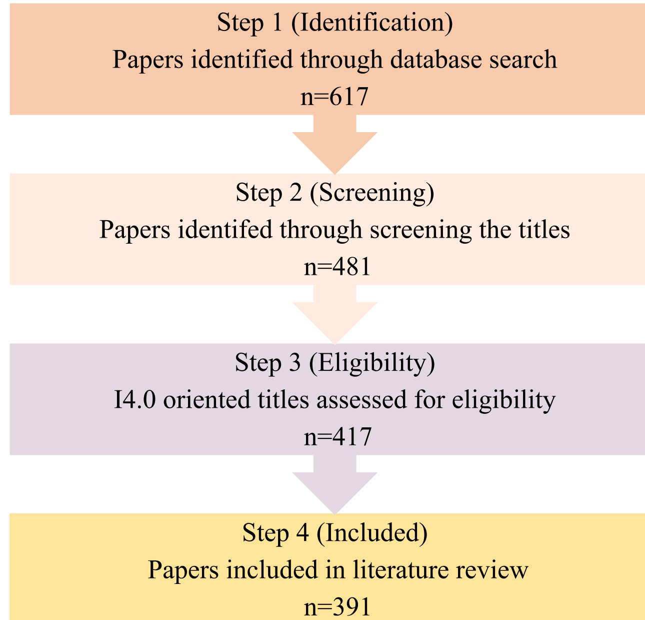

Fig. 2. The literature screening.

3.1.2. *Liquid waste*

There are several types of liquid waste, including polluted water and wastewater. Kumar et al. (2019) applied big data analysis to enhance the quality of the purring process of the remaining waters from waste. Guerra et al. (2020) proposed the use of robotized aerial vehicle platforms to check and analyze basins in wastewater plant management. Using the IoT and sensors, Nasre et al. (2020) designed an economical water filtration with an intelligent control recycling system. Further, Chang et al. (2019) proposed a system based on smart liquid waste barrels monitoring.

3.1.3. *Gaseous waste*

The most common gaseous waste management reviews were about fuel and energy handling. Makarova et al. (2019) suggested a vehicle that, through various sensors, enabled the transport of gas generators for operating pellets from production and homemade waste into generator gas. For a resource efficiency of phosphorus production from apatite-nepheline waste, Dli et al. (2020) offered a digital environment structure via digital twin technology. For an industrial heat transfer place, Kohne et al. (2021) presented a digital twin model.

3.1.4. *Hazardous waste*

Hazardous waste poses significant threats to public health or the ambience. Although it may be detected in different physical states such as gas, liquid, or solid, we assign it to a separate category because of its importance. In this regard, Y. Wu & Li (2022) proposed a digital twin skeleton for dangerous waste landfill systems. Khan et al. (2019) also investigated the role of mobile technologies to identify critical factors in drilling waste in the Mediterranean region.

For medical waste management, Chauhan et al. (2021) proposed a smart disposal system for healthcare waste through I4.0 technologies and circular economy. Also, Kumar et al. (2021) suggested an AI-based automated approach for grouping COVID-related medical waste. Abul Hasan et al. (2021) developed an IoT based method to manage medical waste. Furthermore, Chen et al. (2018) improved the radioactive waste monitoring method using software, RFID, and a cloud-based system, to create an information system.

