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(Citation)
Heliyon,10(7):e29011

(Issue Date)
2024-04-15

(Resource Type)
journal article

(Version)
Version of Record

Heliyon 10 (2024) e29011

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Role and limitations of the in-store waste collection system at supermarkets

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ARTICLE INFO

Keywords:
In-store waste collection
Municipal collection
Recyclables
Cluster analysis
Environmental and cost analysis

ABSTRACT

In-store collection is defined as the activity of installing collection boxes at retail stores, such as supermarkets, for the collection of recyclables. The use of in-store collection reduces the burden of garbage collection in municipalities, which may reduce administrative and environmental burdens and costs. Previous discussions on in-store collection have ignored environmental impacts and the costs to consumers and that supermarkets should become players in the collection of recyclables. Therefore, it is necessary to clarify whether the use of in-store collection effectively contributes to a reduction in environmental burdens and costs for society. This study aimed to analyze the environmental burden and costs associated with integrating in-store collection into municipal solid waste (MSW) management systems. A total of 1734 municipalities in Japan were classified into six clusters using cluster analysis to analyze the characteristics of municipal and in-store collection by municipality. Model cities representing each cluster were created, and three scenarios were established to analyze the CO_2 emissions and costs associated with municipal and in-store collection. The scenarios were cases where recyclables were collected through in-store collection (Scenario 1), recyclables were collected through municipal collection (Scenario 2), and both in-store collection and municipal collection were combined, similar to the current system (Scenario 3). The reduction in CO_2 emissions in each model city in Scenario 1 was −37.0 to 53.5% compared to that in Scenario 3. There was a 0.90–1.96-fold increase in cost in Scenario 1 relative to Scenario 3. Suggestions for the appropriate implementation of in-store collection are proposed based on these results. For example, an increase in in-store collection reduces CO_2 emissions but leads to an increase in costs. When integrating in-store collection into an MSW management system, reviewing the municipal collection system is necessary.

1. Introduction

In Japan, garbage collection is traditionally handled by municipalities. Although collection systems, such as the number of garbage categories, differ from municipality to municipality, garbage has been separated within households, and municipalities have collected garbage by type, either through stations or curbside collection. Such a system presently supports Japan's municipal solid waste (MSW) management. However, indications are that the increase in the number of garbage categories to prioritize recyclables has exerted pressure on local finances due to the cost burden on municipal finances [1]. From the perspective of building a sustainable society,

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https://doi.org/10.1016/j.heliyon.2024.e29011
Received 15 January 2024; Received in revised form 27 March 2024; Accepted 28 March 2024
Available online 3 April 2024

there is increasing pressure for recycling, in addition to reducing and reusing waste. Waste segregation is increasing nationwide [2]. However, many local governments in Japan face financial difficulties and are challenged to reduce their administrative costs. Bohm et al. [3] stated that waste management costs might increase if the operation of waste management services by municipalities lacks competitive pressure from the private sector. Private sector involvement can contribute to a reduction in garbage collection costs in many cases.

Garbage collection by municipalities is a mainstream practice in Japan. Other streams, such as group collection with private sector involvement, local communities, non-profit organizations, and in-store collections[1] by private companies (supermarkets, clothing shops, and electrical retailers), have been spreading throughout the country. In-store collection refers to "activities in which collection boxes are set up in supermarkets and other retail stores to collect recyclables" [4]. Recyclables accepted for collection from supermarkets include paper cartons, beverage cans, plastic bottles, white plastic trays, and clear plastic trays. Recyclables other than beverage cans and plastic bottles are not collected separately by Japanese municipalities.

In-store collection is conducted in many supermarkets in Japan. Collection boxes for each recyclable type are located in front of supermarkets, and consumers can place their household recyclables in the respective boxes while shopping [5]. For municipal collection, consumers have a fixed day on which to remove their recyclables. In contrast, in-store collection is more convenient, as consumers can bring in their recyclables at any time. The Japan Ministry of Environment [6] has been conducting regular demonstrations of point-of-sale collections of plastic products since 2012. This type of activity also occurs in the USA, Canada, and other countries [7]. The Japan Chain Stores Association [8] reports that the amount of recyclable waste collected from supermarkets nationwide in FY2021[2] was approximately 45,000 t. Of this, the amount of plastic bottles collected increased by 68% compared to FY2005. As a type of private sector involvement, in-store collection can play a role in recyclable collection. Garbage collection without public involvement in the informal sector is usually discussed from a negative perspective in developing countries with undeveloped MSW management systems, such as waste pickers in landfills [9,10]. However, private sector involvement in developed MSW management systems can be observed from a positive perspective as a complement to the MSW management systems of municipalities and as a promoter of recycling.

Discussions on garbage collection by sector without public involvement can be broadly divided into studies that discuss the positive and negative effects of informal sector involvement in garbage collection; the effects of garbage collection through private sector involvement, such as in-store collection; and the integration of the informal sector into the MSW management system. Regarding perspectives on informal sector involvement in waste collection, Kirama and Mayo [11] and Adib and Mahapatro [12] argue that while private involvement leads to job creation and increases garbage collection efficiency, wages and benefits are low, and female cleaners are marginalized. Hidalgo-Crespo et al. [13] analyzed the impact of increased recycling rates by waste pickers on the carbon footprint. Gall et al. [14] argued that high-quality plastic waste collection and material recycling are possible and can be implemented. Lu et al. [15] and Xu et al. [16] analyzed the efficiency of waste disposal in the public and private sectors. Zhang and Wen [17] and Velis et al. [18] argued that plastic waste collection by the informal sector plays a major role in building a circular plastic economy. Regarding perspectives on waste collection through private sector involvement, such as store collection, Sidique et al. [19] analyzed the impact of consumer demographic factors on the use of in-store collection sites. Dilixiati et al. [20] noted that plastic bottles collected through in-store collection are of higher quality than those collected through municipal collection and indicated that consumers' unconscious unwillingness and perception are involved. Yamamoto et al. [21], Kitasaka et al. [22], and Numata [23] identified the status of in-store collection and compared the collection and treatment systems in other countries. Okuno et al. [24] and Nishijima-Okuno et al. [25] quantitatively evaluated the environmental impact of sorted collections that incorporated in-store collection. Yang [26] investigated the degree of improvement in citizens' awareness of reuse by setting up reuse stations alongside recycling stations installed in supermarkets. Regarding perspectives on the integration of the informal sector into the MSW management system, Sandhu et al. [27] argued for the importance of integrating the informal sector into MSW management, as well as considering the impact of privatizing MSW management on the informal sector. Tong et al. [28] argued that the informal sector was part of the MSW management system and must be integrated into the formal MSW management system.

