Sorting the Trash: How Smart Waste Management Systems Contribute to Sustainable Development in Smart Cities

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Abstract

Waste management is a relevant challenge for cities around the world to ensure citizens' life quality, and to significantly contribute to environmental protection. Hence, inefficiencies in waste management thwarts the sustainable development of cities. Smart waste management can help improving the waste management services of cities by pursuing strategic goals, including waste reduction, waste collection and transport optimization, and waste treatment optimization. However, current research insufficiently addresses the contribution of information systems used in the context of smart waste management to sustainable development. Based on a literature review, we show how different systems in the smart waste management context contribute to strategic goals and, thereby, to sustainable development. We call for more research on smart waste management that accounts for the information systems' contribution to sustainable development.

Keywords: Smart waste system, smart city, smart waste management system, sustainable development.

1. Introduction

The management of waste is a relevant challenge for cities around the world to ensure citizens' life quality (Bastidas et al., 2022; Esmaeilian et al., 2018), and to significantly contribute to environmental protection (Briones et al., 2018). In this context, waste management includes required activities for the collection, transport, and treatment of waste, from its generation to its final deposit or recycling (Anagnostopoulos et al., 2017; Nema & Modak, 1998; Pardini et al., 2020). Inefficiencies in waste management lead to high resource consumption (Kamm et al., 2020), environmental damages such as water, soil, and air pollution (Briones et al., 2018), or high costs for municipalities (Jadli & Hain, 2020). However, the cores of waste management services in many cities still remain unchanged (e.g., fixed collection intervals) which wastes resources (e.g., fuel for waste collection vehicles) (Kamm et al., 2020) and thereby, thwarts sustainable development of cities.

Previous literature identified smart waste management (SWM) as an opportunity to improve the waste management services and enhance sustainable development in cities (Alexopoulos et al., 2019; Bastidas et al., 2022). Thereby, SWM is based on smart waste management systems (SWMS) intelligently integrating information and communication technology to real-time monitor and sense the environment, collecting, transmitting, and analyzing data to proactively support waste-related services, or provide decision support for users in the SWM context (Castro Lundin et al., 2017; Gounder et al., 2020). However, the mere implementation of SWMS does not yet entail any enhancement in waste management services or sustainable development. To address these goals, the SWMS needs to fulfill at least one of the three major waste related strategic goals for SWM: (1) waste reduction, (2) waste collection and transport optimization and (3) waste treatment optimization (Bastidas et al., 2022; Esmaeilian et al., 2018; Kamm et al., 2020). While previous work in the context of SWM proposed a wide range of studies considering the technical realization of SWMS, the pursued strategic goals and the system's contribution to sustainable development stays insufficiently addressed. As a result, there is a lack of knowledge about the SWMSs' impact on sustainable development which inhibits the unleashing of the full knowledge potential of SWMS. This knowledge gap is particularly relevant for cities, as understanding the SWMSs' impact on sustainable development allows to better state their own contribution to sustainable development.

Our research challenges the identified problem by assessing current research on SWMS with a focus on their contribution to sustainable development. We aim to develop an understanding of the different SWMS and how they are applied in cities pursuing a specific SWM strategic goal. Thereby, we analyze how they contribute to sustainable development. Therefore, our paper is

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guided by the research question: *How can SWMS contribute to sustainable development in smart cities?*

To address this question, we conduct a literature review considering the approaches from vom Brocke et al. (2009) and Webster and Watson (2002) to show how different SWMSs contribute to the SWM strategic goals, and how they impact sustainable development. Our results have substantial implications for research and practice by establishing an understanding of SWMS in the sustainable development context. For academics, our assignment of SWMS to specific SWM strategic goals allows for reinterpretation of previous research, distinguishing their approaches and their contribution to sustainable development. For developers of SWMS, we provide a navigation toward the SWM knowledge body which supports targeted development of new approaches, considering a SWM strategic goal, and the impact on sustainable development. Additionally, we call for research considering the sustainability outcomes of using SWMS.

2. Theoretical background

Our theoretical background draws on two research areas. First, we present a brief conceptualization of sustainability in the smart city context. Second, we provide an overview of SWM, SWM strategies, and the various systems used for SWM. Finally, we present our review framework which incorporates the insights of both research areas.