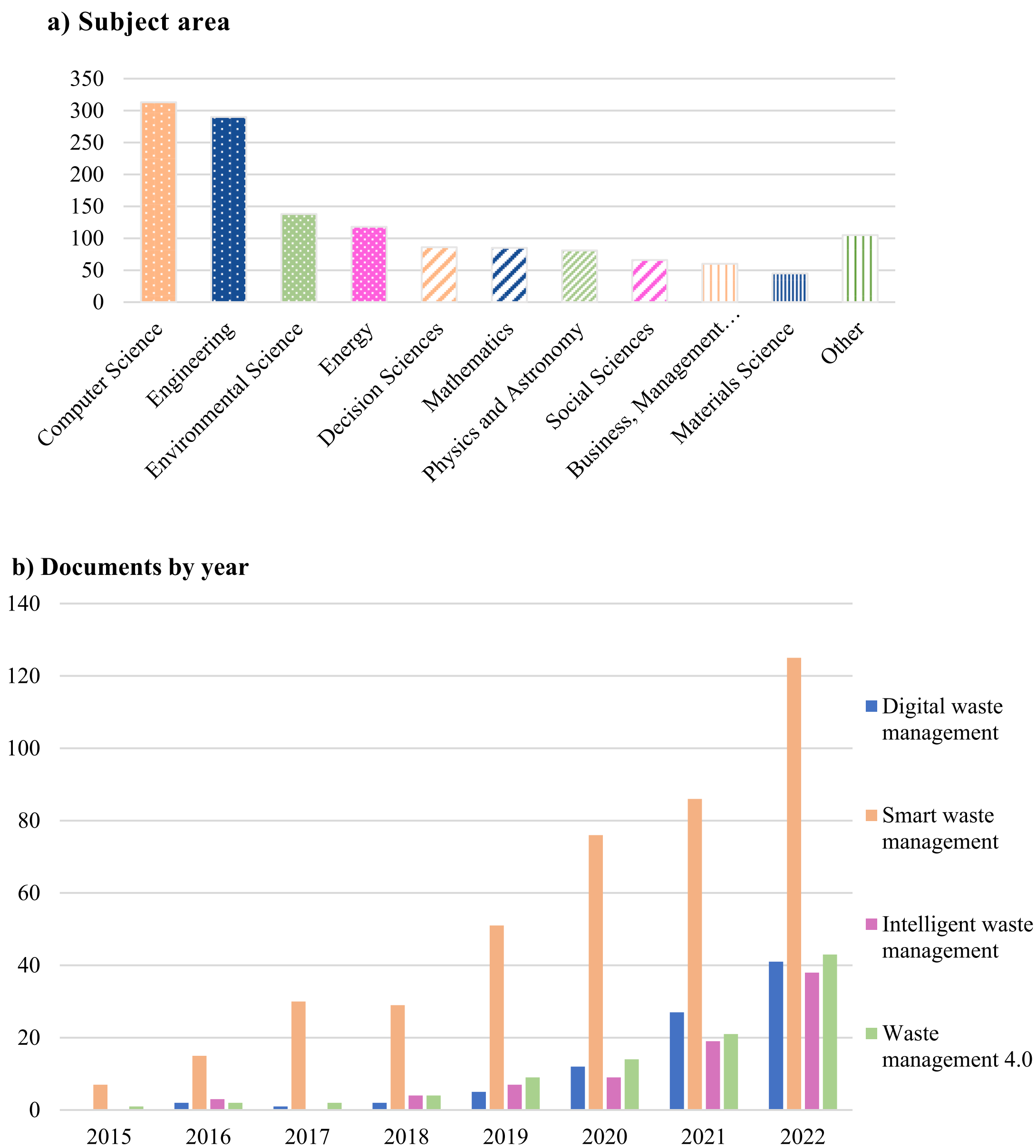

Fig. 3. Literature review: a) Subject area b) Documents by year.

3.2. Role of I4.0 in waste management process

In addition, we need a comprehensive view of the whole actions involved in waste management. In this regard, the waste management process is generally categorized into collection, transportation, recycling, and disposal; therefore, smart methods and different technologies should be applied to improve each action (Demirbas, 2011; Zainu, 2019). In this section, we explore the role of I4.0 in waste management in order to find new solutions.

3.2.1. Collection

Waste collection is the first step in the waste management process; it is the action of transporting from the use point and disposal to a disposal facility. There is a collection of non-waste materials that can be recycled as a section of a municipal landfill diversion plan (McDougall et al., 2001). Fatimah et al. (2020b) developed an intelligent waste collection system that integrates CPS to handle all waste management components. Also, different methods for collecting dry and wet waste were applied. For instance, Harjoseputro et al. (2020) and Pargaien et al. (2021) used IoT, and Mittal and Mittal (2019) applied cloud computing.

In the waste tracking challenge, Gopalakrishnan et al. (2020) and Sidhu et al. (2021) provided sufficient transparency and coordination among different entities using blockchain. Alqahtani et al. (2020) used IoT devices to monitor human activity and analyze the waste type, waste source, and truck size to alert the waste management stations.

In addition, to monitor waste bin containers to measure the filling level, different I4.0 tools have been applied, such as IoT (Aguila et al., 2019), IoT and data analysis (Muquit et al., 2019), IoT and cloud computing (Atayero et al., 2021; John et al., 2022), AI and data analysis (Camero et al., 2019), IoT and mobile technologies (Ghahramani et al., 2022; Jhaveri et al., 2021).

3.2.2. Transportation

The second step in SWM is waste transportation. SWM4.0 integrates smart waste bins into an existing network that identifies the level of filling of the bins and containers. As a result, decision-makers can evaluate the data and plan waste collection based on the daily schedules of waste trucks; in this manner, they can minimize transport costs and encourage positive environmental effects by saving transport/routing distance and fuel waste (El-Haggar, 2007; Rabl et al., 2011).

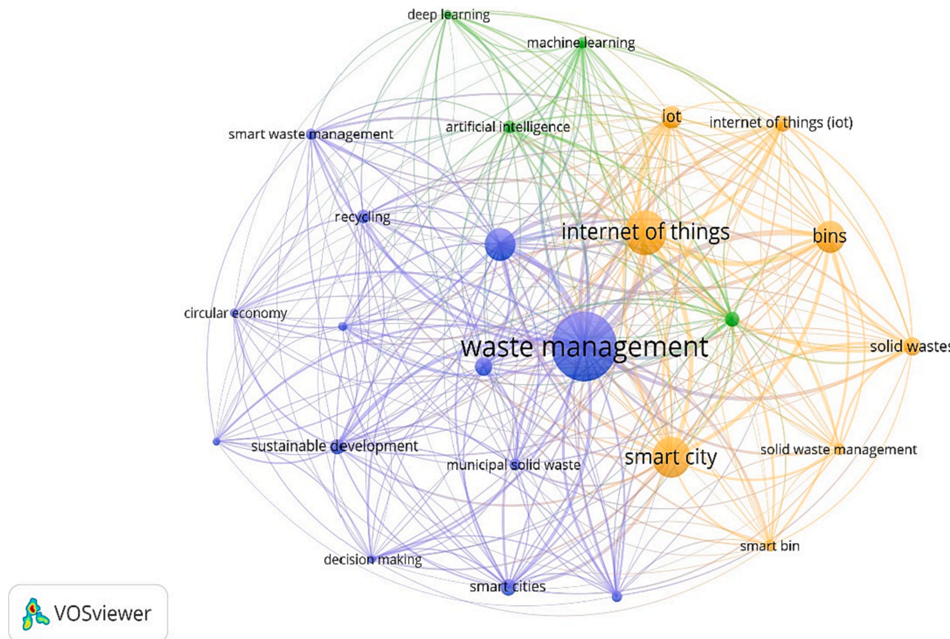

Fig. 4. Network visualization of papers' keywords.

