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CASE STUDY

Demonstration of a contactless waste collection system: A Japanese case study

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Abstract

The COVID-19 pandemic has increased the need for social distancing and improved sanitation to prevent the spread of infectious diseases. In the waste management sector, protecting the safety and health of waste collection labourer has become a priority. In Japan, the labour shortage problem and ageing demography have intensified the need for contactless waste collection technology. This study responds to this need by reviewing the global practice of smart waste collection technologies and observing the situation of the Japanese waste collection system through participant observation. Based on the identified trends and status, the authors developed a contactless waste collection system and tested it on an actual working site. The demonstration showed that the system could safely lift a 700 L waste container containing 212 kg of waste to the collection truck without human contact. Labourers can be reduced from 2 to 1 person to operate the collection truck. This study also discovered the smart bin's potential to motivate the reduction of packaging waste consumption.

KEYWORDS

city design, governance, planning and policy, smart cities, smart cities applications

1 | INTRODUCTION

Under sustainable development goals (SDGs), waste management is monitored in multiple places. For example, SDG number 11 (sustainable cities and communities) and 12 (sustainable consumption and production). Within goal number 11, indicator number 11.6.1 promotes sustainable cities and communities by "*measuring the proportion of municipal solid waste collected and managed in controlled facilities out of total municipal solid waste generated by cities*" [1]. In other words, it measures the collection efficiency of waste and uses it as an indicator of a sustainable community. Using this indicator alone, Japan is doing extremely well, with a near 100% collection rate at the national scale [2]. However, under SDG number 12, the national recycling rate (indicator number 12.5.1) must be improved by reducing waste generation through prevention, reduction, recycling, and reuse [1]. In this aspect, Japan has plenty of room for improvement. Among the Organisation for Economic Cooperation and Development (OECD) countries listed in the global waste index 2022 [3], Japan is performing poorly with a 19.6% recycling rate, which makes it rank 28th among 38 countries. The global waste index considers multiple factors, such as per capita waste generated, recycled, incinerated, landfilled, open dumped, and the recycling rate.

Sensoseno highlighted the "*great recycling myth*," which is problematic for calculating the waste recycling rate. Reported national recycling rates often appear high because waste incineration is considered an energy recovery. However, incineration fundamentally differs from material recycling and must be considered the last resort for waste treatment [4, 5]. Japan acknowledged the lower priority of thermal treatment over mechanical and chemical treatment, especially for plastic waste. The government warns that thermal treatment should only be performed if other methods, such as mechanical and chemical treatment, are impossible [6, 7]. Despite this acknowledgement and seemingly impeccable waste collection practice in Japan, the recycling rate remains low, and incineration remains the main practice to treat municipal waste.

While there must be various factors that contributed to the success of South Korea, Germany, and Denmark in achieving their high recycling rates (60.8%, 47.8%, and 35.6%, respectively), there seems to be a trend of adoption of smart technologies in the waste management sector of these countries. The South Korean Ministry of Environment has been promoting smart technologies such as smartphone applications and innovative recycling technologies to improve the capacity of their citizens, governments, and the recycling industry [8]. Under Germany's Closed Substance Cycle and Waste Management Act" or *Kreislaufwirtschaftsgesetz* (KrWG), municipalities in Germany have been encouraged to adopt advanced waste collection systems, such as underground waste collection systems and automated bin emptying systems [9]. The Danish government also encourages innovation and partnerships to create new solutions for waste management [10]. A leading Danish smart waste technology company, *Nordsense*, widely provides Denmark's smart waste container, waste transport tracking, and routing optimisation with information and communication technologies, such as big data analysis, the Internet of Things (IoT), and artificial intelligence [11].

On the other hand, the current COVID-19 pandemic has stressed the importance of smart waste technologies, particularly contactless waste collection [12]. As Japan faces a serious declining population and an aging demographic [13], the importance of labourer's health and safety protection is more intense than ever.

The aim of this study is therefore threefold: (1) to understand the current state and challenges of municipal waste collection in Japan, (2) to develop and demonstrate a contactless waste collection technology in the actual working site of a Japanese city, and (3) to look for a pointer of how smart technology may help improve Japan's material recycling rate. To achieve these goals, we performed (1) literature reviews, (2) participant observation of an actual waste collection in a Japanese city, (3) developed and demonstrated a technology based on the observation results, and (4) discussed the potential challenges and strategies with experts in the field.

2 | LITERATURE REVIEWS

2.1 | Trends and potential benefits of smart technology adoption in waste management

Using smart technologies can improve waste management process efficiency, sustainability, and effectiveness [14]. These opportunities have driven the growing innovation and adoption of the technology. Examples of smart technology adoption in waste management are smart bin sensors [15], IoT integration [16], data analytics and management [11], automation and robotics [17], mobile applications and digital platforms [18], and blockchain for transparency and traceability [19].

The first step for smart waste management is a smart bin for efficient waste collection [20]. IoT connected to the sensor in the bin is used to report the level of waste content. Reported data are then analysed to make predictions of the social waste-producing behaviour of the people who use the bins. Such predictions can be used for prompt collection and to avoid the unnecessary collection of empty bins [21]. It is important to collect waste bins promptly to reduce the risks of spreading disease [20, 22], and larger bins are recommended for easy collection [22].

The wireless nature of smart bins requires an optimal transportation route to warrant lower cost and energy consumption [21–23]. Furthermore, using data analytics and IoT technology-based optimisation strategies, the collection frequency can also be based on temperature to avoid smell. Other potential uses of smart technologies in waste management are to create waste maps, manage smart bin placement, and change current pricing and business models of waste collection services [24].

The identified benefits of data-driven waste management are promising. For example, a decrease in the number of employees for waste collection service, a decrease in overall workload and work hours, a decrease in costs for maintenance and operation, a decrease in fuel consumption and CO2 emissions, fewer overfilled containers resulting in cleaner cities, better sustainability and environmental friendliness, an increase in transparency about waste generation, and improved communication between municipalities [24]. The benefits are not limited to waste management operators but also to civil society in improving their awareness of responsible waste disposal. A study demonstrating the prototype of a smart bin connected to a smartphone monitoring application showed that it enables people to evaluate and handle their waste more responsibly [25].