2.1. Sustainability and the smart city context

Sustainability is the ability to meet the present needs in production, consumption or services without compromising the ability of future generations to meet their own needs emphasizing resource regeneration (Ekardt, 2020; UN, 1987). While sustainability is a long-term goal, sustainable development refers to measures, processes and ways in which sustainability can be achieved (Jeronen, 2013) and is regarded as a concept that involves balancing economic, social, and environmental considerations to ensure that resources are used with long-term well-being in mind (Holden et al., 2014; UN, 2022). The UN adopted 17 sustainable development goals (SDGs) in 2015 to operationalize sustainable development (Sachs et al., 2019; UN, 2015).We focus our work on using information and communication technology as a pathway towards sustainable development and achieving of the UN's SDGs in smart cities (Höjer & Wangel, 2014; van der Aalst et al., 2023).

A smart city can be defined as a city investing in human and social capital as well as modern information and communication technology, relying on sustainable economic growth, ensuring citizens' life quality, and a management of natural resources through participatory governance (Caragliu et al., 2011). To pay more tribute to sustainability aspects of a smart city, we define it as a city that uses various interconnected, intelligent, and proactive urban information and communication technologys to improve citizens' life quality, efficiency of urban operations and services, and competitiveness in consideration of economic, social, and environmental aspects grounded in the SDGs (Bibri, 2018; Höjer & Wangel, 2014; Peris-Ortiz et al., 2017; UN, 2022).

2.2. Smart waste management

Considering the perspective of smart city characteristics, SWM can be assigned to the smart environment field of activity and aims to enhance waste management services using information and communication technology (Giffinger et al., 2007). Regarding SWMSs, we distinguish smart waste systems (SWSs), which are physical components equipped with information technology, from smart waste information systems (SWIS) which we regard as information systems providing information, decision support, and optimizing services based on the data gathered and transmitted by SWSs or in the context of SWM (Castro Lundin et al., 2017; Kamm et al., 2020; Sosunova & Porras, 2022).

Furthermore, SWM needs to incorporate a technical and a strategic perspective. The three major SWM strategic goals can be distinguished as: (1) waste reduction, (2) waste collection and transport optimization and (3) waste treatment optimization (Bastidas et al., 2022; Esmaeilian et al., 2018; Kamm et al., 2020). The first strategic goal focuses on the generation of waste and pollution. Considering our focus on cities, waste not only refers to an disposed object at the end of its life cycle (Esmaeilian et al., 2018), but also includes the pollution of the environment through littering (Chaudhary et al., 2021) that must be reduced to prevent environmental damages (e.g., water, soil and air pollution) (Briones et al., 2018; Kamm et al., 2020). The second strategic goal focuses on the waste collection and transportation services. This strategy aims to reduce the consumption of process-related resources such as energy or fuel (Kamm et al., 2020) for instance by reducing the travel distances for waste collection vehicles (Bräutigam et al., 2022; Gupta et al., 2022). The third approach emphasizes the treatment of waste after disposal, through recycling or recovery (Esmaeilian et al., 2018). Waste is reintroduced into the economic cycle as a resource (van der Aalst et al., 2023). This allows new products to be produced more sustainably or energy to be generated from waste (Aazam et al., 2016; Dadario et al., 2023). Addressing a

SWM strategic goal is crucial to efficiently enhance the waste management and thereby contribute to the smart cities' sustainable development (Bastidas et al., 2022).

2.3. Review framework

Based on the presented background, we derive a framework for our literature review that comprises the (1) SWM strategic goals, the (2) user groups involved, and the (3) implemented SWMS as input factors. All of which can have an impact on (4) reaching SDGs defined by the UN.

Ad 1) Turning to the lefthand side of our review framework, the *SWM strategic goal* perspective emphasizes the different strategies the use of the SWMS pursues (we already introduced in detail: waste reduction, waste collection and transport optimization and waste treatment optimization).

Ad 2) From the technical perspective our review framework includes a *SWMS*-network of SWSs and connected SWISs building an IoT. The SWSs gather and transmit data about waste related processes to other smart objects and SWISs inside the IoT. Additionally, SWSs can support waste management services based on actively intervene in the waste management process for instance by autonomous waste sorting into different categories or materials. The SWIS are used to analyze the gathered data from the sensor network and to provide information and decision support to the user.