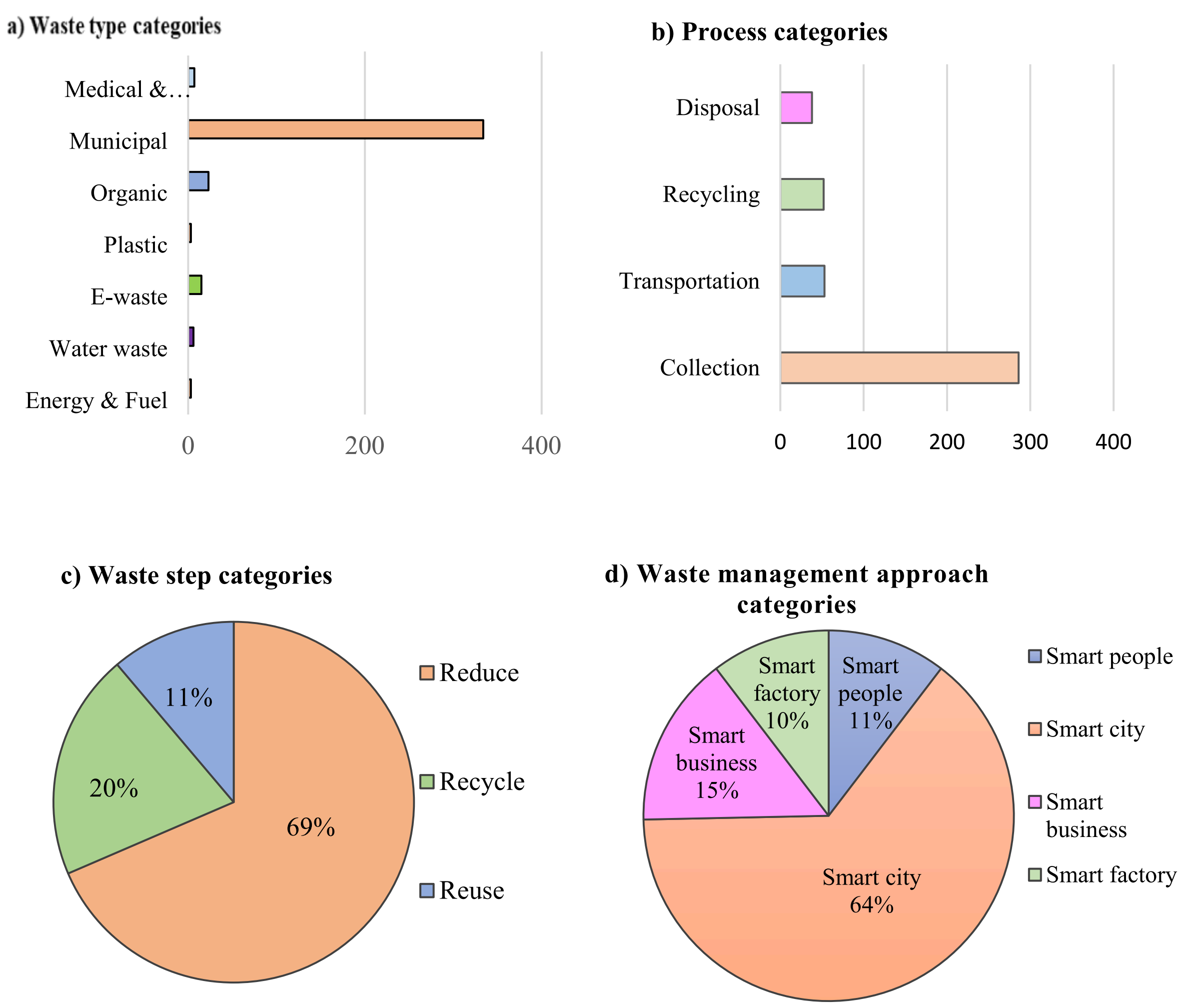

Fig. 5. The analysis of different categories in SWM4.0.

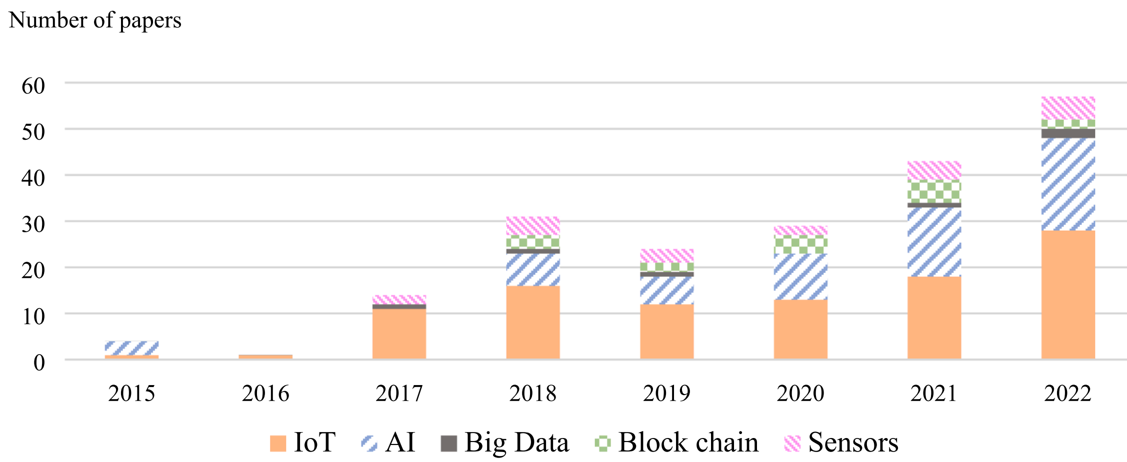

Fig. 6. Trends of applying I4.0 methods in selected papers during 2015–2022.

Accordingly, the main concern of studies in this scope is vehicle routing problems. For example, by wireless sensors, de Morais et al. (2019) employed real-time data on the waste container fill-level sensor over a medium-term horizon.