These studies provide various suggestions regarding the involvement of the informal and private sectors in improving the efficiency of the MSW management system and its challenges. In addition, they present the challenges of in-store collection, including reducing the burden on the store and clarifying the position of in-store collection in MSW management systems. However, these studies did not evaluate the environmental and economic benefits of integrating in-store collection into the MSW management system. In the context of building a circular economy, consumers and private businesses, such as supermarkets, are required to become players in MSW management, not just to devolve MSW management to municipalities. In this case, the scope of the evaluation of MSW management, which is currently completed only by municipalities, will be extended by the addition of consumers and private businesses. Previous studies have not focused on the impact of the establishment of a circular economy on costs and environmental impacts in consideration of this expansion of the system boundary of MSW management. In addition, the collection and treatment methods of MSW differ from municipality to municipality, and the locations of supermarkets, which are indispensable for in-store collection, differ between municipalities. Therefore, to verify the conditions of municipalities that should be used actively for in-store collection, identifying the limitations of in-store collection is necessary.

The use of in-store collection reduces the burden of garbage collection in municipalities, which may reduce administrative costs and environmental impacts. This would be advantageous for municipalities integrating in-store collection into their MSW management

[1] Also known as store drop-off.

[2] FY means Japanese fiscal year. For example, FY2021 starts April 2021 and ends March 2022.

systems. However, consumers must carry their recyclables to in-store collection points, and private companies must prepare collection boxes and send the collected recyclables to recycling facilities themselves. Previous discussions on in-store collection have ignored the costs and environmental impacts of these processes. Therefore, it is necessary to clarify whether the use of in-store collection effectively contributes to a reduction in costs and environmental burdens for society entirely. It is also necessary to clarify the role and limitations of in-store collection in establishing a circular economy. This study aimed to identify the conditions under which in-store collection could be effective in MSW management systems. Therefore, this study examines the hypothesis that integrating in-store collections into MSW management will be effective in reducing CO_2 emissions and costs by conducting economic and environmental analyses. This study focuses on the impact of the establishment of a circular economy by expanding the system boundary of MSW management. This will enable us to identify the roles and limitations of municipalities, private businesses, and consumers as players in the establishment of a circular economy from a scientific perspective.

2. Materials and methods

2.1. Steps of this study

Fig. 1 shows a flowchart of this study. First, cluster analysis was used to divide the nation's 1734 municipalities into several clusters to represent the characteristics of MSW treatment and in-store collection by municipality. Based on this information, model cities representing each cluster were created. Each municipality differed in terms of city size and MSW management policies, such as waste sorting, and whether in-store collection was advantageous or disadvantageous. Creating model cities that combined these features facilitated their comparison. Three scenarios of recyclable collection and treatment were constructed and the CO_2 emissions and costs resulting from recyclable collection and treatment in each model city were calculated. Hence, effective conditions and limitations for the integration of in-store collection into the MSW management system are proposed.

2.2. Cluster analysis and model cities

A cluster analysis was conducted on 1734 municipalities nationwide to identify characteristics related to household waste collection and in-store collection. The distance between each data point was calculated using Euclidean distance, and the distance between clusters was calculated using Ward's method. Five variables (population, population density, number of food and beverage retail stores, number of garbage categories, and collection categories in municipal collection) were selected as input variables because they relate to the amount of garbage generated, residential environment, status of treatment facilities, and collection type [2,29,30]. The number of food and beverage retail stores was used, assuming that the number of stores affected the use of in-store collections. Collection categories indicated the classification of garbage by type, such as combustible, noncombustible, and recyclable.

For each cluster obtained in the above analysis, model cities that represented the characteristics of the municipalities belonging to each cluster were created. The model city was assumed to take the median value of the variables for municipalities belonging to each cluster. In addition to these five variables, the presence or absence of treatment facilities (recycling and incineration facilities and landfills) was included as a variable. The presence or absence of treatment facilities was set as a dummy variable (with operating facilities:1, without operating facilities:0) based on a survey of the actual status of waste treatment in each municipality as of FY2015 [2]. The median value was calculated based on these results. If the median value was >0.5, the city was considered to have facilities within the model city; if the value was <0.5, the city was considered not to have such facilities.

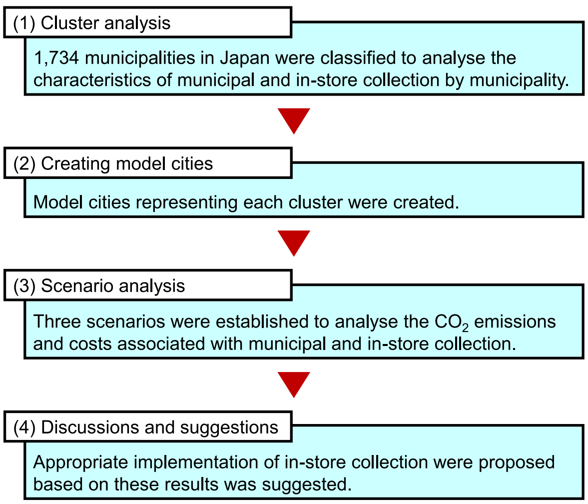

Fig. 1. Flowchart of this study.

2.3. Scenario analysis

2.3.1. System boundary

Fig. 2 shows system boundary of each scenario. Each scenario consisted of a municipality, supermarket, and household. CO_2 emissions and costs were calculated for each sector. The five recyclables used in this study were paper cartons, beverage cans, plastic bottles, white plastic trays, and clear plastic trays. In Japan, these recyclables are often subjected to in-store collection.

All generated recyclables were collected through municipal collection. All recyclables were sorted and compacted at the recycling center (RC). The sorted residues generated in the RC were treated at the closest municipal treatment facility.

There was no in-store collection, and the collection was conducted only through municipal collection. In Transportation 1, recyclables were collected and compacted by packer trucks on separate days, depending on the type of garbage. During the recycling process, all garbage, regardless of its type, was sorted and compacted.