Ad 3) The different *user groups* involved in the SWM are considered in our review framework. We distinguish between citizens and organizational users which use SWMS differently and with a focus on different SWM strategic goals.

Ad 4) We reviewed the SDGs and associated subgoals and indicators provided by the UN (2022) from the perspective of SWM. It must be noted that the UN's definition considers sustainability from a global perspective, which must be clearly defined in an applied context to become a useful tool (Holden et al., 2014). Reflecting our understanding of SWM we consider the SDGs 3 (good health), 8 (decent work and economic growth), 11 (sustainable cities and communities) and 12 (responsible consumption and production) as the most suitable to assess the research in the context of SWM to. Considering the SWM context, we included the two dimensions (1) reduced resource consumption and (2) reduced environmental pollution as the crucial *sustainability outcomes*. The dimensions consider the objectives of the suitable SDG and subgoals. Further, we consider the effect reduced resource consumption may have on environmental pollution in specific cases. For instance, we assume, that optimized travel distances for waste collection and transport vehicles results in less fuel consumption as a main outcome which may lead to reduced emission of greenhouse gases and thereby less environmental pollution (Gupta et al., 2022; van der Aalst et al., 2023).

Citizens changing their waste behavior based on SWIS use have a significant impact on the sustainability outcomes (Briones et al., 2018; Esmaeilian et al., 2018; Hasan & Hasan, 2020). Citizens are a lever to waste reduction (e.g., through less littering) and waste treatment optimization (e.g., by engage in recycling) whereas organizational users are mostly concerned with waste collection and transport optimization. Organizations turning to data-driven and on demand SWM and SWSs have been proven to successfully contribute to reduced resource consumption (Badotra et al., 2021; Gupta et al., 2022; Janeera et al., 2021; Slavík et al., 2021). Hence, the user is an active contributor to realize the SWM strategic goal using the SWIS. We summarized the relationship between the SWM strategic goals, the SWMS, the users and the sustainability outcomes in our review framework in Figure 1.

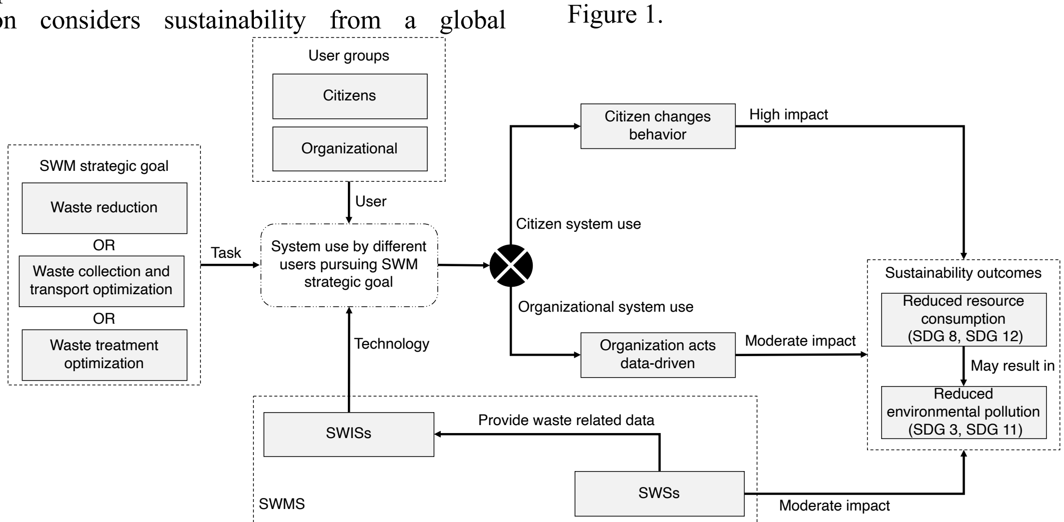

Figure 1. Review framework

3. Research method and process

To attain our research objective how SWMS can contribute to sustainable development in smart cities, we seek to identify the current state of knowledge in the field of SWMS. We structure this knowledge according to our review framework to understand the use of SWS and SWIS related to the different SWM strategic goals. Finally, we sought to identify how previous research in the SWM context accounts for the sustainable development using SWMS and SWM strategic goals. Thus, we seek to identify the merits of SWMS regarding the SDGs. To that end, we conducted a literature review based on the proceeding of Webster and Watson (2002) and vom Brocke et al. (2009). A literature review can help in consolidating, aggregating and streamlining existing knowledge of research, and can serve as a foundation for generating novel insights (Rowe, 2014). For our work this means highlighting the contribution to sustainable development in smart cities by SWMS. Our literature review focuses on two perspectives of the SWMSs. On the one hand, we regard the technological and SWM strategic goals perspective of the different approaches. On the other hand, we consider whether and how the researchers consider the SWMS's contribution to sustainable development.