Bebortta et al. (2020) and Hrabec et al. (2019) presented a dynamic routing by IoT and mathematical optimization. Idwan et al. (2020) and Ma et al. (2021) devised an IoT-based solution in optimal planning for waste collection through optimal routes. Wang et al. (2021) and Yang et al. (2022a) proposed the application of electric vehicles, and chance-constrained programming was used to change the uncertain model into a determined model. Murugesan et al. (2021) and Zeb et al. (2019) proposed an IoT-based architecture for smart cities and a routing method considering minimum delay.

For route minimization of waste collection vehicles with a capacitated vehicle-routing model, Mishra and Ray (2020) proposed IoT cloud-based CPS, and Saeidi et al. (2021) used ICT and IoT in dangerous waste location and routing problems.

Designing a smart waste bin for efficient route selection is another popular approach. For instance, Pallavi et al. (2019) applied RPL protocol analysis in IoT applications. Anagnostopoulos et al. (2021) and Xenya et al. (2020) designed an IoT-based smart waste storage system to provide a monitoring platform to manage the alert records via orders and routing plans for the garbage collectors that was accessed through a mobile application.

3.2.3. Recycle

Waste is only waste when it cannot be reused or its economic value is not economically feasible to become a resource (Worrell & Reuter, 2014). Due to I4.0 in waste management, the use of first-hand materials can be reduced by 25% by 2030 (Kurniawan et al., 2022). A detailed study of the performance of the I4.0 tool in recycling is presented in subsection 3.3.3 to avoid duplication.

3.2.4. Disposal

Waste will threaten the environment and public health if it is not managed correctly. Perceiving waste as an undesirable material with no value is a prevalent attitude towards disposal. The COVID-19 pandemic has raised issues of waste disposal management, too (Hantoko et al., 2021). In this regard, using I4.0 technologies would be helpful if we could exploit them in a wide range of applications.

Accordingly, Sunny et al. (2019) presented the idea of an AI-powered smart disposal system. Furthermore, Kabugo et al. (2019) applied IoT platforms, algorithms of machine learning, and big data analytics towards a waste-to-energy plant. Designing smart dustbins is also a famous solution to categorize waste and collect them in an effective way (Gayanthika et al., 2019). Hassani et al. (2020) presented an IoT-based context management platform that could recognize the type of waste according to a photo taken by a mobile phone. Prabhu et al. (2020) suggested a solution through sensors to detect waste into metallic, nonmetallic, and wet classifications for domestic purposes. Wanderley & Bonacin (2019) proposed a solution based on mobile and IoT technologies for electronic waste disposal. Also, Khan et al. (2019) detected damaging factors of produced water and drilling waste by mobile technologies.

3.3. Role of I4.0 in waste management steps

Since space on Earth is limited to dispose of all waste, it is crucial to have strategies for waste control by applying smart technologies. In their explanations, these authors present a range from the 3Rs to the 10Rs, with the 5Rs version being the most frequently proposed. According to the 5Rs, four actions should be taken, if possible, before recycling: refuse, reduce, reuse, repurpose, and then recycle (Balwan et al., 2022; Sharma et al., 2020, Rahman et al., 2021; Reike et al., 2022). Although based on this SLR, the most common research examines reduce, repurpose, and recycle strategies, probably because refuse and reuse depend on our behavior. Therefore, in this section, the role of I4.0 tools in achieving the 3Rs is reviewed.

3.3.1. Reduce

Wang et al. (2019) developed a set of IoT-based smart fridge architectures to reduce food waste. Mobile applications are emerging that pursue responsible food consumption, food ecology, and self-management of access to connect people and used food such as that explored by Kumar and Chimmani (2019), Cane and Parra (2020), and Mazzucchelli et al. (2021).

Moreover, lean management is an approach where value is created through waste reduction (Liker, 2004). Modern manufacturing plants are shifting to I4.0, which promotes a variety of technological solutions to increase innovation and competitive advantages. Romero et al. (2019) discuss the cycle of Mura (Unevenness), Muri (Overburden), and Muda (Waste) and what this means within a CPS. Ejsmont and Gładysz (2020) analyzed the synergies of lean management and I4.0 technologies and El Jazzar and Nassereddine (2021) investigated the impacts of I4.0 technologies on the eight types of lean construction waste.

3.3.2. Repurpose

While there are many creative solutions for repurposing waste management, few studies have applied I4.0 technologies. For example, Makarova et al. (2019) designed transport gas generators based on I4.0 tools. Kohne et al. (2021) proposed a model for an industrial heat transfer via digital twins technique. Akhmadiev et al. (2022) developed

Table 3
Overview of relevant papers in the SLR.