The combination of the smart technologies mentioned is often called smart waste management. The authors in Ref. [26] defined smart waste management as waste management that is globally connected so that decision-making can be considered based on waste data and information delivered through IoT systems using automated technology that increases efficiency. The study also summarised the characteristics of smart waste management as dynamic, unique, adaptive, flexible, and integrated.

2.2 | Smart waste management development in Japan

IoT technology is not a foreigner in Japan. Waste facilities in the country are connected to a central data system where information such as toxins, emissions, and technical troubles are reported in real-time to obtain an immediate response. Supported by this technology, of the nearly 44 million tons of waste generated annually in Japan, almost 100% is collected, and only 1% is landfilled. The remainder is incinerated for energy recovery or recycled [2].

On the other hand, Japan is also Asia's largest emitter of plastic waste. According to the "Plastic Atlas Asia Edition," Japan ranks second only after the US. The average number of people in Japan who consume plastic bags is 11 times higher than that in Indonesia and 17 times higher than that in the United Kingdom (UK). Moreover, an average Japanese person buys 183 PET bottles annually, resulting in 23.2 billion bottles nationwide. While PET bottle collection and recycling rates are high at 93% and 85%, respectively, only 22% of the total collected plastic waste (that includes non-PET) is recycled. This number already includes those recycled in Japan and overseas. From 1988 to 2016, Japan was the world's third largest plastic waste exporter, just behind Hong Kong and the US. Approximately 70% of these exports were shipped to China [27].

Since the 2018 China plastic waste import ban, plastic waste exports from Japan have overflowed to Southeast Asian countries, which also eventually banned the practice. Japan is left with the option of expanding its recycling market domestically. The author in Ref. [27] reported that domestic recycling companies have increased their investment in recycling plants. Examples include Daiei Kankyo in Osaka City, Japan Environment PLANning (JPLAN) in Kawasaki City, and Kitakyushu City.

Although it is important to accommodate the increased demand for recycling at the "end of the pipe," it is more important to "close the tap." New regulations have emerged following this way of thinking. Since July 1, 2020, retailers must charge consumers for consuming single-use plastic bags [28]. The authors observed this practice in supermarkets, convenience stores, and department stores. Most retailers charge approximately 3 to 20 JPY per disposable shopping bag, similar to or more than those practiced in the UK and the US [29]. However, wrapping a single fresh produce or snack is still observable.

The fact that Japan does not charge households based on the weight of waste produced, like those practiced in Germany, might be one key contributor to packaging overuse in Japan. Germany practices the "pay-as-you-throw" approach, which is an adoption of the "polluters pay principle" that places direct responsibility on waste generators [30]. The volume or weight of the waste disposed of determines the charge of waste management in this approach. In Japan, the cost of waste management does not depend on how much the inhabitants produce and is paid through taxes collected by the local government.

A Japanese study estimated the weight of waste collected in specific areas of Kanazawa City [31]. However, the aim of measuring weight was not to determine payments of waste emitters but rather for workload balancing calculations. Conventionally, waste in Japan is only weighted in the final disposal area. Therefore, the study installed a vibration-based sensor in the garbage collection truck to identify the weight of garbage scooped by the rotation plate into the truck chamber. The sensor data are collected to estimate the regional amount of solid waste in each collection area to plan the collection trucks' workload balancing [31]. Another smart waste management study in Japan was performed by the authors in Ref. [32]. The study simulates using a geographical information system and a smart recycling centre for three Tokyo Metropolitan Area satellite cities. The study showed that the strategy could reduce CO2 and overall costs.

The private sector has also performed pilot projects on smart waste management in Japan. For example, in October 2020, the Morinaga group, a packaged food company, sponsored the first smart public waste bin project. The bins supplied by Force Tech Co., Ltd. are equipped with sensors and IoT technology that detects how full the bins have become and reports them through a cloud server over a 3G network. When the bin is full, a compactor inside the unit will compress the waste so that the bin can capacity is five to six times more waste compared to ordinary trash bins of the same size. While it sounds promising, corporate advertising is not typically allowed in public facilities in Japan. Therefore, the private sector must be creative to go about this regulation, for example, by proposing it as part of an SDG initiative [33].

The pandemic has caused a change in the type and volume of waste in Japan. More packaging waste is produced as more people order their daily necessities online. Single-use masks and testing kits may also pose infection risks to waste collection personnel [12]. On the government side, the Japan Ministry of Environment has started developing a contactless garbage collection system for household waste to reduce the risk of COVID-19 infections [34]. This study presents the current state of technological development contributing to that initiative.

In our previous study [12], we highlighted the enactment of the Super City Act on May 27, 2020. This act allows the collection and organisation of data requested by business entities to national and local governments, including information about waste generation and treatment. Such improved transparency opens opportunities to develop more innovative, safe, and efficient garbage collections, such as smart garbage bins with sensors, compression functions, and a robotic arm [12]. The present study demonstrates the simulation of those ideas.

2.3 | Development of contactless waste collection

There are three identified potential areas in waste management where contactless technology can be introduced: (1) customer acquisition, (2) waste collection and processing, and (3) waste recycling [35] (Figure 1). Within the waste collection and processing area, there are three stages that can be served in a contactless manner: collection, transfer, and processing. First, in the collection stage, a streamlined collection process, smart waste collection, and route optimisation for waste collection using big data can decrease employee exposure. Automatic sanitation of the waste bins during pick up can also improve sanitation of the collection activity. Second, sensors can automate transfer station operations and maintenance in the transfer stage. Finally, automated waste sorting, recovery, segregation, baling processes, and contactless digital payments or paperless receipts can be applied in the process stage.