3.1. Literature selection

We reviewed SWM research in established databases for information systems and computer science (ACM Digital Library, AIS eLibrary, and IEEE Xplorer/ Digital Library, Ebscohost Business Source Complete, Elsevier). We started our literature review by searching article abstracts, titles, and keywords for the string "Smart cit*" AND "SWM OR SWS OR SWIS OR SWMS" AND "sustainab* OR environment OR strateg*" (vom Brocke et al., 2009). Furthermore, we used backward and forward search to gather relevant articles (Webster & Watson, 2002). We restricted our review to research published from 2016 until December 2022 to ensure the timeliness of our results and conclusions. First, we checked the relevance of the resulting papers considering their fit with our review framework. To that end, more than 360 results were assessed for relevance based on their abstracts. In this iteration papers focusing on algorithmic improvements or mere prototype sketches were excluded. This step resulted in 175 publications selected for a more detailed analysis. In the next step, two of the authors discussed the relevance of each research paper and whether papers report on SWMS use to pursue a SWM strategic goal or contribution to sustainable development in smart cities. We excluded papers focusing overviews on SWM, SWM frameworks and SWM architectures. Finally, we agreed on 78 publications for further analysis. Included studies employed SWMS to enhance the waste management services and to pursue a SWM strategic goal with a smart city focus, thus contribute to sustainable development in smart cities. We continued with an in-depth analysis of the publications and decided on a subset of 31 papers.

3.2. Literature classification

To gain a better understanding of the research field, we classified the literature regarding (1) historical and temporal aspects and (2) the various conceptual approaches for SWMS. In our analysis of the historical and temporal aspects, we only ascertained 7 publications before 2020, all with a highly technical focus on SWS development. Further, we identified a significantly increase of publications since 2020 with broader contributions beyond mere system development. Together, this reflects the still young discourse on SWMS. Figure 2 provides an overview of the identified publications' distribution from 2016 to December 2022.

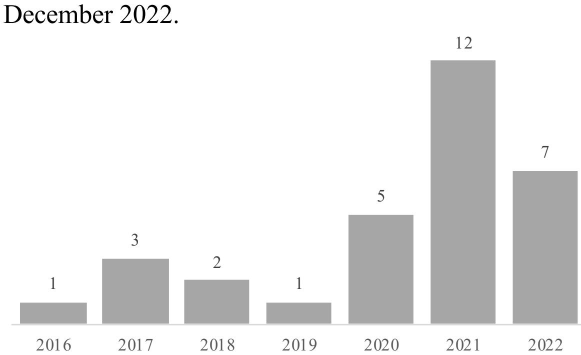

Figure 2. Overview identified articles by year

To systematically categorize the final list of papers, we utilized a two-stage process for concept identification and analysis. As a first step we performed a concept centric analysis (Webster & Watson, 2002) regarding our understanding of SWS and SWMS as depicted in Figure 1.

After we established an understanding of different concepts for SWSs and SWISs, we wanted to gain a richer understanding of the relationship between the concepts, the SWM strategic goals and the sustainability outcomes. First, we analyzed the papers considering the different SWM strategic goals. Additionally, we examined the papers to see if the researchers consider the SWMS's influence on sustainability. We were particularly interested in whether the researchers describe and discuss their approaches' contribution to enhance sustainable development. We found that most of the researchers do not reflect their contribution to enhance sustainable development. Therefore, we classified the relevant research papers based on our understanding whether a contribution to enhance the sustainability is implicitly recognizable or assumed by the researchers. Again, most of the approaches contribute to more than one of the sustainability outcomes which we will deal with in detail in section 4.3.