This scenario was similar to the current situation in Japan. The incineration and landfill processes in the in-store collection flow

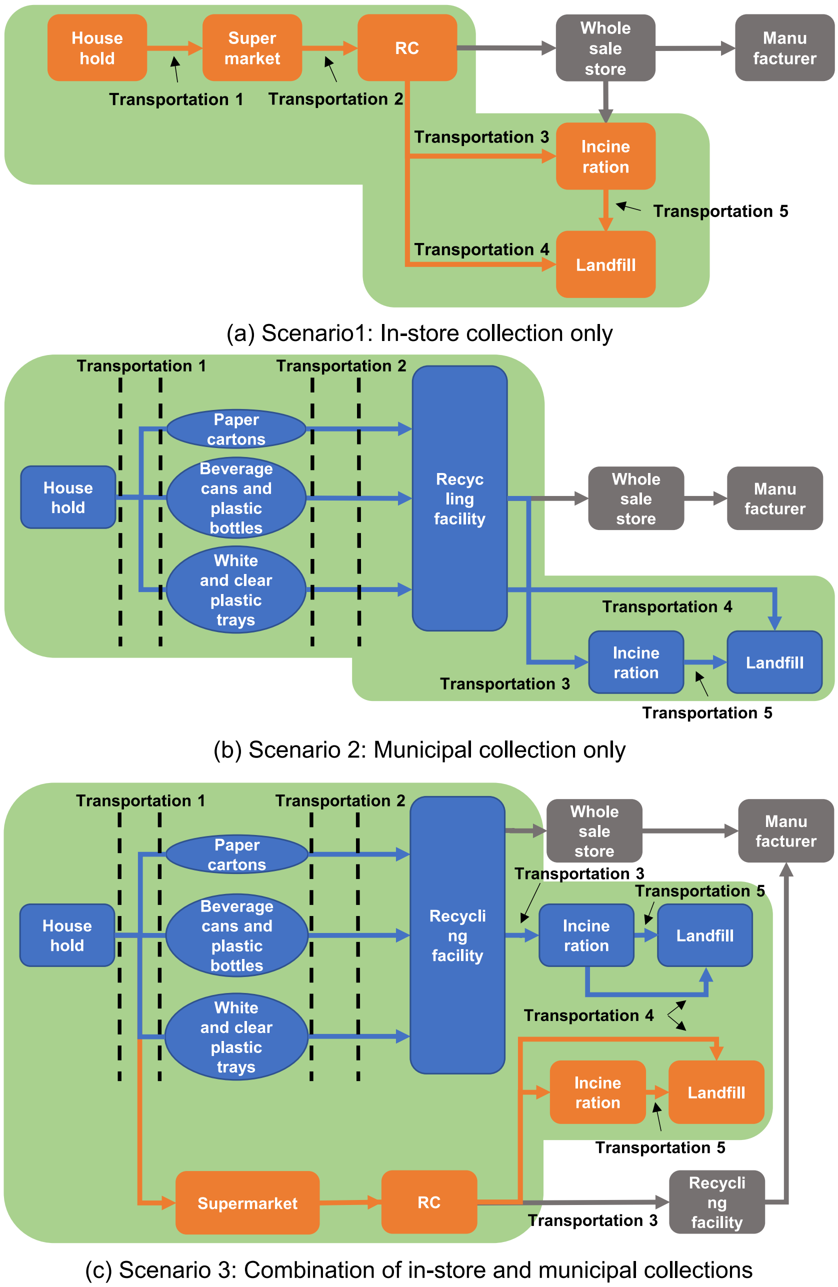

Fig. 2. System boundary of each scenario.

were assumed to be conducted at the facility closest to the RC. The collection flow for in-store collection was based on an example of in-store collection in a supermarket, and the flow for municipal collection was based on Tabata et al. [31].

2.3.2. Data settings

The data used for the transport, recycling, incineration, and landfill processes are presented in Tables A1 and A2 in the Supplementary Material. Data on recyclables are presented in Table A3 of the Supplementary Material. The data in Table A3 are for the entire Japan; therefore, they were converted into data for each model city using the following equation:

$$W^c_{mx} = W^c_{px} \times \frac{W_{mx}}{W_{mx} + W_{sx}} \tag{1}$$

$$W^c_{sx} = W^c_{px} \times \frac{W_{sx}}{W_{mx} + W_{sx}} \tag{2}$$

$$W^c_{px} = \frac{W_x}{P} \times P^c \tag{3}$$

where W^c_{mx} is the municipal collection of item x in model city, c [t]; W^c_{px} is the annual per capita discharge of item, x, *in* model cit,y c [t]; W_m is the national municipal collection of item, x [t]; W_s is the national in-store collection of item x [t], W^c_{sx} is the in-store collection of item x *in* model city c [t], W_x is the national collection of item x [t]; P is the total population of Japan [person]; P^c is the total population of model city c [person], c is the model city (depends on the number of clusters created), and x is the type of recyclable (paper cartons, beverage cans, plastic bottles, white plastic trays, and clear plastic trays).

2.3.3. Transportation process settings

For each model city, distances in the transportation process were constructed. All supermarkets that offered in-store collections were of the form that collect recyclables, and the location relationship from the supermarket to the RC was the same in each model city.

2.3.3.1. Supermarket for households. The distance from the supermarket to the households varies across municipalities. Therefore, the following method was established for calculating the average distance ($D_{h\text{-}s}$) from the household to the closest supermarket, using a vehicle. Walking and bicycles were selected as transportation methods for <5 km travelled, whereas cars were selected for >5 km travelled [32]. Based on this situation, this study assumed that the area covered by a single supermarket was a concentric circle with the supermarket at the center, and the households were evenly distributed within these circles (Fig. A1 in the Supplementary Material). The midpoint between node A in the outer circle within the vehicle zone and node B in the outer circle within the bicycle zone was $D_{h\text{-}s}$. $D_{h\text{-}s}$ was calculated using the following equation:

$$D_{h-s} = \frac{r - D_{bike}}{2} + D_{bike} \tag{4}$$

where $D_{h\text{-}s}$ is the average distance from the household to the closest supermarket using a car [km], r is the radius [km], and D_{bike} is the travel distance for customers who visit the supermarket by bicycle [km].

These variables were calculated based on the results of cluster analysis. Of these variables, r was calculated using the following equation, based on the area of inhabitable land and the number of food and beverage retail stores in each model city:

$$r = \sqrt{\frac{F^c \times \pi}{N^c_{store} \times 0.092}} \tag{5}$$

where F^c is the area of inhabitable land in model city, c [km^2]; N^c_{store} is the number of food and beverage retail stores in model city, c [stores]; and 0.092 refers to the ratio of supermarkets to food and beverage retail stores (approximately 9.2%) [30,33].

This study assumes that households mainly visit supermarkets and that the number of customers visiting by vehicle is equal to the number of households visiting by vehicle. Based on this assumption, the number of households using vehicles to visit supermarkets was calculated using the following equation:

$$N_{households} = H^c \times \frac{r - D_{bike}}{r} \tag{6}$$

where $N_{housholds}$ is the number of households that use a car to visit a supermarket [households], and H^c is the total number of households in model city c [households].

The percentage of customers who visit supermarkets only for in-store collection (α) was calculated based on a questionnaire survey conducted by the authors at a supermarket in Kobe City (conducted on September 14–16, 2020; in total, 198 respondents were recruited). The questionnaire list and results are presented in Tables A4 and A5 of the Supplementary Material.

