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ORIGINAL ARTICLE

Does simplification of plastic waste separation promote plastic recycling?

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Abstract

This study explores the effects of a policy intervention designed to simplify the standards for plastic waste separation on collection volume and the quality of recyclables. We employ a causal impact analysis based on a Bayesian structural time-series approach to estimate the effects of simplifying the municipal solid waste-separation process for plastic waste in Japan. We find that simplifying plastic waste-separation standards increases plastic packaging waste-collection volume. This effect seems to be largely driven by behavioral changes such as decreased time spent on waste separation. We also find that simplifying home separation increases the percentage of contaminated plastic packaging waste collected for recycling and other materials not subject to collection in the post-collection period. Several robustness and falsification tests corroborated these results. Our results highlight the importance of considering the trade-off between the quantity and quality of recyclables when designing plastic waste recycling policies.

Keywords Plastic waste · Recycling · Waste separation

Abbreviations

CI	Confidence interval
CIA	Causal impact analysis
CPRL	Containers and packaging recycling law
JCPRA	Japan Containers and Packaging Recycling Association
MOE	Japanese Ministry of Environment
MSW	Municipal solid waste

Introduction

Plastic waste is predicted to increase from 4.6 million tons in 2019 to 12.31 million tons by 2060 [1]. Given the future growth of the world's population, efforts to increase household waste-separation behavior, which directly affects recycling volume, will continue to feature prominently in environmental policies designed to increase plastic recycling and reduce other environmental externalities. Plastic waste-collection programs have been introduced worldwide [2]. However, complex separation standards for collection may adversely affect household waste-separation behavior [3–5]. Stricter requirements for source separation imposes greater burdens and opportunity costs on households related to factors such as containers, storage space, and the time involved in separating materials [6–9]. The increased burden and opportunity cost for household waste separation raises questions about whether these requirements, contrary to the intentions behind these policies, might actually hinder recycling or if relaxing them could boost recycling rates. To answer this question, we investigate the impact of simplifying home separation on collection volume by merging the two previously separate categories of plastic packaging waste and plastic product waste into the same category.[1]

This study aims to provide a better understanding of the relationship between plastic waste-separation standards and recycling. Simplifying waste separation may encourage household recycling and consequently increase the amount of plastic waste collected [5]. However, simplifying waste separation may also lead to lower-quality recyclables after

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[1] The precise definition of plastic packaging waste and plastic product waste is given in "Background and methodology".

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the post-collection stage [10]. Thus, we examine whether simplifying plastic waste-separation standards could enhance household waste-separation behavior and how this change may impact the quality of recyclables after post-collection separation. We first investigate whether combining the two previously separated categories of plastic packaging waste and plastic product waste would increase the amount of plastic packaging waste collected in Japan. Then, using additional detailed and standardized annual data, we analyze the effects of simplifying plastic waste separation in households on contamination levels, i.e., the percentage of contaminated plastic packaging waste collected for recycling and other materials not subject to collection.

This study contributes to literature on recycling policies by broadening our understanding of the relationship between the inconvenience of separating waste and household recycling behavior. Literature on the drivers of household recycling behavior predominantly focuses on economic incentives, social influence, and psychologic insights; however, these studies have not considered the inconvenience of separating waste [11–17]. Our findings also contribute to literature on the effects of post-collection separation of plastic waste on recycling outcomes by providing, for the first time, evidence of a trade-off between recycling volume at the collection stage and the quality of recyclables after post-collection separation due to simplified waste separation. In particular, we add to literature by evaluating the contamination levels of plastic waste separation in the post-collection stage, which is less commonly studied in the context of recycling policies. Bell et al. [4] and Dijkgraaf and Gradus [5] focused on the effects of post-collection separation and reported that it increases the recycling volume and cost-effectiveness compared with those of household separation. However, given that plastic waste is collected from other types of waste, post-collection separation may affect the quality of recyclables. This study identifies the effects of waste-separation standards on the amount of plastic waste collected and the quality of recyclables after post-collection separation.