Demonstrations of smart collection using waste collection robots and route optimisation have been performed in many

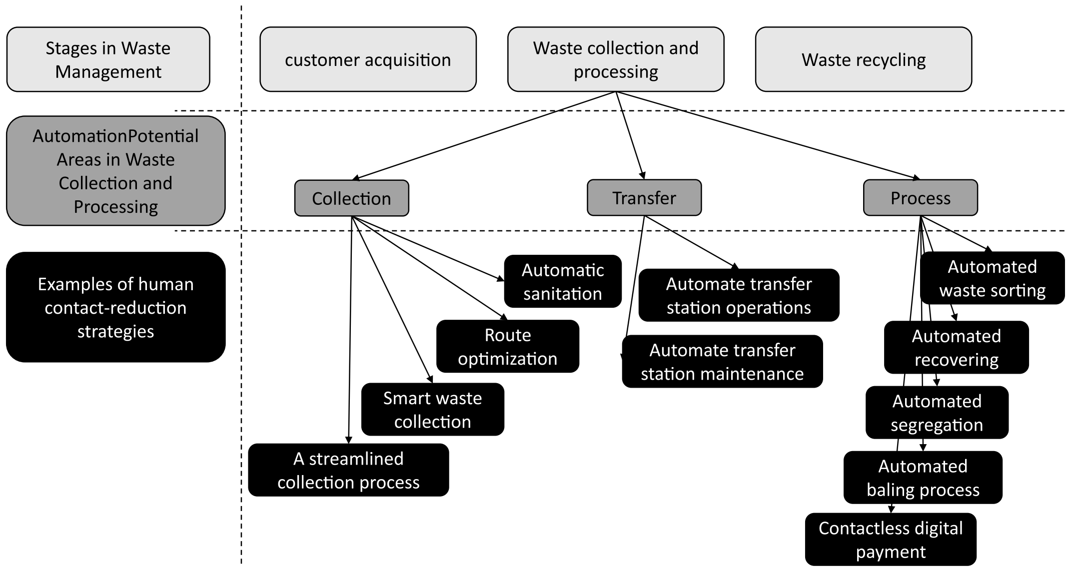


FIGURE 1 Waste management potential improvement areas with contactless technology (summarised by the author from Ref. [35]).

studies [20, 21, 24, 25, 36]. Elements used in the simulation are typically a smart bin, an IoT system to transfer data, and a collection robot that receives prompts from the information received about the optimised routes to pick up, carry, and dump the waste content to a collection truck.

In the Massachusetts Institute of Technology laboratory in the US, a waste-collecting robot was demonstrated by the authors in Ref. [36]. The robot was equipped with a sensor and performed in the following states: (1) the wandering state, where the robot estimates the distance of roads to cross and travel sufficiently with the remaining battery; (2) the recharging state, when the battery is not sufficient and returning to the charging station is needed; and (3) the carry state, which is when the robot approaches the trash bin, reads its ID and information about the waste content status, and then carries it for transfer if the content is confirmed. In the carrying state, the robot will ignore other trash bins on the way.

In Sweden, a pilot project of the autonomous waste truck by Volvo and Renova used the light detection and ranging surveying method to measure the distance to a target by illuminating that target with pulsed laser light and measuring the reflected pulses with a sensor. The truck uses a vehicle data hub solution on the 2-compartment vehicle with the in-cab on-board computer. These elements allow the truck to record relevant data for its pay-by-weight operation [37].

In China, China Tianying Inc. operates a contactless waste collection system that can classify waste and transfer waste from the waste containers to the collection truck to be transported to the final disposal facility. The system is already in full operation in two cities in China: Guyuan City in Ningxia Province and Xi'an City in Shaanxi Province, serving hundreds of thousands of people with smart data analytics that adjust the service with the resident's waste disposal habits [38].

The three case studies imply the following messages: (1) that the training of the mobility robot for waste collection is likely done in a laboratory/educational institution setting, (2) to test the technology on the field, a collaboration with the private sector is likely needed, and (3) although automated and contactless waste collection at the higher level of readiness is still quite rare, the full commercialised operation in China is encouraging for feasibility perspectives.

3 | MATERIALS AND METHODS

The methodological framework employed in this study is illustrated in Figure 2. First, we identified the research gap in the literature review. Then, we identified the current state and challenges faced by municipal waste collection labourers in Japan through participant observation. Participant observation is a data collection method widely used in qualitative social research [39]. The method is popular among anthropologists and social scientists, who take part in a group of people's daily activities, rituals, interactions, and events to learn their life routines and culture [40]. Previous studies have shown that properly understanding a target community's social needs and challenges is key to sustainable technology innovation [41, 42]. As we seek to understand the daily challenges faced by municipal waste collectors in Japan, we performed an observation in this study by participating in waste collection by riding a waste collection truck with the truck driver on a regular operation day and assisting in collecting waste disposed of by residents around a city in Japan.

Other methods could help to identify smart technology needs, such as the enactment method [43, 44], focus group discussion [45], survey questionnaires [46, 47], or interviews [48] with targeted potential users. In the enactment method, a sample of the target population would pretend to use the proposed technology and then provide feedback for an appropriate design. In the focus group discussion, a sample of

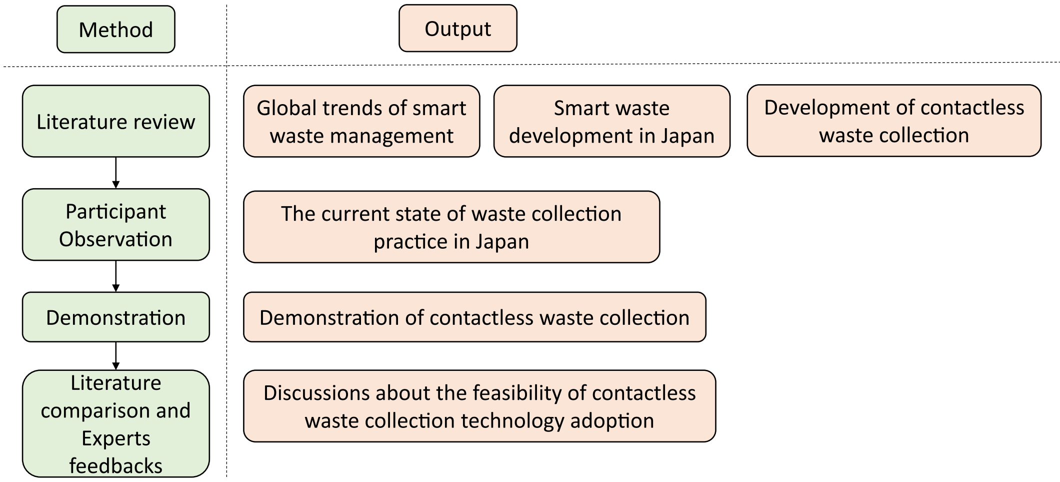


FIGURE 2 Methodological framework.