Author(s)/Year	I4.0 technique	Waste type	Process	Stage
Anil et al., 2019	IoT	Solid		
Chen et al., 2018	Cloud computing	Hazardous waste		
Romero et al., 2018	CPS	Solid		
Chang et al., 2019	IoT	Liquid		
Elhassan et al., 2019	IoT			Recycle
Hrabec et al., 2019	IoT		Transportation	
Jain et al., 2019	Cloud computing	Solid		
Kabugo et al., 2019	IoT		Disposal	
Khan et al., 2019	Mobile Tech	Hazardous waste	Disposal	
Kumar et al., 2019	Big data Analytics	Liquid		
Kumar & Chimmani, 2019	AI			Reduce
Makarova et al., 2019	IoT	Gas		
Marques et al., 2019	Block chain			Recycle
Muquit et al., 2019	Big data Analytics		Collection	
Romero et al., 2019	CPS			Reduce
Srikanth et al., 2019	Cloud computing			Recycle
Sunny et al., 2019	AI		Disposal	
Wanderley & Bonacin, 2019	Mobile Tech	Solid		
Zeb et al., 2019	IoT		Transportation	
Ziouzios & Dasygenis, 2019	Big data Analytics			Recycle
Baras et al., 2020	Cloud computing	Solid		
Ciulli et al., 2020	Mobile Tech			Repurpose
Dli et al., 2020	Digital twin	Gas		
Dua et al., 2020	Block chain	Solid		
Fatimah et al., 2020a	CPS		Collection	
Gopalakrishnan et al., 2020	Block chain		Collection	
Guerra et al., 2020	Robotics	Solid		
Harjoseputro et al., 2020	IoT	Liquid	Collection	Repurpose
Pardini et al., 2020	Mobile Tech	Solid		
Rutqvist et al., 2020	Big data Analytics			Recycle
Saranyadevi et al., 2020	IoT			Recycle
Kazancoglu et al., 2020	Big data Analytics	Solid		
Abul Hasan et al., 2021	AI	Hazardous waste		
Ahmad et al., 2021	Block chain	Solid		
Atayero et al., 2021	Cloud computing		Collection	
Azhaguramyaa et al., 2021	IoT			Recycle
Kanaga & Jacob, 2021	Big data Analytics	Solid		
Kohne et al., 2021	Digital twins	Gas		Repurpose
Kumar et al., 2021	IoT	Hazardous waste		
Ma et al., 2021	IoT		Transportation	
Mazzucchelli et al., 2021	Mobile Tech			Reduce
Mullick et al., 2021	Mobile Tech			Repurpose
Murugesan et al., 2021	IoT		Transportation	
Pargaien et al., 2021	IoT	Solid	Transportation	
Pramana et al., 2021	Block chain	Solid		
Saeidi et al., 2021	CPS		Transportation	
Sidhu et al., 2021	Block chain		Collection	
Xi et al., 2021	Big data Analytics	Solid		
Amaral & Orsato, 2022	Mobile Tech	Solid		
Cappelletti et al., 2022	IoT	Solid		
Ghahramani et al., 2022	Mobile tech		Collection	
Roshan & Rishi, 2022	IoT			
Ab Wahab et al., 2022	Big data Analytics	Solid		
Yang et al., 2022b	Big data Analytics	Solid		
Wu & Li, 2022	Digital twin	Hazardous waste		
Zaman, 2022	AI			Recycle

an autoclave sterilizer and a pasteurizer with a digital technology design for processing agricultural waste. Goel et al. (2021) proposed a smart dustbin system to convert the wet waste into compost.

For food waste recovery, Ciulli et al. (2020) focused on the food supply chain and presented a waste recycling facility. Mullick et al. (2021) developed a digital platform to join local retail shops. Furthermore, Harjoseputro et al. (2020) presented a waste recycling device to convert organic garbage into liquid fertilizer with IoT.

3.3.3. *Recycle*

Recycling is an ideal solution for disposing of inorganic waste such as plastic, glass, and metal. Latif et al. (2019) used blockchain and IoT to automate waste management systems. Furthermore, Marques et al. (2019) presented a multi-level smart cities management based on IoT design. Azhaguramyaa et al. (2021) proposed an IoT and AI-integrated system for an intelligent separation method.

In addition, smart waste bins are frequently used as a modern approach for waste classification by big data analytics and machine learning approaches (Rutqvist et al., 2020; Ziouzios & Dasygenis, 2019), by IoT technologies (Elhassan et al., 2019; Saranyadevi et al., 2020), by IoT and GPS (Kansara et al., 2019), by IoT and cloud computing (Srikanth et al., 2019), and by sensors with specific applications (Harshith et al., 2020). Moreover, Zaman (2022) identified waste contamination through machine learning model by focusing on household waste recycling practices.

4. Discussion and framework

In this section, we reply to the RQs based on the SLR findings. To answer the first RQ, the SLR reveals that most researchers focused on solid waste. If we search into the categories of each type, we find that concentrating on municipal waste in a solid group is primarily dedicated to the design and usage of smart bins. In addition, e-waste, organic, and C&D research studies are limited.

The SLR clearly implies that the first process of SWM, collection, was the most attractive topic and many studies explore improvements in municipal smart bin performance. Furthermore, the most favorite step of SWM which has been impacted by I4.0 technologies was recycling.

Actually, the SLR reveals that few studies investigate innovative I4.0 based solutions to improve 5R steps.

Moreover, the most frequent I4.0 technology is IoT; then, applying sensors/RFID, mobile technologies, big data analysis, and AI were more commonly studied than the other techniques in the selected papers.

Finally, the proposed framework answers the last RQ, which is the result of SLR and a group discussion consisting of 12 experts who approved the validation of it. In this regard, the deep exploration of the selected papers reveals four main pillars for successful waste management implementation: people, businesses, cities, and factories. Consequently, the SWM4.0 framework integrates the roles of smart factories, smart businesses, smart cities, and smart people to apply I4.0 technologies to various waste management goals. The role of each pillar in SWM4.0 is then implied in the following sections.

4.1. Smart factory

Since product manufacturing is one of the bottlenecks of waste production, digitalizing the production path could help improve the performance of SWM4.0. IR4.0 develops a smart factory, intelligent factory, or digital factory. Through modular constructed smart factories, cyberphysical systems (CPS) can monitor physical tasks, produce a virtual model of the real world, and can make decisions in decentralized functions. Through the IoT, CPS communications with personals in synchronic time, internally and between organizations handled by members of the value chain (Chen et al., 2017). Based on this research, the facilities of smart factories (Tamás et al., 2016), Agriculture4.0 (Akhmadiev et al., 2022), Construction4.0 (El Jazzar & Nassereddine, 2021), and Lean4.0 (Ejsmont & Gładysz, 2020) can be significantly useful.