Our results show that simplifying waste-separation standards increases the amount of plastic packaging waste collected and the contamination of separated plastic packaging waste in the post-collection stage. Post-collection separation increases the burden and cost of separation for recyclers and decreases the quality of recyclables. In general, our findings highlight the magnitude of the burden and opportunity costs of waste separation in recycling.

Our study also contributes to the growing economic literature on plastic waste recycling [18–21]. Policymakers struggle to recycle post-consumer plastic waste because of the high recycling costs [6, 22]. Designing policies that minimize recycling costs, including the opportunity costs of plastic waste separation in households and the treatment costs for government or private recyclers, is challenging. Although the benefits of plastic recycling appear to justify the opportunity costs of the home separation of plastic waste, the magnitude of these costs makes it critical to understand the differences in policy efficiency between complex and simplified waste-separation standards for households.

Only a few areas have participated in policy interventions to simplify plastic waste separation, potentially making it difficult to estimate the causal effects. To overcome this problem, we employ a Bayesian structural time-series approach, which provides an estimated counterfactual time series [23, 24]. This approach accounts for a fundamental issue in econometric analyses of causal effects: the lack of a controlled experimental setting for analyzing real-world phenomena or policies [25–28].

The remainder of this paper is organized as follows. Section "Background and methodology" provides background information on the collection programs for plastic waste in Japan and introduces the empirical strategy. Section "Results" presents our estimation results. Section "Robustness checks" presents an array of robustness checks. Section "Conclusion" presents our conclusions.

Background and methodology

Plastic waste separation in Japan

To examine the relationship between simplifying separation standards for plastic waste and recycling, we focus on plastic packaging waste in Japan. According to the Japan Containers and Packaging Recycling Association (JCPRA) [29], plastic packaging waste is defined as plastic containers or packaging, including those made of flexible or rigid plastic, such as film bags for food, shampoo bottles, and plastic bottle caps. Plastics not used for packaging, such as toothbrushes and hangers, are not considered plastic packaging waste. Therefore, plastic packaging waste is not defined by the type of plastic used and includes various materials primarily made from plastic resin, such as polyethylene (PE), polyethylene terephthalate (PET), polystyrene (PS), and polypropylene (PP).[2] One exception is plastic bottles made of PET. In Japan, this type of plastic bottle is distinguished from plastic packaging waste and is collected and recycled separately. Figure 1 shows the classification of containers and packaging waste and plastic packaging waste, which is the focus of this study. In Japan, 4.24 million tons of plastic waste is generated annually in the form of municipal solid waste

[2] For details on the definition of plastic packaging waste, refer to the JCPRA [29] and the Japanese Ministry of Economy, Trade and Industry [30].