the targeted population comes together to discuss and suggest a technological design. A survey questionnaire usually involves a larger sample of the targeted population who answer a set of questions determined by the researcher. Finally, in the interview approach, the researcher directly asks the questions to the respondents. All these methodologies have advantages and disadvantages. However, none of them can serve this study's purpose and the participant observation method. In a participant observation method, researchers can witness and experience the daily activities and challenges of waste collectors. Enactment is not required because participant observation allows the researcher and the potential technology users to have an actual experience.

Moreover, more natural and personal discussions can emerge between the researchers and potential technology users during the experience. Finally, experiencing waste collection activities first-hand could lead to a good "understanding of the users' pain," a key factor mentioned in Ref. [49] for a successful technology. The drawback of the participant observation method is that it requires the potential technology user to allow the researcher to join their day-to-day activities and positively cooperate in the technology development process. As it may intervene with the potential technology user's daily routines, the number of institutions that would cooperate and the length of time the researchers allowed to participate may be limited.

In this study, we cooperate with one Japanese city where the author joined the waste collection activity for a day. The author carried a camera around the neck to take videos along the waste collection trip (Figure 3). In this participant observation trip, we aimed to understand (1) the types of temporary disposal sites, (2) the prevalence and characteristics of each temporary disposal type, (3) the speed of waste collection, and (4) the challenges faced by the waste collector. The observation results are summarised in Section 3.1 and Table 1. We prepared a contactless waste collection system (Section 3.2) based on our findings and tested it in an actual environment. We simulated whether our designed system could approach the waste container, carry it, and lift it to dump the waste content into the truck. Finally, we consulted three Japanese waste management experts to discuss what factors need to be addressed to adopt our demonstrated contactless collection technology nationally in Japan. Figure 2 summarises the research framework of this study.

FIGURE 3 Camera to record the waste collection activities.

3.1 | Observation of the current state of municipal waste collection in Japan and device testing

To understand the state and challenges faced by waste collection labourers in Japan, we participated in a waste collection activity by riding the truck and performing the tasks usually performed by actual waste collection labourers. The collection truck is equipped with a packing chamber, which is also called the packer vehicle. The camera carried by the author on the neck to record the waste collection activities is depicted in Figure 3.

Something that we did not expect from the observation was the very high prevalence of the side-road type of temporary disposal site (90%) compared to the other two identified types (storage rooms and containers). We also found that carrying, lifting, and dumping large waste containers into the truck was the heaviest and most laborious task. On the other hand, the container type allows the quickest time to collect large amounts of waste bags at once.

3.2 | Preparation of contactless waste collection demonstration

Making use of the information gathered from the participant observation, we developed an automated and contactless waste collection system. We demonstrate the system to test whether it can carry and dump a large waste container (700 L) filled to its maximum capacity (Figure 4a) We also wanted to know if the proposed system can help reduce the number of labourers working in waste collection activities.

TABLE 1 Classification of temporary waste disposal.

Types of temporary waste disposal site	Type ① Roadside, on-the-road, fenced site	Type ② Box, basket, storage room	Type ③ Waste containers
Image			
Number of the temporary disposal site	225	21	4
Rate of prevalence (%)	90	8.4	1.6
Typically, used by	Detached houses	Collective housing	Housing complexes with many residents
Number of waste bags in each site	1 to 20	5 to 40	30 to 50
Collection time per location (seconds)	1 to 4	1 to 4	1 to 2

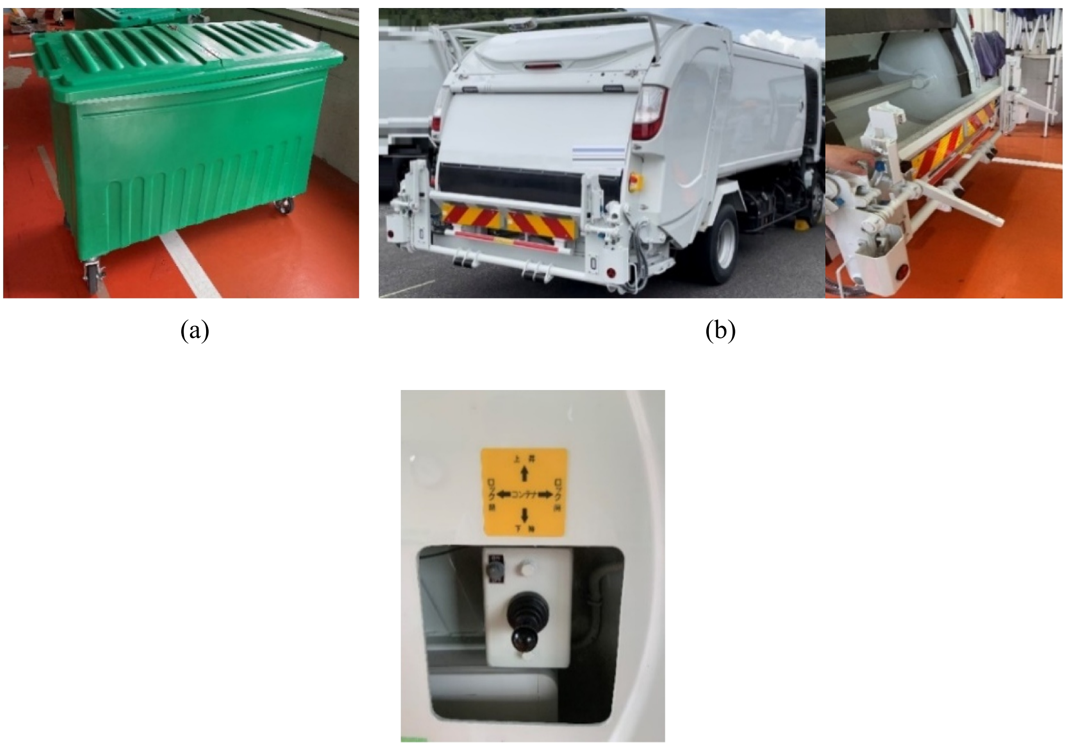
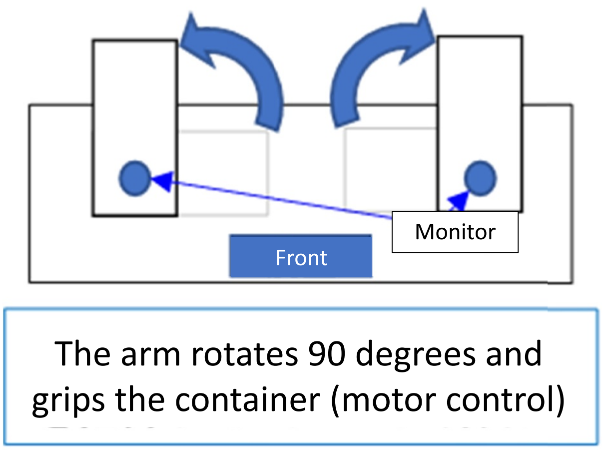