2.3.3.2. Supermarket to RC. The distance from the supermarket to the RC was assumed to equal the sum of the average distance from each supermarket to the RC, and the average distance between each supermarket was calculated using the following formula:

$$D_{s-r} = D_{rc} + 2 \times D_{super} \tag{7}$$

where $D_{s\text{-}r}$ is the distance from the supermarket to the RC [km], D_{rc} is the average distance from each supermarket to the RC [km], D_{super} is the average distance between supermarkets [km], and 2 refers to the average number of supermarket trips by delivery trucks.

The average number of supermarkets visited by customers was set to two, based on interviews with supermarkets in Kobe. The distance between each supermarket and the RC owned by the supermarket and the distance from each supermarket to the closest supermarket were measured using Google Maps. The average distance between each store and the RC and the average distance between each supermarket and the closest supermarket in each model city were also measured using Google Maps.

2.3.3.3. Facilities for RC. The distances from the RC to the incineration facility ($D_{r\text{-}i}$), the RC to the landfill ($D_{r\text{-}f}$), and the incineration facility to the landfill ($D_{i\text{-}f}$) were measured from the RC to the closest incineration facility or landfill and from the incineration facility to the landfill, respectively, using Google Maps.

2.3.3.4. Municipal collection and disposal. The transportation distance for the municipal collection was estimated using Matsuto's method [34]. For station collection, the distance for a round trip to all collection stations was calculated using the following formula:

$$D_h = \frac{P^c}{a_7} \times a_7 \tag{8}$$

where D_h is the distance for a round trip around all collection stations (km). For curbside collection, the value (calculated in the same way as for station collection) was multiplied by the ratio of the travel distance [35].

To estimate the distances from a collection station to a recycling facility ($D_{h\text{-}r}$), from an RC to an incineration facility ($D_{r\text{-}i'}$), from a recycling facility to a landfill ($D_{r\text{-}f'}$), and from an incineration facility to a landfill ($D_{i\text{-}f'}$), five municipalities were selected, each with similar conditions to each model city created. The selected municipalities were divided into two groups: those with and without a municipally-operated treatment facility in the same municipality. The average distance between each treatment facility was calculated using Google Maps. If a municipality did not operate treatment facilities, the average distance between the treatment facilities of the municipality and contractors that outsourced treatment was calculated. $D_{h\text{-}r}$ assumed that the collection stations were located in municipal offices.

2.3.4. CO_2 emissions and costs for in-store collection

The formulae for calculating the CO_2 emissions and costs for each process of in-store collection are shown in Table A6 of the Supplementary Material. The number of times in-store collection was used (N_{visit}) was estimated based on the results obtained from the questionnaire survey. Noncombustible residues derived from beverage cans delivered from RC were calculated by multiplying the amount of beverage cans collected by the percentage of sorted residues discharged (β). Combustible residues derived from recyclables other than beverage cans delivered from RC were calculated by multiplying the amount of these residues collected by β. Transportation 5 was conducted by a municipality or contractor. If the number of trips (T_5) for Transportation 5 was <260, the number of working days per week was assumed to be one. If $T_5 = 52$, T_5 was assumed to be equal to the number of working days per year. In this case, the maximum annual working hours (J_{year}) were calculated using formula (A-3-31) in Table A3 of the Supplementary Material.

2.3.5. CO_2 emissions and costs for municipal collection

The formulae for calculating the CO_2 emissions and costs for each municipal collection process are shown in Table A7 of the Supplementary Material. In Transportation 1, recyclables were collected on different days. The collection category was set to k, where $k = 1$ (paper cartons), $k = 2$ (plastic bottles and beverage cans), and $k = 3$ (white and transparent plastic trays). N^k_{trucks} is the number of trucks required for collection category, k. Working days per week (U) in Transportation 3, 4, and 5 were one day per week if the number of trips was <260; if the number of trips was <52, the number of trips was calculated to be equal to the number of working days per year. The number of workdays per week was set to one day per week if the number of trips (T_n) was <260, or T_n was equal to the number of workdays per year if the number of trips (T) was <52. In such cases, J_{year} was calculated using formula (A-4-40) in Table

Table 1
Specification of model cities by each cluster.

		Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Model city		1	2	3	4	5	6
Total population [thousands]		1230	18	134	14	24	301
Population density[a] [persons/10 ha]		585	43	262	34	46	1266
Number of garbage segregation		13	10	13	10	17	12
Collection Category[b]		3	0	5	4	6	2
Number of food and beverage retail stores[a] [stores/10 ha]		0.75	0.15	0.43	0.11	0.12	2.06
The presence or absence of treatment facilities	Recycling facility	0.8	0.3	0.5	0.2	0.3	0.3
	Incineration facility	0.9	0.4	0.7	0.4	0.4	0.7
	Landfill	0.8	0.4	0.4	0.4	0.4	0.0

[a] Population density and number of food and retail stores are both per inhabitable land area.
[b] For station collection only.

A6 of the Supplementary Material.

3. Results and discussion

3.1. Cluster analysis

The results of the cluster analysis facilitated the classification of the characteristics of in-store collection in Japan into six clusters, considering the city size and the implementation of MSW management policies. A dendrogram for this case is shown in Fig. A2 of the Supplementary Material. Table 1 shows the specifications of the model city by cluster, as created in each cluster. Clusters 1 and 6 were the most populous municipalities in Japan. Cluster 1 comprised cities that play a central role in various parts of Japan. Cluster 6 had a smaller total population than Cluster 1, a much larger population per 10 ha of inhabitable land, and a much larger number of food and retail stores. Clusters 2, 4, and 5 were similar in terms of total population and the number of food and retail stores, whereas Cluster 3 differed from the three clusters mentioned above. The dendrogram suggests that the main factors that constituted Clusters 2, 3, 4, and 5 were variables related to garbage disposal, such as the number of garbage categories and collection categories for station collection. Clusters 2 and 4 had a lower amount of garbage segregation than the other clusters. Approximately half of the municipalities belonging to these clusters did not use plastic containers or packaging for municipal collection [2]. Based on this fact, the model cities in Clusters 2 and 4 were assumed to have white and transparent plastic trays as combustibles.

For each created model city, the parameters for transport distance and the amount of collected recyclables were set (Table A6 in the Supplementary Material. D_{bike} was set to 15.6 km and was obtained by dividing the average bicycle speed of 15.2 km [36] by the average bicycle travel time obtained from the aforementioned questionnaire survey. $D_{h\text{-}s}$ was set as the average time taken by vehicles obtained from the aforementioned questionnaire survey by dividing the regulatory speed of vehicles by 50 km [37]. N_{visit} was calculated 52 times based on the average frequency of use of each recyclable material; α was set to 11%, i.e., the percentage of customers visiting the supermarket only for in-store collection (obtained from the aforementioned questionnaire survey).