4.2. Smart business

After manufacturing companies, the next influential pillar of waste production is a business unit, an organization, or a business entity engaged in commercial, industrial, or professional activities. Smart companies adopt new technologies to achieve their business strategy, operational excellence in internal processes and supply chain, and lead IT development for operational teams. Thus, implementing Sustainability4.0 (Fatimah et al., 2020a), circular economy (Zhang et al., 2021), and supply chain4.0 (Mohajeri et al., 2021) has an important role in SWM4.0. Also, as an essential channel for establishing connections between producers and consumers, they could easily impress people by promoting the 5R goals (Abul Hasan et al., 2021; Latif et al., 2019).

4.3. Smart city

Cities are vital places that play a crucial role in the production of municipal waste. In this field, smart cities use modern technologies to improve daily operations such as transportation systems, law enforcement, health care, and the other municipal services (Musa, 2018). Within SWM4.0, several variables need to be studied when a city develops a collection system (Cotet et al., 2020), treatment (Kanojia & Visvanathan, 2021), and disposal (Chauhan et al., 2021); these factors vary from city to city (Monzambe et al., 2019).

4.4. Smart people

People themselves will have the greatest impact on the success of SWM4.0, since they will ultimately be the ones to apply all these advances in tools and technologies. Consequently, in order to adhere to the offered solutions and technological methods, it is necessary that facing today's world challenges such as global warming, high greenhouse gas or fossil fuel consumption has become a priority for all people. More studies have considered the role of international organizations, governments, laws and policies (Chen et al., 2020; Sharma et al., 2021; Zhang et al., 2021), so it is clear that this approach has not been very successful. Meanwhile, there are significant differences between countries and people, but this global problem should be addressed as a pandemic problem.

In this study, the term "smart people" is used for the first time in the era of IR4.0 to refer to the influence of people in the use of smart technologies and the effect of smart technologies for universal use. Based on studies to achieve SWM4.0, the targeted use of digital systems and public access to social networks for awareness (Chowdhury et al., 2021), education and culturalization of the 5Rs (Raghu & Rodrigues, 2020), creation of green jobs (Sharma et al., 2021) as well as the use of smart bins (Harjoseputro et al., 2020), food sharing or the sharing of anything useful for others (Ruggieri et al., 2020), and smart homes (Dua et al., 2020) can be useful.

4.5. Integrated framework

As mentioned above, we have extensively studied SWM4.0 issues and extracted the common innovative solutions based on I4.0 technologies from the SLR. These outcomes are: smart resource efficiency technology (Dli et al., 2021), smart monitoring system (Gopalakrishnan et al., 2020), smart bins (Bano et al., 2020), smart heating system (Kohne et al., 2021), smart waste collection (Fatimah et al., 2020b), food sharing (Mazzucchelli et al., 2021), smart waste to energy (Kabugo et al., 2020), smart waste transportation (Zeb et al., 2019), smart refrigerator (Wang et al., 2019), smart e-waste recycling (Wanderley & Bonacin, 2019), smart waste classification (Kazancoglu et al., 2020), automated detection garbage (Sunny et al., 2019), dynamic vehicle routing (Bebortta et al., 2020), smart detection hazardous waste (Yonghui Wu & Li, 2022), and smart landfill systems (Dey et al., 2022). Then, the role of four main pillars to successfully implement the solutions is examined by 12 waste management experts. They evaluated the impact of the four pillars to implement the SLR outcomes based on I4.0 technologies by giving a score from 1 to 5. The normalized responses are summarized in Fig. 7, which illustrates the average share of each pillar to achieve 15 cited outcomes.

Accordingly, to achieve the SWM goals, Fig. 8 proposes a developed framework that groups 15 approaches into four key pillars based on their level of importance. In fact, regardless of the innovative solutions, cooperation among people, cities, businesses, and factories involved in SWM is necessary.

Finally, Fig. 9 unifies all the findings and extracted results toward SWM4.0, which allows managers to better decide how to implement I4.0 tools. In order to achieve SWM4.0, we need to consider the role of key players: smart people, smart businesses, smart cities, and smart factories to effectively achieve innovative solutions. Moreover, in addition to the I4.0 technology yield, such as Construction4.0, Agriculture4.0, Lean4.0, it is crucial that sustainability and circular economy are considered as the basic platforms of linkages and interfaces. These strategies also make the role of 5Rs' steps much more remarkable.

5. Future research directions

In this section, different directions of research are suggested for future researchers based on this study. The proposed scope is divided into three main categories of SLR (waste type, waste management process, and 5R steps) as explained earlier in the discussion. Hence, detailed explanations of the future research directions of each topic are given below.

5.1. Future research based on waste types management

By investigating research on the waste types, it could be revealed that the number of papers in gas, liquid, and hazardous waste is rare, so the gap observed in this aspect is that there are few studies in SWM4.0. Environmental concerns for having green and clean earth lead