4. Results

The aim of this section is to provide a comprehensive overview on current SWM research. To address our research question, we first analyze the different systems applied for SWM and seek to understand their affordances with respect to specific technical and strategic SWM goals. Next, we analyze the SWM strategic goal(s) and the SWMS' contributions to the sustainability outcomes. Finally, to understand how SWMS may contribute to the sustainable development in smart cities, we analyze the relationships between the different systems applied for SWM and the SWMS' contributions.

4.1. General findings

Before delving into the specific categories, it is important to delineate some general insights from our literature analysis. First, Table 1 presents various concepts for SWMS we derived from literature and provides a short concept description. Further, we associated the concepts to the system category SWS or SWIS.

The classification of our selected papers according to our review framework from Figure 1 can be found in Table 2 which, due to space limitations, presents an excerpt of the paper classification,

Three major findings emerged from our literature analysis. (1) Physical systems (SWSs, such as smart bins) and information systems (SWISs, such as route optimization systems) are inadequately separated by the researchers. We argue that it is important to distinguish SWSs and SWISs, because their contribution to the sustainability outcomes of SWM is based on different optimization potentials. Considering their contribution to sustainable development in smart cities, SWSs themselves can enhance resource consumption by being energy-efficient designed (Kamm et al., 2020). In contrast, SWIS enhance the sustainability of SWM through optimizing services mainly based on data analysis such as route optimization which leads to reduced resource consumption (Gounder et al., 2020). Considering this distinction and our previous definition of SWSs and SWISs, we examined the publications according to their use of SWSs and SWISs. A second finding is, (2) most research papers focus on the technical perspective and realization of SWSs and SWISs and leaves the strategic perspective unconsidered. As a result, little is known about how the system influences the sustainability outcomes of SWM, thus how SWMS contribute to sustainable development in smart cities. The two previous findings lead to the third finding, (3) there is a lack of knowledge about the SWMSs' impact on sustainable development.

Table 1. Overview of SWMS

Concept	System category	Description
Smart Bin	SWS	Using sensing technology (e.g., ultrasonic, infrared, humidity, and weight sensors), smart bins collect data about their fill level and their environment and make this data available in a network (Gounder et al., 2020; Sosunova & Porras, 2022)
Waste Collection Robots	SWS	Self-driving vehicles and robots drive up to waste bins to empty them autonomously and transport the collected waste to a collection point (waste truck or landfill) (Bräutigam et al., 2022; Gupta et al., 2022).
Waste Segregation Systems	SWS	Autonomous sorting systems use sensory to identify different kinds of waste (e.g., glass, plastic, metal) and segregate it (Badotra et al., 2021; Janeera et al., 2021; Sallang et al., 2021).
Organizational Decision Support Systems	SWIS	Based on collected data, applications optimize services and activities such as the routes of waste disposal vehicles (Gounder et al., 2020; Kamm et al., 2020).
Smart Waste Applications	SWIS	User centered systems, such as smartphone applications, inform, educate, and motivate sustainable use of waste systems or recycling. The objective is a change or improvement in waste behavior (Aguiar-Castillo et al., 2019; Briones et al., 2018; Delnevo et al., 2021)

Table 2. Excerpt of identified papers and their research perspective

Source	SWS	SWIS	Strategic goal: Waste …			Sustainability outcome: Reduced …	
			… reduction	… collection and transport optimization	… treatment optimization	… resource consumption	… environmental pollution
Aazam et al. (2016)	X	X		X		X	
Aguiar-Castillo et al. (2019)		X	X			X	X
Alwis et al. (2022)	X	X	X				X

Badotra et al. (2021)					X	X	
Bräutigam et al. (2022)	X			X		X	
Briones et al. (2018)		X	X			X	X
Castro Lundin et al. (2017)	X	X	X				X
D'Agostini et al. (2022)		X		X		X	X
Delnevo et al. (2021)		X	X			X	X
Gupta et al. (2022)	X			X		X	
Hasan and Hasan (2020)		X	X				X
Hoffmann and Pfeiffer (2021)		X	X			X	X
Jadli and Hain (2020)	X	X		X		X	X
Janeera et al. (2021)	X				X	X	
Jimeno et al. (2021)	X				X	X	
Kamm et al. (2020)	X	X		X		X	X
Kumar et al. (2022)	X		X				X
Moni et al. (2022)		X		X		X	X
Sampedro et al. (2021)	X	X	X				X
…	…	…	…	…	…	…	…
Total	**31**	**18**	**11**	**11**	**10**	**22**	**15**