3.2. CO_2 emissions and cost results by model city

Table 2 shows the results of CO_2 emissions and costs for the model city. The ratios of CO_2 emissions and costs by scenario by model city are shown in Figs. 3 and 4, when the result of Scenario 3 was set to 1.0. Results for CO_2 emissions decreased from −37.0% to 53.5% for Scenario 1, with Scenario 3 as the reference. Except for Model City 5, Scenario 1 had the lowest CO_2 emissions. The reason for the increase in CO_2 emissions in Model City 5 was the very long distance of Transportation 2 in the in-store collection, and the municipal collection was station collection. There was no substantial difference between Scenarios 2 and 3. This is because the percentage of in-store collection (weight base) in Scenario 3 was less than 5%. The CO_2 emissions from the incineration process in Scenario 1 were very low compared to those from the other processes. One of the reasons for this is the small amount of combustible residues discharged from the RC. For example, according to the Japan Containers and Packaging Recycling Association [38], of the 656,000 tons taken up by the association in FY2018, approximately 33% was treated as residue. The incentive to clean recyclables more thoroughly, for reasons such as being seen by other consumers when putting them in sorting bins, is considered to reduce the amount of combustible residue compared with municipality collections.

The results showed the highest percentage of CO_2 emissions from incineration. The ratio of CO_2 emissions in the incineration process in Scenario 1 was 4.3% in model cities 1, 3, 5, and 6, and 2.3% in model cities 2 and 4. The reason for the lower ratios in model cities 2 and 4 than that in the other model cities was that these cities collected white and transparent plastic trays as combustibles. These results suggest that in-store collection effectively reduces CO_2 emissions during combustion.

In the cost results, the increase in Scenario 1 was 0.90–1.96 times greater than that in Scenario 3. The cost was only reduced in model city 6. Model cities 1, 3, 4, and 5 had the highest costs in Scenario 1. In particular, the results of model cities 1, 3, and 5 were almost twice as high as those of Scenario 3. For these model cities, the contribution of Transportation 2 was large. This is due to the longer distance between the supermarket and the RC, compared to the distance between the collection station and the recycling facility. However, in model cities 2, 4, and 6, the cost differences among the scenarios were not very large. This is because the cost of municipal collection was higher than that of in-store collection. In particular, because the number of collection categories was small in Model City 6, the reduction in the amount of collection and treatment by the municipality due to in-store collection was effective in

Table 2
CO_2 emissions and costs by model cities.

Model cities	CO_2 emissions [t-CO_2]			Costs [million JPY]		
	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
1	1448	2172	2142	896	409	460
2	33	55	54	18	17	19
3	158	230	227	106	45	52
4	32	39	38	17	11	13
5	63	44	46	30	13	15
6	340	742	731	223	236	249

Note: 1 JPY = 0.0067 USD (13 October 2023).

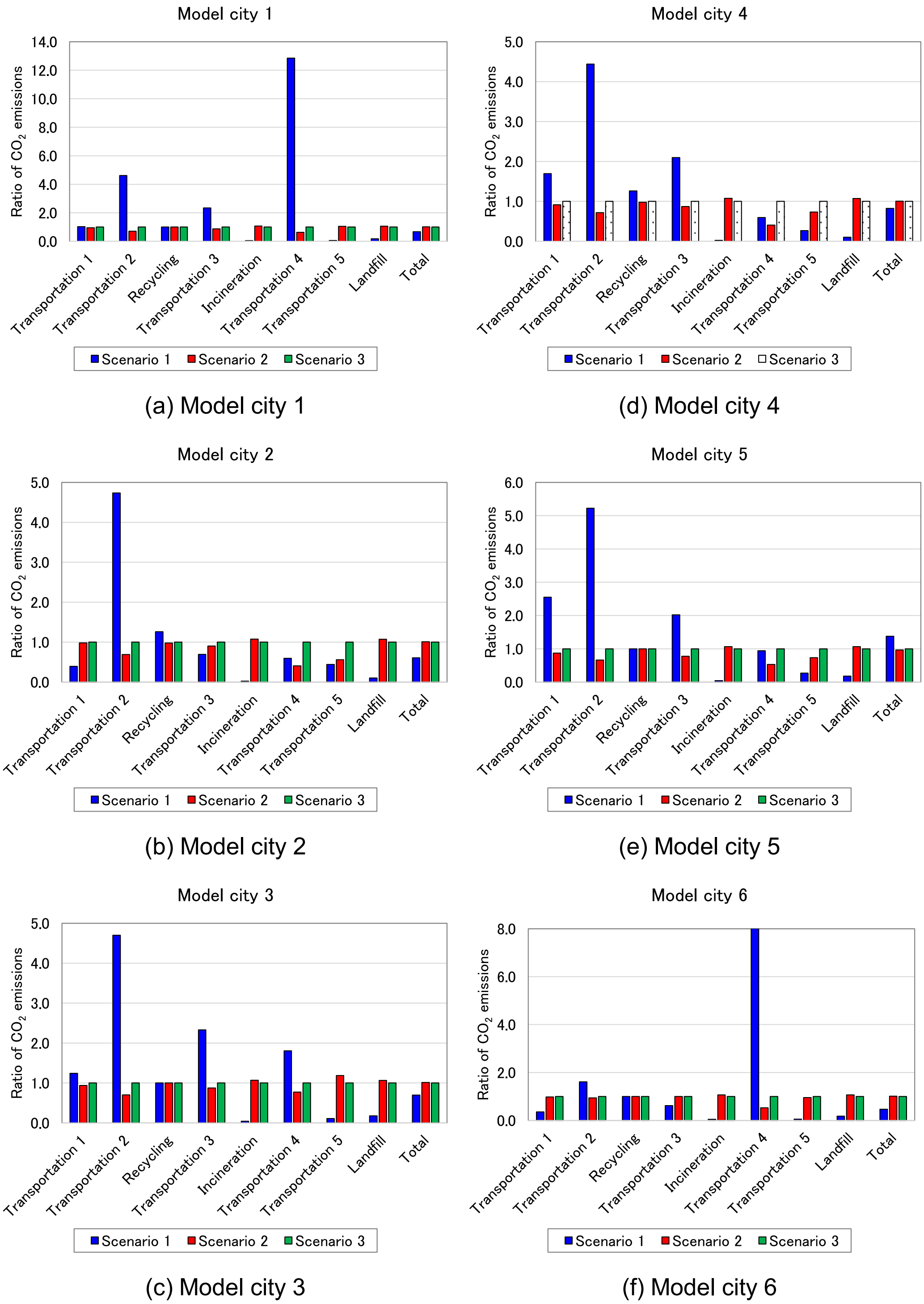

Fig. 3. Ratio of CO_2 emissions by model cities. Note: Result of Scenario 3 set to 1.0.