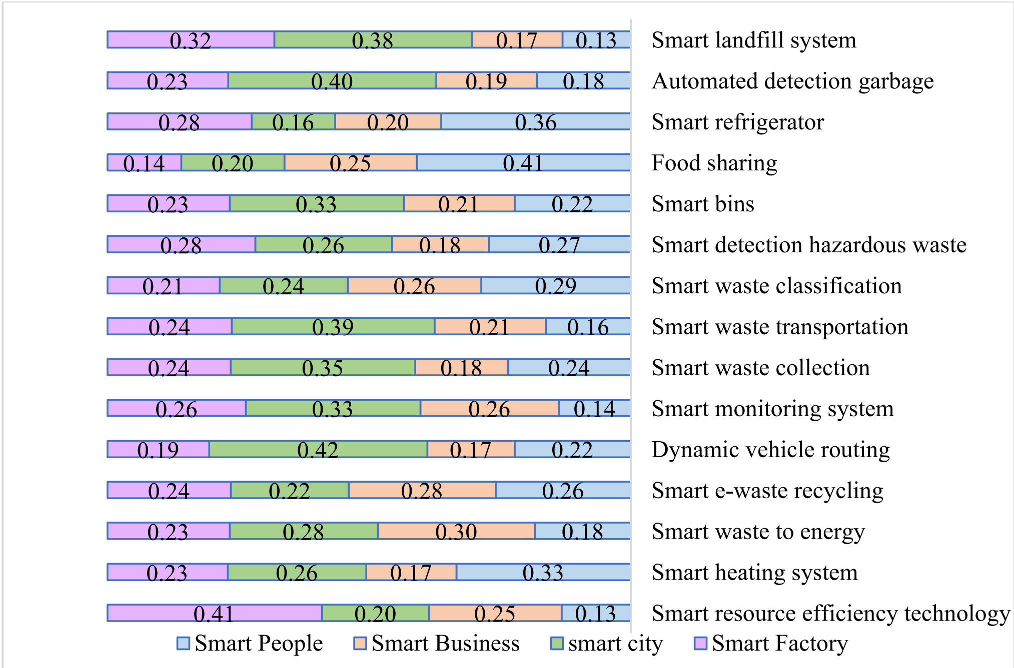

Fig. 7. The share of each pillar to accomplish innovative outcomes based on expert opinions.

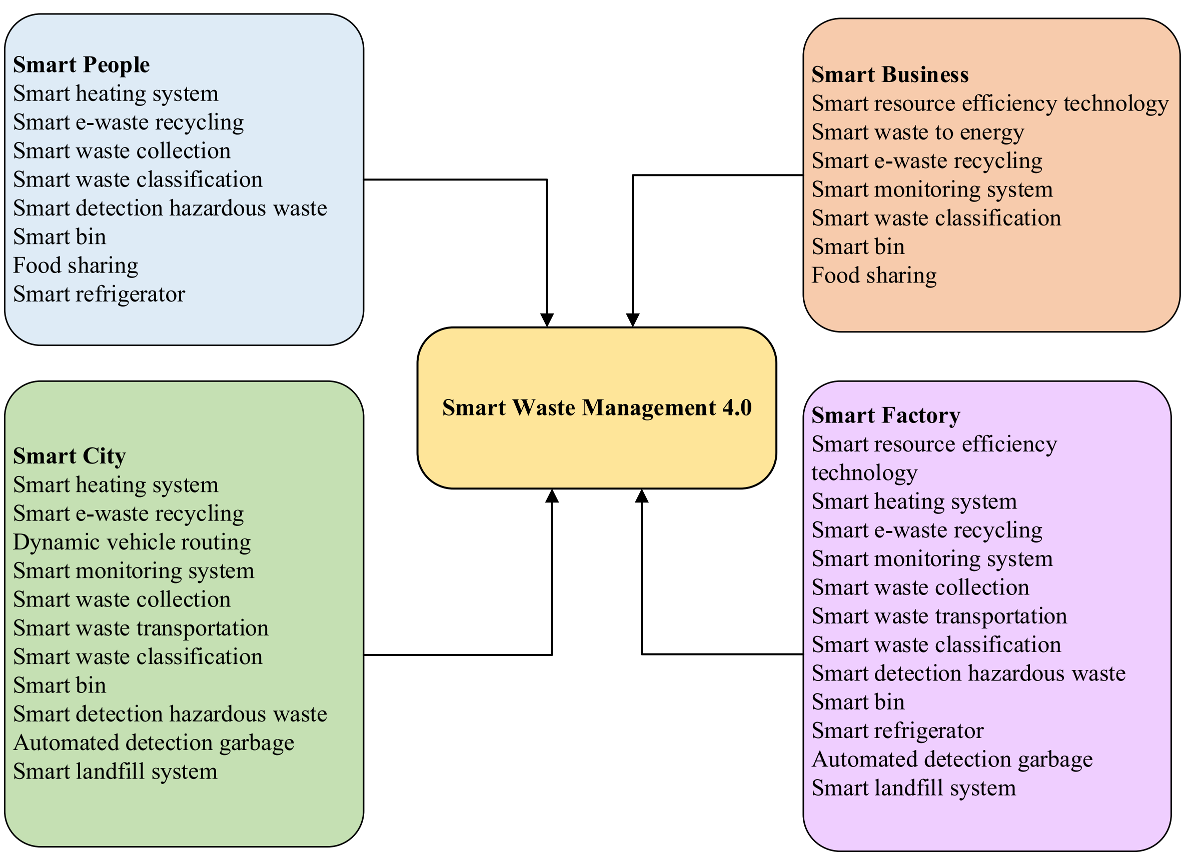

Fig. 8. SWM4.0 framework.

researchers to focus on all types of waste, especially gas waste, to reduce CO_2 emissions and other greenhouse gases. Also, there is a gap in research on SWM4.0, focusing on the disposal of medical waste via I4.0 techniques.