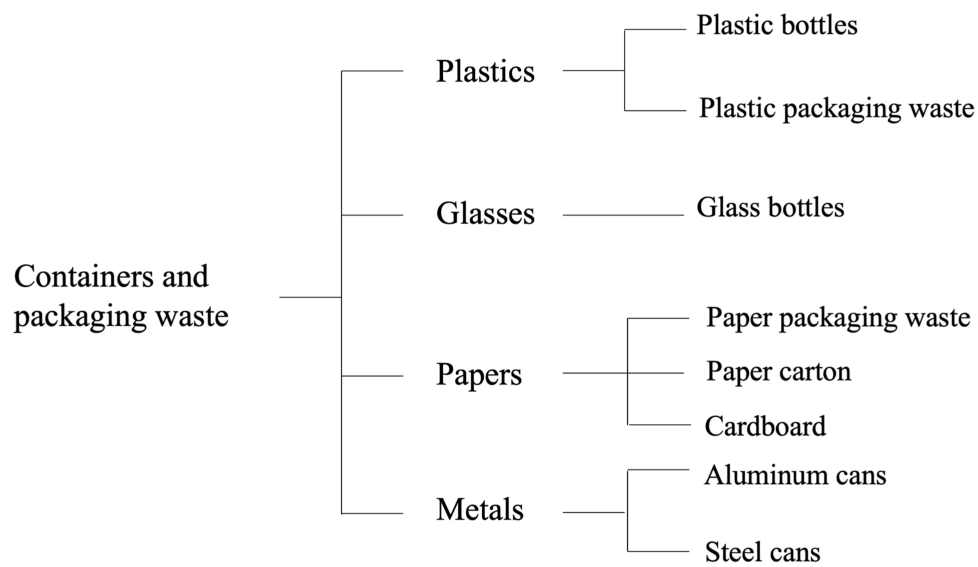


Fig. 1 Category of containers and packaging waste in Japan. Source: JCPRA [29]

(MSW), of which plastic containers and packaging waste, including plastic bottles, account for 77.4% as of 2022 [31].[3] The Japanese Ministry of the Environment (MOE) enacted the Containers and Packaging Recycling Law (CPRL) in 2007 to encourage municipalities to collect and recycle plastic packaging waste, plastic bottles, glass bottles, and paper packaging waste from MSW. Each municipality can decide whether to collect these containers and packaging waste; as of 2022, 75.6% of municipalities collect plastic packaging waste.[4] Almost all plastic waste collected by the JCPRA recycling program is fed into the recycling process. Thus, as long as plastic packaging waste is collected through the JCPRA recycling program, it is recycled. This implies that collecting as much plastic waste as possible is important because an increase in the amount of collected plastic waste directly leads to increased recycling.

In Japan, while MSW is collected in several ways, such as door-to-door system, collection stations,[5] self-delivery, and voluntary group collection, plastic packaging waste is usually collected through either a door-to-door system or a collection-station system at fixed times and locations. Some countries use a community bin system to collect plastic and recyclable waste; however, many countries, including Japan, have adopted a door-to-door system and curbside pick-up, similar to the collection-station system [32]. As will be discussed later, in the municipality analyzed in this study, both door-to-door and station collection systems are adopted for collecting plastic packaging waste.

The separation standards for household plastic packaging waste are complex. Because the CPRL covers only plastic packaging waste, not plastic product waste,[6] households must identify and separate waste into plastic packaging waste and other types of waste, including plastic product waste, by commodity. Almost all municipalities require residents to adhere to the following conditions when separating plastic packaging waste: (1) it should not have non-plastic packaging material attached to it; (2) it should not be contaminated; and (3) it should not include other types of plastic waste, such as plastic product waste. Moreover, in most municipalities, residents must separate plastic bottles from plastic packaging waste, as plastic bottles are collected separately from other waste. The caps of plastic bottles must also be separated as plastic packaging waste. Although such higher waste-separation standards for households increase the quality of recyclables post-collection, they increase the complexity of separating plastic packaging waste for households and thus may reduce the collection amount.

Data

Our analysis aimed to estimate the effects of simplifying plastic waste-separation standards for home separation on the quantity of plastic packaging waste collected and the quality of recyclables after post-collection separation. We

[3] MSW is collected and disposed of by local municipalities, whereas industrial waste is usually collected and disposed of by private companies.

[4] Local governments in Japan have two tiers: prefectural governments and municipalities (ward, cities, towns, and villages). As of January 2023, Japan had 47 prefectures and 1741 municipalities.

[5] The collection-station system is a collection system where several households use a shared waste collection station, similar to the curbside pick-up and point programs.

[6] Plastic product waste includes, for example, items: polyethene buckets, wash basins, videotapes, ballpoint pens, rulers, and hangers.