reducing costs. For Transportation 1, the ratio was lower in Scenario 1 than in Scenarios 2 and 3. Model cities 2 and 6 were particularly affected by the increase in distance due to curbside collection. Model 4 indicated higher costs for Transportation 1. However, Scenarios 2 and 3 were not as high as those in model cities 2 and 6. This is because white and transparent plastic trays, accounting for a large proportion of the volume ratio among the recyclables, were collected as combustibles, which were collected more frequently. In model

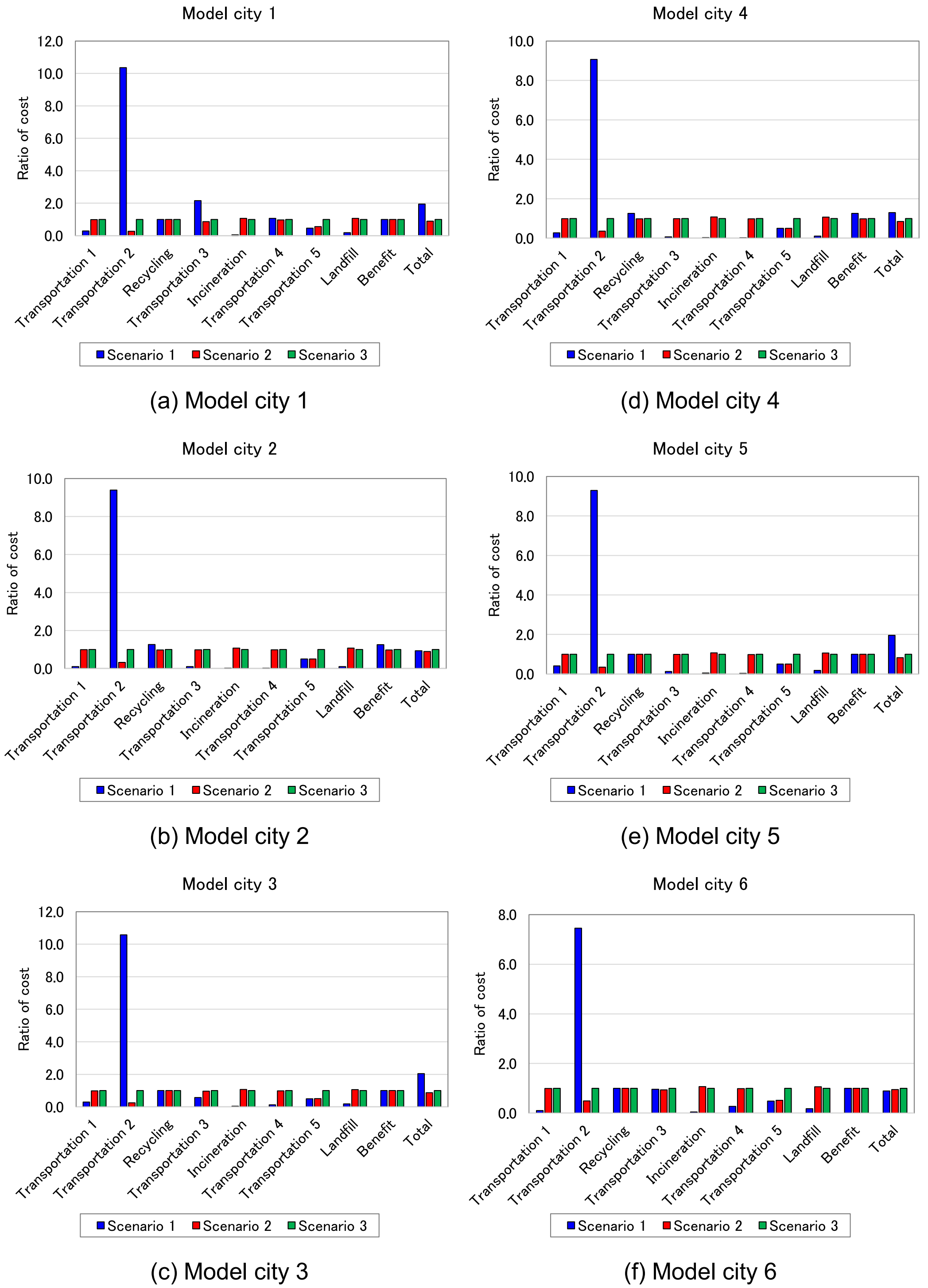

Fig. 4. Ratio of cost by model cities.
Note: Result of Scenario 3 set to 1.0.

cities 2 and 4, recyclables were collected less than once per week, whereas combustibles were collected twice per week. This contributed to an increased cost in Transportation 1.

The bottleneck in the in-store collection was Transportation 2. Transportation 2 accounted for 30–70% of the CO_2 emissions in Scenario 1, whereas costs accounted for 70–80% of the costs in Scenario 1. However, there was no marked difference in the overall cost