4.2. Strategic, user and technical perspective in SWM

To better understand the "how" dimension in our research question, in our research framework, we differentiate between strategic, user-oriented and technical perspectives in SWM. The main use of smart waste applications pursues the waste reduction strategic goal (e.g., Briones et al., 2018; Delnevo et al., 2021; Hasan & Hasan, 2020; Sampedro et al., 2021). To avoid improper and illegal waste disposal, users are provided with information about nearby waste bins through a smartphone application and navigation support to the nearest empty waste bin to reduce littering (Hasan & Hasan, 2020). Furthermore, the use of gamification in smart waste applications is considered an appropriate way to support users' waste behavior, particularly disposal of waste in waste bins and recycling (Briones et al., 2018; Delnevo et al., 2021). The objective of the systems is to encourage users to enhance their waste behavior by providing external stimuli and create value for proper behavior. Users are provided with a smartphone application which allows tracking disposal of waste in designated containers (Briones et al., 2018). Various gamification elements are implemented into the smart waste applications to motivate the users' disposal behavior and reward users for different disposal related tasks (Delnevo et al., 2021; Sampedro et al., 2021). By using smart waste management applications, there is a significant potential for improving the amount of waste disposed in waste bins (Briones et al., 2018), thereby reducing littering and contributing to waste reduction.

Using data gathered by SWSs, data transfer and IoT-technologies with the objective to shift inefficient traditional waste management services to data-driven and on demand SWM is the focus of organizational decision support systems pursuing the waste collection and transport optimization strategic goal (Alwis et al., 2022; D'Agostini et al., 2022; Kamm et al., 2020). Thus, organizational decision support systems are provided with data from a network of smart bins which collect data through sensing technology (e.g., fill level). Based on this data, the organizational decision support systems support the waste management service through data-based planning, scheduling, and optimizing of waste collection routes (Jadli & Hain, 2020; Kamm et al., 2020). In their work, Bräutigam et al. (2022) also analyze the waste collection optimization with an SWIS but additionally use collection robots which collect the waste from smart bins and bring it to a human driven electrical truck. Their aim is to present an approach where a SWS supports humans carry out services to improve the efficiency during waste collection and decrease resource consumption.

For the waste treatment optimization, the systems are occasionally intertwined with the waste disposal. Waste bins are equipped with sensors and actors (e.g., robotic arms) to automatically sort waste into different categories (e.g., plastic, metal, e-waste) (Jimeno et al., 2021; Sallang et al., 2021). We assign these systems to the waste treatment strategic goal, due to their focus on recycling enhancement. Further, the energy recovery from waste is already discussed in the literature based on systems sorting landfill waste (Aazam et al., 2016; Janeera et al., 2021).

While most of the relevant research papers primarily focus on the technical realization and optimization of the SWMS, still they can be classified to the different SWM strategic goals. Another finding from our literature analysis is SWMS can be distinguished according to the point they are used in the waste management processes. Most approaches focus scenarios where waste is already disposed in a waste bin but there are also approaches to improve users' disposal and recycling behavior. As displayed in our review framework, we regard users acting on data provided by an SWIS having the highest impact on the sustainability outcomes and therefore on sustainable development in smart cities. We found the highest citizen centricity at the beginning of the waste management process where the researchers directly refer to the waste reduction strategic goal. As the waste management processes progresses, approaches shift to more technical and organizational approaches, and the focus on specific SWM strategic goals needs to be implicitly derived.

4.3. Sustainability in SWM

SWM is regarded as a crucial field of action to enhance the sustainability of smart cities (Castro Lundin et al., 2017; Esmaeilian et al., 2018). However, most of the relevant research papers do not directly highlight the contribution to sustainability outcomes. Based on our earlier discussions, we conclude our literature review with an analysis of the SWMS' contribution to the sustainability outcomes.

The only researchers in our set of relevant research papers that directly refer their work to one of the SDGs are Hoffmann and Pfeiffer (2021). The aim of their research "is to contribute to the rise of sustainable behavior through gameful design, specifically with regard to waste management" (Hoffmann & Pfeiffer, 2021, p. 17). Therefore, the researchers developed and tested a gamified system providing people with relevant information about waste behavior, educates people about recycling and emphasizes the impacts of sustainable waste behavior on the environment to fulfil the claims of the SDG 12 and the subgoal 12.8 ("Ensure that people everywhere have the relevant information and awareness for sustainable development and lifestyles in harmony with nature (UN, 2022)). This increases the recycling rate and protects the environment by reducing new resources brought into the economic cycle. Therefore, the sustainability outcome of using the system, however, also indirectly contributes to reduced resource consumption.