FIGURE 4 Automatic dumping device in a contactless waste collection system. (a) 700 L garbage container compatible with a dumping device. (b) An automatic dumping device attached to a packer vehicle. (c) Operational button.

A manual dumping device is installed in the current Japanese packer vehicles. This dumping device needs to be manually gripped to the dumping device by the metal rod attached to the top of the container (Figure 4a). After gripping manually, the container can be dumped by pressing the button on the side of the vehicle. However, the rod must be manually unlocked again [50]. In the demonstration of this study, we installed an automatic dumping device (Figure 4b) on a waste collection truck (also known as a packer vehicle). We use a regular 3-t capacity packer vehicle that is regularly used for waste collection in Japan. The steps of the automated contactless dumping device are as follows: the dumping device (1) attaches itself to the upper side of the 700 L waste container using a gripping mechanism, (2) lifts the container, and (3) tilts the container to dump the waste content into the hopper. The claws on the dumping device that grips waste containers can be automatically locked and unlocked by an operator by pushing the operating button (Figure 4c).

The automated contactless dumping device allowed the container emptying mechanism to be automated. However, a mobility device is required to transport the waste container to the truck. We developed the mobility device in our previous study [50] (Figure 5a). The mobility device also has an automatic gripping mechanism (Figure 5b). In the previous study,

(a)



(b)

FIGURE 5 Mobility device to automate waste container transportation.

we successfully demonstrated the mobility device to tow a filled 700 L garbage container.

To demonstrate whether these two elements can work smoothly together, we filled 5–14 kg of waste into various waste bags imitating the situation investigated during the participant observation. As a result, we found that 212 kg of waste can fill the prepared 700 L container (Figure 6).

We simulated the actual waste collection environment, including waste placement, distance, and road surface condition (Figure 7a). Specifically, two 700 L waste containers and one mobility device were placed away from each other. The placement distances of these objects are shown in Figure 7b. For comparison, we also experimented with manually moving the container by two labourers under the same conditions.

4 | RESULTS

4.1 | Current state of municipal waste collection in Japan and device testing results

Based on the author's participant observation in collecting waste using the packer vehicle around the city, temporary disposal sites and their characteristics are summarised in Table 1. There are three main types of temporary disposal sites observed.

The first type is where waste bags are placed on the roadside, road, or fenced site. This type is often seen on roads lined with detached houses. The waste bags are usually piled up at intervals on the corners of the roads. To collect waste bags disposed of in this way, labourers must pick and dump the bags into the packer car manually. At the same time, they must be running along the road beside the moving vehicle. Although it only takes 1–4 s to dump the bags from each site, the burden is quite heavy, representing 90% of the total waste that must be collected. Furthermore, labourers must continuously run to catch up with the moving vehicle.

The second temporary disposal type uses a box, a basket, or a storage room to store the waste bags. This type is often seen in collective housing. The boxes are usually lined up in a direction that makes it easy for residents to dispose of their waste bags. The waste bags are sometimes stored in storage rooms with doors or under a small, roofed area. The labourers must manually pick and dump the bags into the packer vehicle for this disposal site. The time required to complete the collection task at each site is longer because there are more bags to pick and dump, but the labourers do not need to run as the vehicle is parked near the site.

The third type is a container compatible with the dumping device attached to the packer vehicle. This type is often seen in large housing complexes. Usually, waste bags are placed in the container, and the container is lined up in a direction that makes it easy to tilt into the packer vehicle. In this type of temporary disposal site, although the number of bags is more than the other two types, the time required to dump them into the vehicle is the shortest. It takes a mere 1–2 s per container to empty each container. However, carrying and manually attaching the containers was hard work. It must be done by two labourers, and based on our experiment, the full weight capacity of one container is approximately 212 kg. While we did not weigh the total weight of the collected waste bags for the corresponding types, the weight range of each bag collected was between less than 1 and 13.9 kg.