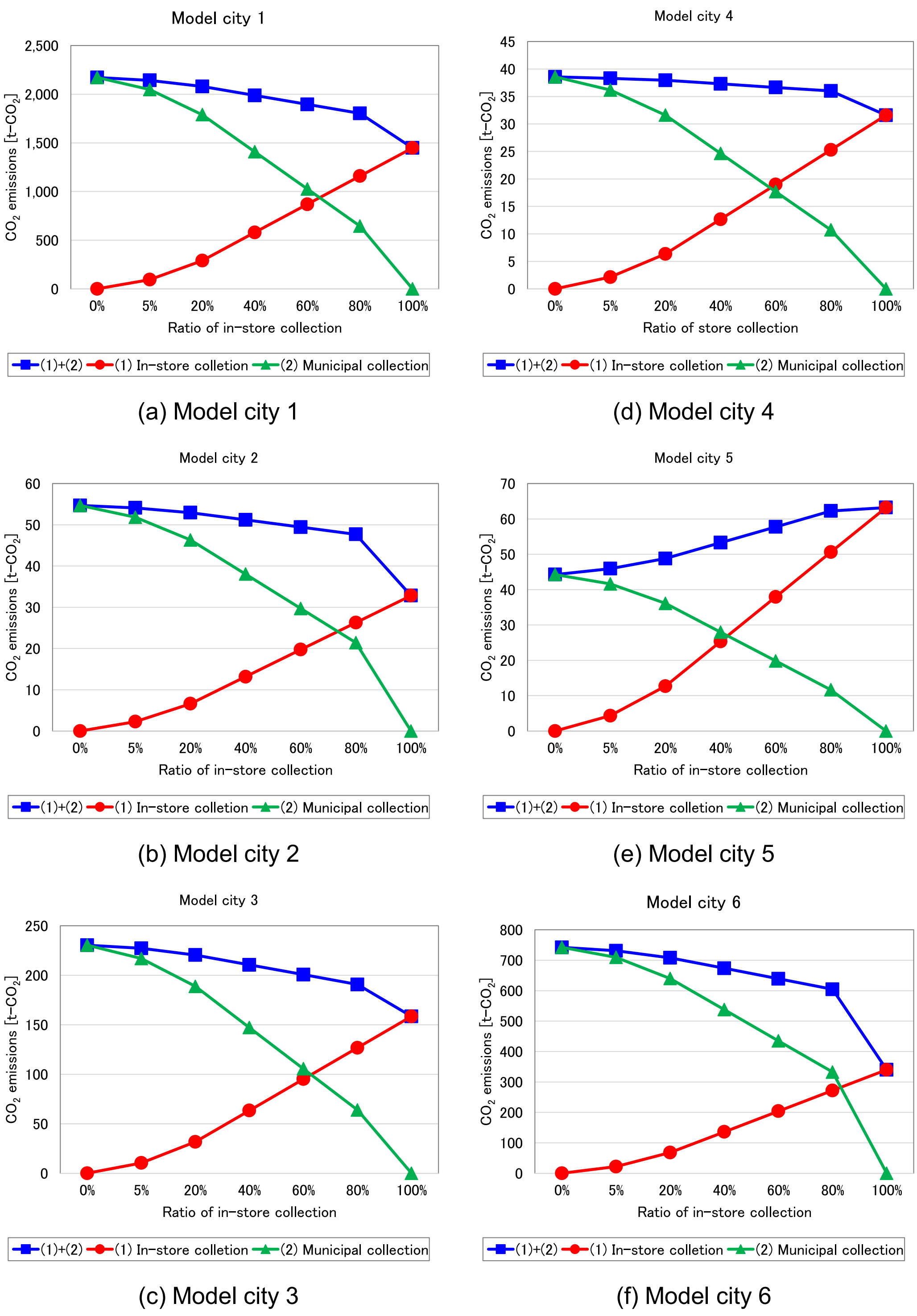

Fig. 5. Change in CO_2 emissions with change in percentage of in-store collection. Note: Scenario 3 only.

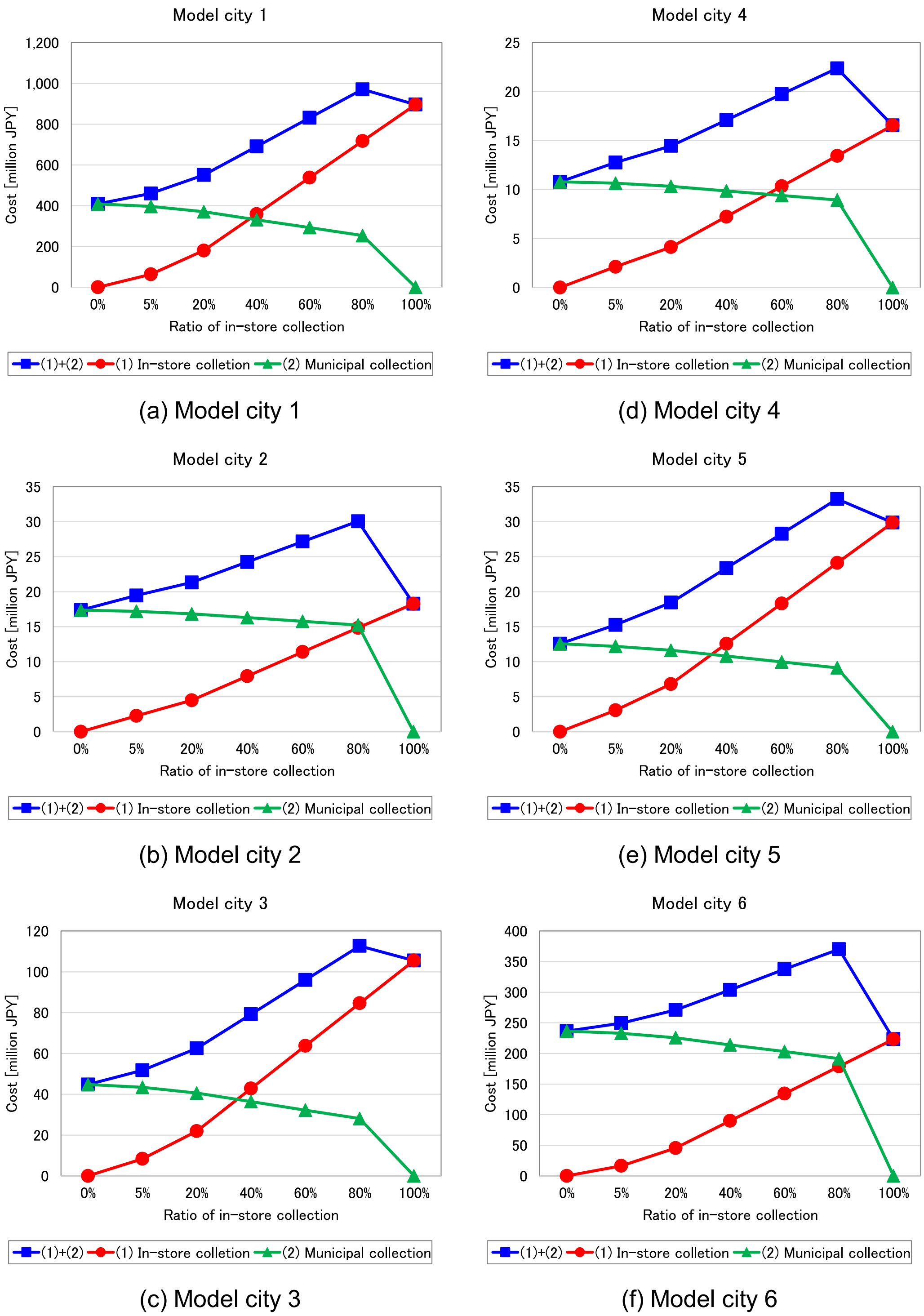

Fig. 6. Change in cost with change in percentage of in-store collection.
Note: Scenario 3 only.

between Scenarios 1 and 2 for model cities 2 and 6. This suggests that municipalities with nearby RC can implement in-store collection at a relatively low cost and reduce their CO_2 emissions.