In contrast, gamified smart waste applications to reduce waste focus on citizens' waste disposal behavior (Aguiar-Castillo et al., 2019; Hasan & Hasan, 2020). To that end, the researchers use gamified smartphone applications fostering users' recycling motivation. The underlaying aim is to reduce littering which leads to higher disposal rates in waste bins and a higher recycling rate. As already discussed, higher recycling rates contribute to the reduction of resource consumption. Additionally, the gamified application contributes to the awareness of sustainable development and a way of life considering the consequences of the own waste behavior on the environment. Therefore, less waste is disposed in the environment whereby these approaches also contribute to the reduction of environmental pollution. The impacts on sustainability outcomes stay unconsidered by the researchers. However, the approach focuses on promotion of sustainable behavior, thus, implicitly addressing the sustainability outcomes from our framework.

Another discussed solution to enhance the sustainability of waste management services is the optimization of waste collection routes based on data transmitted by smart bins (e.g., Aazam et al., 2016; Moni et al., 2022). The distances between the smart bins are fixed and cannot be change, but the objective is to only drive to the smart bins that are above a specific fill-level and need to be emptied which avoids unnecessary travel distances of the waste collection vehicles. In contrast to the previous approaches which indirectly contribute to the sustainability outcomes the lever to enhance sustainability here is (a) the direct minimization of resource consumption during the services, and (b) the reduction of pollution by carrying out the waste collection services. From the perspective of the sustainability outcomes (a) directly contributes to the reduction of resource consumption by achieving efficient use of natural resources to carry out the waste collection service (SDG 12). Additionally, (b) contributes to the reduction of environmental pollution (SDG 3 and SDG 11). The minimization of travel distances shall reduce the consumption of fuel; thus, the emission of greenhouse gas and the pollution of air is minimized as stressed by the SDG 3 and SDG 11. These contributions are also emphasized by some researchers (e.g., Bräutigam et al., 2022; Kamm et al., 2020).

As a last set of systems pursuing to enhance waste treatment, we assess waste segregation systems that are capable to autonomously segregate waste in different types, thereby separate recyclable materials from non-recyclable materials (e.g., Janeera et al., 2021; Jimeno et al., 2021). Increasing the recycling rates reduces new resources brought into the economic cycle. Therefore, the main sustainable outcome of these systems is the reduction of resource consumption. On the one hand, the systems contribute to the SDG 12, by achieving efficient recycling. On the other hand, to the SDG 8, by providing a way for responsible consumption and production through a circular economy. We argue that in order to design sustainable SWMS, it is important to consider waste as a resource which can be reused and recovered (Esmaeilian et al., 2018; van der Aalst et al., 2023).

5. Discussion

Upon conducting our literature review, we can conclude that significant progress has been made in research on SWMS since 2016. Recent research yields various system approaches in the SWM context for different SWM strategies. We acknowledge the necessary work on the technical realization of SWMS (such as Aazam et al., 2016), since the knowledge about the efficient use of ICTs such as sensory and wireless data transfer technologies builds the basis for enhancing waste management. We found that most approaches are still in a prototyping phase (Gupta et al., 2022; Kumar et al., 2022), and only few papers provide insights on implemented and evaluated systems in real-world settings (Castro Lundin et al., 2017; Kamm et al., 2020). We also identified that research regarding the SWM strategic goal perspective of SWMS is still at the beginning. Approaches with a rather waste reduction focus were either concepts (Aguiar-Castillo et al., 2019), prototypes (Delnevo et al., 2021), or pilot studies limited to a specific time period (Briones et al., 2018). Future research should therefore strive to sufficiently consider the waste reduction perspective of SWMS with a socio-technical perspective as also postulated by Castro Lundin et al. (2017).

Furthermore, we concur on the point that for SWM both physical systems as well as information systems should be used in an IoT (Badotra et al., 2021). Building on this, we extend the current state of research by providing a literature derived overview for systems in the SWM context considering the pursued SWM strategic goal.