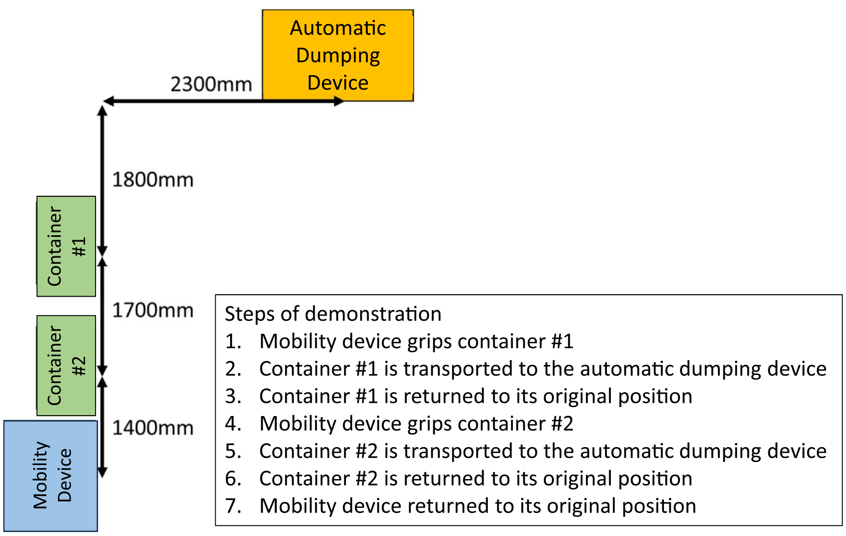
In Japan, the time for households to take out their filled waste bags is determined. For example, every Wednesday and Saturday before 8 AM for burnable in wards X, Y, and Z. The actual collection takes place within hours after these waste bags are placed. Therefore, the time when waste is placed in these temporary disposal sites is limited (a few hours in the allocated days). Increasing time efficiency is highly desirable to reduce the cost of human labourers.

4.2 | Demonstration result

The automatic transport and dumping demonstration using the contactless system developed in this study confirmed that the

FIGURE 6 The simulated waste used for the demonstration and the state where all the waste bags are loaded into the 700 L waste container.

(a)



(b)

FIGURE 7 Demonstration of contactless waste collection.

operation could be performed successfully without any problems. Furthermore, no human contact with the waste bins or bags was required in the demonstration. These results were observed for handling 212 kg of waste and 100 kg of waste.

However, the contactless system required 213 s (Figure 8) to complete the steps for collection safely (described in Figure 7b). This is a significant increase compared to the time required if the tasks were done manually by human labourers, which only takes 63 s (Figure 9). To complete the task of contactless waste collection where the mobility device carries two waste containers and dumps the waste content of the garbage truck, the following actions are involved:

1. The mobility device carries a waste container to a position where it can be locked with an inverting device.
2. One labourer operates the lever of the dumping device to empty the contents of the waste container into the garbage truck.
3. Same labourer prompts the unlocking mechanism, and the mobility device returns the garbage container to its original location.
4. Steps 1–3 are repeated for the second container.

Meanwhile, in the case of manually completing the tasks by two labourers, the following actions are involved:

1. The first labourer manually pushes the trash container into a position where the dumping device can lock it.
2. The second labourer operates the inverter lever to dump the contents of the garbage container into the garbage truck.

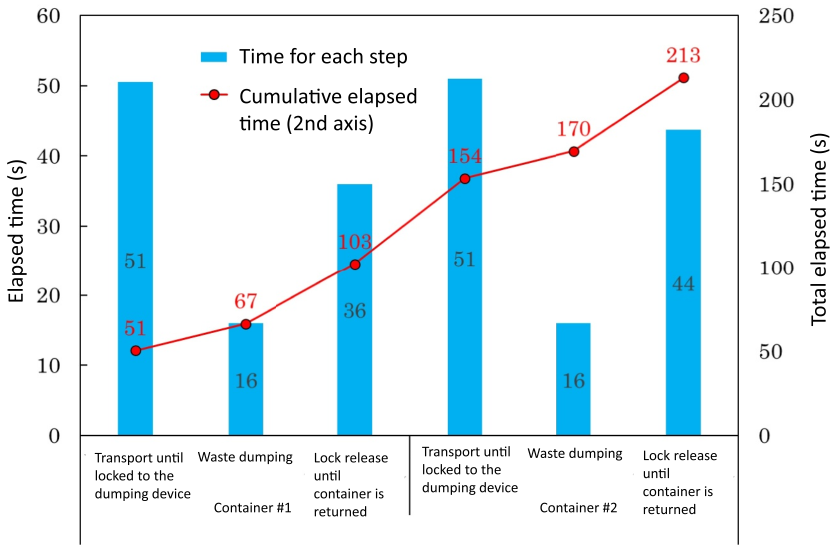


FIGURE 8 Container collection time manually by the contactless system.

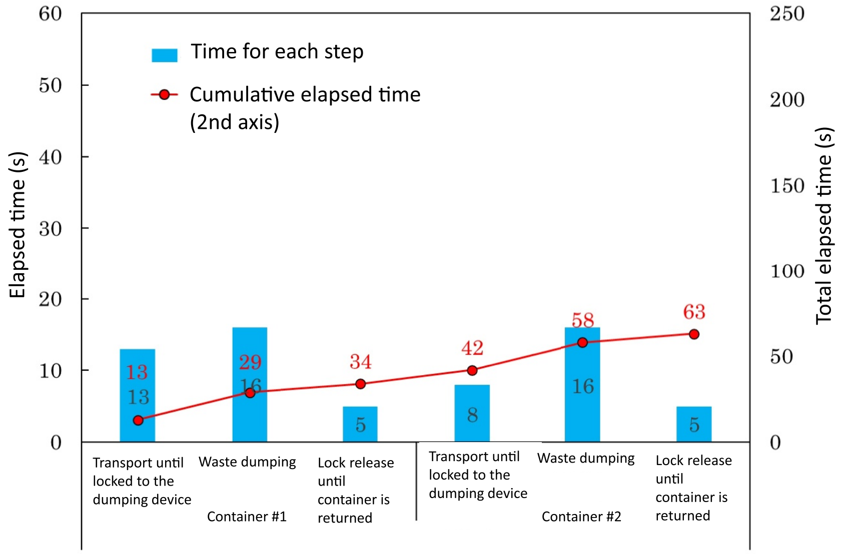


FIGURE 9 Container collection time by human labourers.

3. The second labourer unlocks the dumping device, and the first labourer lifts the container. Then, the first labourer returns the container to its original location.
4. Steps 1–3 are repeated for the second container.