Moreover, the overuse of electronic devices and the digitization of daily human life have led to the high production of e-waste. Anticipating this severe problem in the future makes us pursue solutions for managing this type of waste. Besides, it is highlighted in analyzing the papers

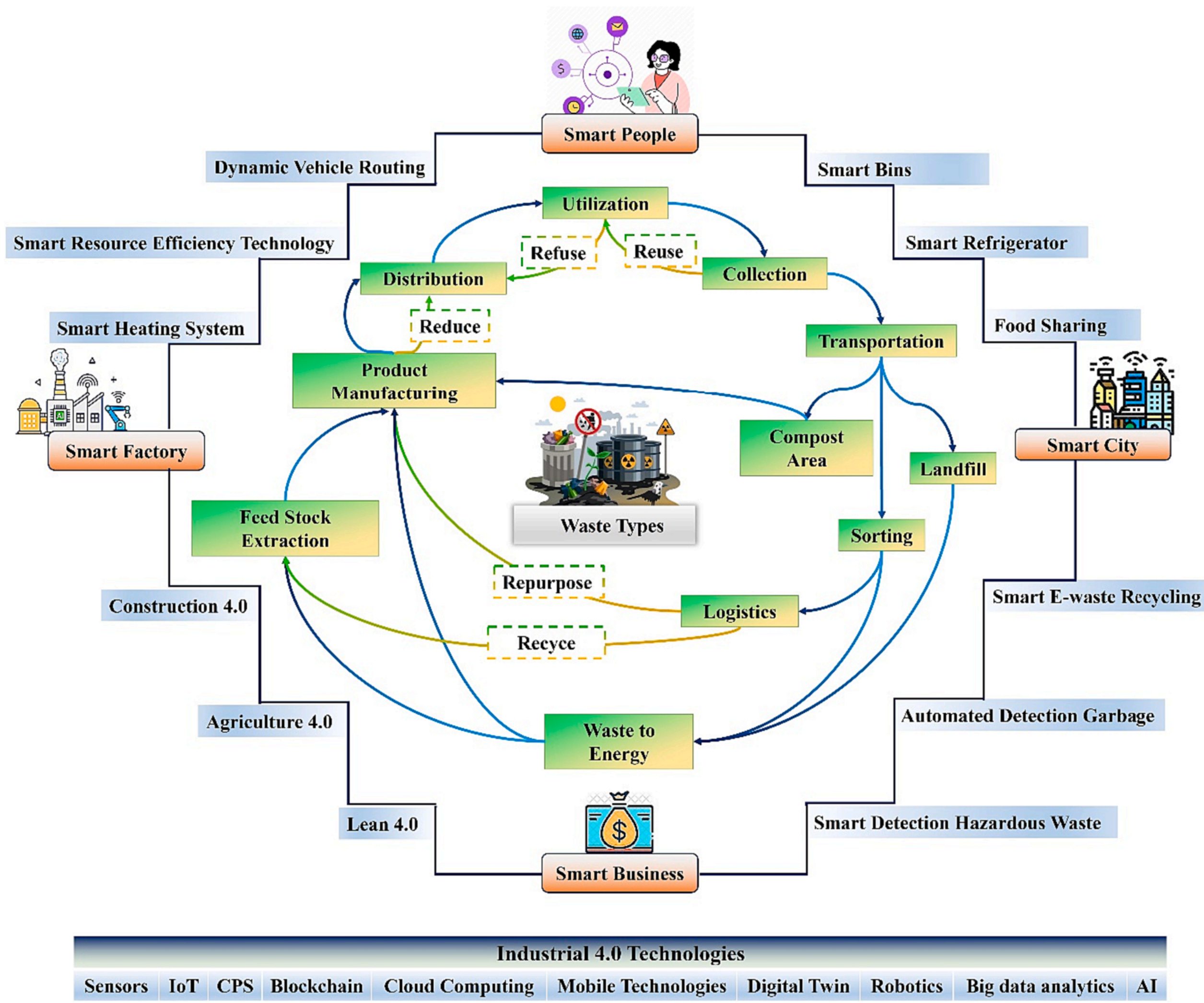

Fig. 9. Overview of SWM4.0 framework.

that studies in this field are poor and sparse. A title for future studies should be working on e-waste's disposal and recycling. The diversity of I4.0 tools is limited, and most studies focused on the IoT.

5.2. Future research based on waste management process

Focusing on papers seeking to use I4.0 techniques for waste management revealed that most research concentrated on the collection and transportation of municipal waste more than others. Some gaps were found in studies of waste management processes in produce, recycling, and disposal in waste disposal plants.

5.3. Future research based on waste management steps

The 5R steps are introduced to decrease waste on our Earth. This section's overview of papers shows the biggest gap where there is little literature on I4.0 technologies for 5Rs' steps. Three reducing, repurpose, and recycle steps are more applicable to I4.0 technologies than refuse and reuse, while these steps are related to the culture of treatments on Earth to achieve sustainable societies. With the progress of the digital age, it is necessary to deploy 5R's culture in SWM4.0.

6. Conclusion

As I4.0 is becoming more widespread these days, this study focuses on I4.0 technologies and waste management. From the previous literature review, there is a lack of comprehensive reviews on the role of I4.0 technologies in the achievement of SWM goals. Therefore, this paper aimed to discover I4.0 technologies in terms of waste types, waste management processes, and 5R strategies. The results revealed that the interest of I4.0 scope has grown with an increase in the number of papers over the past eight years. The SLR also indicated that sensors, IoT, cybersecurity/blockchain, big data analytics, and AI were among the most prominent I4.0 technologies. In addition, the majority of studies focused on municipal waste management, waste collection processes, and recycling steps. Finally, 15 innovative solutions based on I4.0 technologies were extracted from the SLR. Accordingly, a SWM4.0 framework was developed that considered the role of key stakeholders, including smart people, smart businesses, smart cities, and smart factories, to accomplish citation outcomes.

The validity of the findings from the SLR was verified by 12 waste management experts, and the results were extracted to finalize the framework. Furthermore, this study suggested the possibility of unifying and extending existing solutions and identifying the necessary links and interfaces. The proposed framework will be considered as a guide for practitioners to better understand how I4.0 tools and solutions can be applied to improve waste management. In addition, this research provided various research directions to address specific SWM4.0 tasks and to promote new technological ideas for future studies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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