Turning to a sustainability perspective, the SWMSs effects on sustainable outcomes has only been considered occasionally. It is evident that most researchers implicitly assume a positive influence of the systems on sustainability. Along the waste management process in smart cities, approaches regarding the reduction of waste are mainly SWIS. Through utilizing gamification, citizens could be motivated and informed about correct waste behavior (Aguiar-Castillo et al., 2019). These systems contribute to the SDG 12, as also stated by Delnevo et al. (2021) and Hoffmann and Pfeiffer (2021). Additionally, one major objective is the reduction of resource consumption during collection and transport of waste (Gupta et al., 2022; Kamm et al., 2020). Through the reduction of waste collection vehicles' travel distances, the consumption of fuel and energy can significantly be reduced (Gupta et al., 2022). Thus, resources are preserved which contribute to SDG 8 but also to SDG 3 and SDG 11. We found that several researchers develop SWSs, regarding waste as a resource. These researchers aim to increase recycling rates which lowers the need for new resources extraction from the environment (Badotra et al., 2021) thereby contributing to SDG 8.

Another point to consider when looking at sustainability outcomes of SWM is based on the resource consumption by the used SWMS. One of the major reasons SWMS are used for is the collection, transfer and analysis of data (Kamm et al., 2020). This process consumes energy and resources itself (Bräutigam et al., 2022). Kamm et al. (2020) address this paradox in their research from two perspectives. First, the researchers emphasize the energy consumption of their approach and assess different ways of wireless data transfer technologies to minimize the energy consumption required for inquiring and transferring data. Second, they stress the point that the lack of information leads to inefficient decision making and resource wasting (e.g., fuel waste collection vehicles) in the SWM context which necessitates the use of SWMS. We argue that SWM must therefore always fulfil the principle adapted from Watson et al. (2010):
Resource consumption + SWM = reduced resource consumption

We summarize our findings along with the related research opportunities in Table 3.

Table 3. Research opportunities

Research agenda	Description
Validation of existing research	• Research regarding the use of SWMS is still at the beginning. Many papers are conceptual in nature or still in a prototyping phase. • Application of existing prototypes and concepts in different empirical contexts is necessary to validate the existing body of knowledge.
Focusing SWM strategic goals to enhance sustainability	• Most research has been drawn to the technical realization of the SWMS; the users' perspectives are thereby often neglected. • The SWM strategic goal needs to be considered in the design of SWMS to effectively contribute to the sustainability outcomes. Furthermore, the perspective of measuring and controlling progress towards the SDGs in smart cities using SWMS should be emphasized.
Regarding the systems sustainability economy	• Hardly any publication considers the resource consumption of the proposed SWMS which themselves need resources and energy. • Future research should address this paradox during the design of SWMS for instance by using economic calculations.

6. Conclusion

In this paper, we performed a literature analysis on the current state of SWMS research to understand how these systems contribute to the sustainable development in smart cities. With most research focusing on the systems' technical realization, strategic aspects are hardly regarded. Hence, we provide an association of different systems to the three major SWM strategic goals and demonstrate how the various kinds of systems contribute to different goals of sustainable development. Thus, there is still a significant gap in research that addresses the systems' contribution to sustainable development. We wish to encourage future research to consider a system's contribution to sustainable development as crucial during the development and research process. Additionally, we also see a need for more research on the socio-technical perspective of SWMS because the user's role in SWM is insufficiently considered by most publications.

Beyond these contributions, from a methodical perspective, the literature search and classification process may have inherent biases due to keyword selection and subjective interpretations. Therefore, certain publications, which other researchers may consider relevant, were not included in this study. Second, we intentionally excluded literature on SWMS in the industry context, since we were particularly interested on the systems applied in a smart city context. However, in a next step, the review scope should be broadened systematically to such research. Third, our research framework only differentiates between two sustainability outcomes based on the SDG that we regarded as the most relevant to the SWM context. This framing impacts our view on, and understanding of, existing research. Future researchers who may analyze the existing body of knowledge with different lenses may thus come up with different interpretations and insights. Nevertheless, we pointed out the tremendous contribution that ICT application in SWM can have to reach sustainability goals of smart cities and provided a fruitful ground for future research to take this contribution more into consideration when developing such systems.

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