Delegating the work to the contactless system can reduce the number of labourers; however, the time required increases. It should also be noted that we only used one mobility device in the demonstration. The time required is expected to be significantly reduced if multiple mobility devices operate simultaneously. Moreover, humans can experience fatigue, whereas the device would not. Therefore, it is expected that the speed of human labourers would decrease if the same task had to be performed multiple times.

To imagine the degree of fatigue and risks or injury faced by waste collection labourers, it might be useful to understand the weight of each waste bag. A study in Fukuoka City, Japan, measured the weight of waste bags for each type of waste collected [51] (Table 2). A range of average weights between 1.3 and 4.2 kg per waste bag must be collected by labourers, mostly while running beside a moving truck. Meanwhile, in our participant observation study, the maximum observed weight of the collected waste bag was 13.9 kg.

Additionally, we observed that various road elevations exist in the actual waste collection environment. Therefore, we also tested a light slope of 2°. We confirmed that the system can still work smoothly at that elevation level, even with a full load.

5 | DISCUSSIONS

A contactless system is needed to reduce the contact between waste collection labourers with household waste and other labourers to lower the risk of disease infection. The need is becoming more pronounced, especially after the COVID-19 pandemic [12]. The results from the demonstration of a contactless collection system developed in this study showed both the technology's advantages and bottlenecks. The advantages are (1) increased labourer safety due to eliminating human contact with waste and waste containers and (2) reduced human labourer because only one person is required to monitor automated processes. On the other hand, the bottleneck to be addressed is the time required to perform the collection safely and more testing for more tricky topography in the field. The following subsections discuss in more detail are the technical and social conditioning that must be performed to adopt the technology on a larger scale.

TABLE 2 Average weight of waste bags collected by type [51].

Type of waste and size of waste bags	Average weight (g)
Burnable waste (kitchen waste and non-recyclables)	
45 L bag	3907
30 L bag	2528
15 L bag	1541
Non-burnable waste (plastic waste, packaging waste, and recyclables)	
45 L bag	4168
30 L bag	2366
15 L bag	1295

5.1 | Required technical improvements

It took approximately 3.4 times longer for the contactless system to collect waste safely in the demonstration of this study. This drawback is mainly caused by multiple mobility devices performing the task. The speed may be improved by increasing the number of mobility devices. Developing swarm control technology for this particular purpose is required to enable multiple mobility devices to work together. For example, to set the travel routes of each mobile device and ensure its safety.

Additionally, other things can be done to increase the speed, for example, by integrating a balancing technology into the modular mobility system. The suspension technology is usually required to achieve balance when a moving device carries a load at speed. Such suspension technology for transporting robots has recently been commercialised in restaurants for ordering food delivery to customers [52, 53]. However, the weight of restaurant meals significantly differs from that of waste containers in this study. Another challenge would be, as there will be a variance of slopes and smoothness of the road surface, the robot must be trained to overcome this variation signalled by a sensor communicating with the swarm control. Since a robot makes responses and decisions based on a preregistered set of conditions, "training" refers to adding more variations of the registered types and possibilities of the obstacles the robot may encounter. In this way, the robot's "intellectual" level can be improved to make a better judgement for smoother and safer operation.

It may require some time until elements of contactless collection systems mature, but experiments, simulations, and demonstration projects are taking place around the world [20, 21, 54, 55]. The present study contributes to these global efforts to create a safer environment for a waste collection labourer and a more sustainable waste management practice. Revisiting the US [36], Swedish [37], and Chinese [38] case studies reviewed in this study, our study is positioned at a similar level to the US study, which is at a readiness level between the research stage and the early stage of demonstration. However, we have already collaborated with the practitioners, which is similar to the Swedish and Chinese cases. Our study's technical findings, such as the need for simultaneously operating multiple mobility devices, may speed up the waste collection process even for the fully commercialised Chinese case study.

5.2 | Social conditionings for and potential benefits of contactless collection system adoption

With Japan's near-perfect waste collection rate [2], some social restraints may likely occur against changes in long-standing practices. The fact that the present high waste collection rate achievement is primarily contributed by human efforts [27] may mean that a significant effort in social conditioning is needed.

Currently, the contactless collection system demonstrated in this study only applies to type 3 (the container type) of the temporary disposal site described in Table 1 [34]. Furthermore, an anonymous Japanese waste management expert consulted in this study noted the high number of small alleys in Japanese neighbourhoods that would not benefit from the proposed technology. This anonymous expert referred to type 1 of the temporary disposal site described in Table 1. A solution for this problem could be to place the containers on larger roads [34]. While this idea might work, the residents of detached houses in the small alleys must be willing to carry their waste to the containers on the bigger roads. Looking at the history of waste management in Japan, residents' awareness and cooperation were gainable through continuous campaigns, educational events, and activities held by the local city governments, schools, and neighbourhood associations [56]. However, looking at the rate of population ageing, more people will face physical challenges in carrying their waste to the temporary disposal site further from their houses due to their advanced age and lower physical strength. The weight of collected waste can be reduced by increasing the collection frequency [57]. If the number of mobility devices can be increased at a minimal cost, the collection frequency can be increased without increasing human labourer and collection points.

With Japan facing a serious labour shortage in recent years [58–61], employing robots for mechanical work such as waste collection will become indispensable. Furthermore, hard mechanical work such as waste collection requires intensive physical work, especially when the weather is bad. Furthermore, with the severe Japanese ageing and declining population rate [13, 62], similar efforts taken to achieve residents' cooperation for waste separation in the past should be repeated. This effort is needed to refresh and gain people's cooperation with various new smart waste collection technologies. The efforts include socialisation through neighbourhood associations, schools, and cooperation with various stakeholders.

Finally, regarding reducing Japan's plastics and packaging waste rate, using large containers would allow local weighting. Improved transparency of who disposes of how much waste such as this can allow the adoption of the "polluters pay principle" practiced by more packaging-efficient consumer countries in the European region [30, 63]. The current condition in Japan regarding packaging and high plastic consumption [27] might be addressed if financial responsibility is directly addressed to consumers.