3.3. Sensitivity analysis

Figs. 5 and 6 show the results of examining the degree of change in CO_2 emissions and costs when the percentage of in-store collection varied from 0 to 100% in Scenario 3 for each model city. The 0% rate of the in-store collection was identical to Scenario 2, the 5% rate was identical to Scenario 3, and the 100% rate was identical to Scenario 1. Consequently, the amount of CO_2 emissions decreased as the ratio of in-store collection increased for all model cities, except for Model City 5. However, the decrease in the ratio of in-store collection of up to 80% was smaller than that in model cities 2 and 4. In contrast, CO_2 emissions increased in Model City 5. The aforementioned results indicate that municipal collection incurs higher costs in Transportation 1. This process does not change the number of patrolling collection stations, even if the volume of municipal collection decreases. Therefore, the range of cost fluctuations in the municipal collection was small, and the overall cost was considered to increase with an increase in the volume of in-store collection. Models 3 and 5 exhibited similar results.

In each model city, the range of the increase in costs increased after 20%. CO_2 emissions (except for Model City 5) and costs decreased substantially when the amount of in-store collection exceeded 80% in each city. This is because the decrease in the cost of municipal collection was greater than the increase in the cost of in-store collection. The cost in Model City 6 decreased substantially after 80% and was lower than that in Scenario 2.

4. Conclusion

This study evaluated the CO_2 emissions and costs of integrating in-store collection into MSW management systems. A total of 1734 municipalities in Japan were classified into six clusters using cluster analysis to analyze the characteristics of municipal and in-store collection by municipality. Model cities representing each cluster were created, and three scenarios were established to analyze the CO_2 emissions and costs associated with municipal and in-store collection. The scenarios were cases where recyclables were collected through in-store collection (Scenario 1); recyclables were collected through municipal collection (Scenario 2); and in-store collection and municipal collection were combined, similar to the current system (Scenario 3). Regarding CO_2 emissions in each model city, the reduction in Scenario 1 was −37.0 to 53.5%, compared to that in Scenario 3. The increase in the in-store collection of recyclable waste led to a decrease in emissions, except for some model cities. In terms of cost, the increase in Scenario 1 based on Scenario 3 was 0.90–1.96-fold. The hypothesis of the study was that integrating in-store collections into MSW management would be effective in reducing CO_2 emissions and costs. This hypothesis is accepted in terms of CO_2 emissions but not in terms of costs. This result is important in promoting the circular economy, and local municipalities are required to determine how to implement policies that can resolve the balance between CO_2 emissions and costs.

In-store collection is an essential part of the establishment of a circular economy. The current study indicated that integrating in-store collection into municipal MSW management may result in lower CO_2 emissions but higher costs. Municipalities should be aware that conditions conducive to the integration of in-store collections into MSW management will vary depending on the size of the city and waste management policies. To integrate in-store collection into the MSW management system, users of in-store collection and local authorities, as well as supermarkets need to cooperate; companies producing goods and consumers who do not use in-store collection need to discuss the cost and labor burden and their role in the circular economy. In addition to reducing the burden by improving business efficiency, it is also necessary to consider optimizing the distribution of burdens, responsibilities, and benefits across society.

Municipal policy makers can determine which model city their municipality is closest to, according to the specifications in Table 1. They can then determine the CO_2 emissions and costs their municipality are likely to incur when introducing in-store collection into their MSW management policy. Based on these implications, each municipality can consider how much in-store collection should be introduced. When municipalities introduce in-store collection, the following are recommendations regarding the conditions and limitations that make in-store collection effective in MSW management. Municipalities can use these recommendations as a basis for considering the implementation of in-store collections into MSW management.

(1) An increase in in-store collection reduces CO_2 emissions but leads to an increase in costs. This is partly because the increase in in-store collection decreases the number of sorted residues to be incinerated, whereas the increase in in-store collection does not change the municipal collection system, and only the cost of in-store collection appears to be a burden. When integrating in-store collection into an MSW management system, reviewing the municipal collection system is necessary. If the review is difficult, municipalities similar to model cities 1 and 3 in Clusters 1 and 3, respectively, should set a target ratio of 20% for in-store collection volumes. The reason for this is that the range of the cost increase becomes larger after approximately 20%. When the percentage of in-store collection exceeds 80%, costs begin to decrease but still exceed Scenario 3 by a factor of two.

(2) For model cities 2, 4, and 6 in Clusters 2, 4, and 6, respectively, the range of cost increases was larger after 20%, similar to model cities 1 and 3. However, the range of increase was smaller than that in model cities 1 and 3. When the ratio of in-store collection exceeded 80%, the cost decreased substantially and was lower than in Scenario 2 in Model City 6. However, in model cities 2 and 4, CO_2 emission reductions of up to 80% for in-store collection were smaller than those in other clusters. Emission reduction cannot be expected unless the target value of the percentage of in-store collections is set to 100%.

(3) In Model City 5 of Cluster 5, both the CO_2 emissions and costs increased as the amount of in-store collection increased. Therefore, active use of in-store collections, while maintaining the current system, is not recommended for municipalities similar to the model cities in this cluster. For municipalities similar to Model City 6 in Cluster 6, setting a clear target value for the percentage of in-store collection is difficult; however, it may be desirable to set it above 50%, depending on the financial situation of the municipality.

A limitation of this study is the fact that the results of the cluster analysis vary considerably depending on the variables selected. Therefore, the analysis should be carried out with other variables and a comparative analysis should be made with the typology of this study. A questionnaire survey was used to set the parameters, but the results are not representative of the model cities due to the small number of supermarkets covered. Therefore, a more comprehensive survey should be used to calculate them. In addition, there is little publicly-available data corresponding to in-store collections, and much had to be based on estimates. The accuracy of the environmental burden and cost results needs to be improved by examining the actual amount of each item collected and the capacity of each facility and equipment. In the scenario where all items are collected and treated through in-store collection, study is needed on the burden incurred by supermarkets.

Data availability statement

Not applicable.

CRediT authorship contribution statement

Mayuko Suzuki: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tomohiro Tabata:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

Tomohiro Tabata reports financial support was provided by Japan Society for the Promotion of Science (JSPS). Tomohiro Tabata reports financial support was provided by Environmental Restoration and Conservation Agency. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the Japan Society for the Promotion of Science (JSPS) KAKENHI Grant Number JP23K11546 and Council for Science, Technology and Innovation (CSTI), Cross-ministerial Strategic Innovation Promotion Program (SIP), "Development of environmental assessment method for plastic resource recycling system"(Funding agency: ERCA).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e29011.

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