Another benefit that can be gained from using containers would be to attach sensors to make it a smart container. In this way, the problem of collection truck task distribution [31] could be improved because the state of waste content in the container can be informed through the IoT system.

The developed technology is highly intuitive (similar to operating a simple home electric appliance) and requires no extensive training. However, explaining how to implement remote control, risk prevention, and troubleshooting is necessary. A manual is prepared, and, in our estimation, mastering everything would require less than 6 h of on-the-job training than can be completed in a day.

5.3 | The potential role of a contactless waste collection system in supporting the Japanese ageing population

Japan is the world's 1st leading country regarding the magnitude and speed of population ageing [13]. Ageing is associated with declining cognitive functions [64] and physical strengths [65]. Older adults are also more susceptible to viral diseases [66]. The author in Ref. [64] discovered that some of the cognitive declines associated with normal ageing are (1) the skill to process or transform information to make a decision, (2) the speed of information processing, (3) the skill that allows us to work with information without losing track of what we are doing, and (4) the ability to execute the decision made based on the processed information.

In the scope of waste separation and collection, older adults in their advanced age may face difficulty in (1) properly separating the waste (particularly for plastic and packaging waste that requires peeling and separating various types of plastics and other materials), (2) carrying the waste to temporary disposal sites, and (3) the risk of infection in temporary disposal sites.

The contactless waste collection system proposed in this study has the potential to address the 2nd (carrying) and 3rd (infection) challenges. Particularly, the modular mobility device could be further designed and trained to pick up waste in closer proximity for the older population. Through individual collection, older adults are prevented from being in contact with waste disposed of by others, which diseases may contaminate.

6 | CONCLUSION

This study reviewed the current trend of smart waste management technologies and the development of contactless waste collection technology, both in the world and Japan. It was found that there is a global movement towards automatising waste collection and processing using smart technologies such as smart bin sensors, IoT integration, data analytics and management, automation, mobile robotics applications, and digital platforms. However, while IoT integration, data analytics, and management have been well practiced in Japanese waste management systems, adopting smart and contactless waste collection is new. Furthermore, despite the high waste collection rate, the recycling rate in Japan is relatively low among the OECD countries, and plastic consumption is among the highest in the world.

To understand the situation of waste collection and the challenges faced by waste collection labourers in Japan, the authors conducted a participant observation study by experiencing first-hand the role of waste collection labourers around a Japanese city's neighbourhood. We found that three types of temporary disposal sites can be found in a typical Japanese neighbourhood. The first type is the plastic bags piled on the side and corners of the road, typically used by detached houses. The second type is inside a box, a storage room, or a roofed area, typically used by collective housings. The third type is in a large waste container typically used in large-sized housing complexes. The third type was the most time-effective, requiring at least two labourers to completely empty the container.

To reduce the burden of human labourers to lift, carry, and attach large waste containers from large housing complexes, this study developed and demonstrated the performance of an automated contactless waste collection system with two elements. The first element is the automatic dumping device, and the second is the mobility to transport the container towards the truck. The results showed that while the system can replace the work of labourers, it works rather slower than a human labourer.

On the other hand, Japan is facing the following problems: (1) an ageing society, (2) a declining population, (3) labour shortage, (4) packaging and plastic overconsumption, and (5) a poor recycling rate. Therefore, some technical and social conditions are required to improve the speed of the proposed automated contactless collection system and address the possible social constraints in technology implementation at a national level.

The required technical improvements are as follows:

1. Additional technological elements, such as suspension for the stabilisation of the modular mobility device, must be adopted to improve the speed of waste collection operation by using the contactless collection system.
2. Sensors and data analysis systems must be attached to the container and the modular mobility device to help the transport mechanism cope with various road surfaces and elevations.
3. An integrated swarm control technology must be developed to simultaneously operate multiple modular mobility devices.

The required social conditionings are as follows:

1. Changing type 1 and type 2 temporary disposal sites into type 3 is compatible with the contactless waste collection system.
2. Socialisation of the proposed system, especially for residents living in detached houses who have been disposing of their waste on the side of small alleys.

The potential benefits of adopting the contactless collection system are as follows:

1. Helping with the labour shortage situation.
2. Improving waste collection labourer's safety.
3. By adding sensors to the container, the following benefits can be attained:
   a. Increased transparency of waste weight and volume generated by residents.
   b. Allowing the possibility of polluters' pay principal adoption.
   c. It increased collection efficiency due to more accurate task distribution based on the waste content detected by the sensors.

To realise these proposed strategies, efforts from various stakeholders are needed. Technology developers must increase the readiness levels of each element in the system. The government, local government, educational institutions, and neighbourhood associations must work on the socialisation of the new system to gain citizen cooperation.

This study has demonstrated the first simulation of a contactless waste collection system in Japan. However, there are technical limitations, such as the number of variations in simulation conditions and missing elements of the system. Due to the research project's time and budget limitations, these limitations are reserved for further studies. Furthermore, when the technology achieves a higher level of readiness, we plan to perform studies from financial and social perspectives. For example, a comparative financial study between manual and automated waste collection and a survey of the Japanese population regarding their acceptance of possible transformation of the waste collection system must be conducted to strategise the required social conditioning.

Considering the progress of other contactless technology developments triggered by the pandemic, there is a promising global future for the proposed technology's readiness progress. Moreover, reflecting on the past success of Japanese residents' compliance with waste separation practices, Japan certainly has what it takes to allow the required sociotechnological intervention.

AUTHOR CONTRIBUTIONS

Akihisa Ogawa: Data curation; formal analysis; investigation; validation; visualisation; writing – original draft. **Andante Hadi Pandyaswargo**: Conceptualisation; funding acquisition; methodology; project administration; resources; supervision; visualisation; writing – original draft; writing – review and editing. **Ryota Tsubouchi**: Data curation; investigation; project administration; software. **Hiroshi Onoda**: Conceptualisation; funding acquisition; project administration; resources; supervision.

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CONFLICT OF INTEREST STATEMENT

All authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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