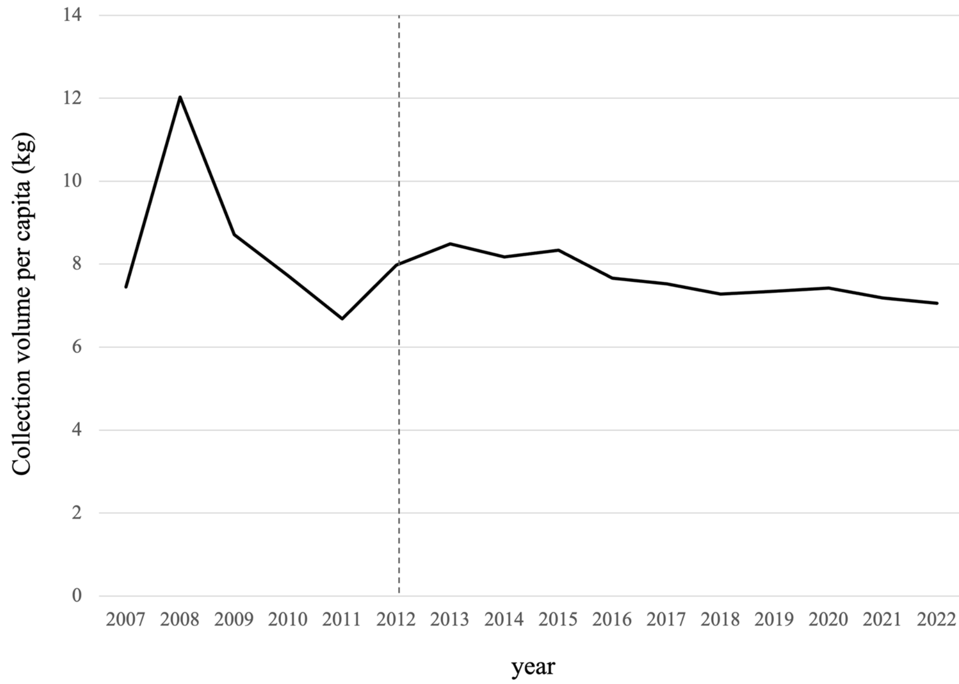


Fig. 2 Trends of collection volume for plastic packaging waste. The gray vertical dotted line represents the moment of the intervention

focus on the fact that many municipalities collect plastic containers and packaging separately from plastic products, whereas some municipalities collect them together without separating them. Because the separation standard for plastic waste is simpler in the latter type of municipality, we can use this situation to analyze the effect of simplifying plastic waste-separation standards. According to the dataset obtained from our survey, plastic product waste was collected in only 4.5% of the municipalities during the survey period. Unfortunately, the dataset shows that most municipalities began collecting plastic packaging waste and plastic product waste simultaneously. Therefore, directly measuring the causal effect of simplifying plastic waste-separation standards on the quantity of collected plastic packaging waste and the quality of recyclables is difficult.

To overcome these problems, we focus on Chiyoda Ward in Tokyo Prefecture, which is the capital of Japan, and employ a causal impact analysis (CIA) based on the Bayesian structural time-series approach [23, 24].[7] The advantage of the Chiyoda Ward dataset is that it contains multiple timepoints data and different policy-implementation periods. Chiyoda Ward collected plastic packaging waste and plastic product waste under different collection categories until 2011 and began collecting them under the same collection category in 2012. While plastic packaging waste has been collected since 2007, plastic product waste was collected with kitchens and non-recyclable waste as combustible waste until 2011. Since 2012, these two types of waste have been collected under the same category through either a door-to-door system or a collection-station system, wherein collection is conducted at fixed times and locations.[8] The Chiyoda Ward authority sorts these plastic wastes in the post-collection stage and recycles them separately.

The consistently and continually updated Chiyoda Ward datasets allow us to compare the quantity of plastic packaging waste at the collection stages over time. Figure 2 shows the trend of collection amounts for plastic packaging waste in Chiyoda Ward. This trend temporarily increased in 2008 and then declined until 2011. From 2007 to 2011, all municipalities in Tokyo Prefecture collected 9.252 kg of plastic packaging waste per capita per year, whereas Chiyoda Ward collected 8.515 kg per capita per year. Thus, the amount of plastic packaging waste in Chiyoda Ward was approximately the average amount for the prefecture before the intervention in 2012. The amount of plastic packaging waste began to increase in 2012, when the simplification of plastic waste

[7] Chiyoda Ward is a municipality belonging to Tokyo prefecture, the capital of Japan. The municipality contained over 67,000 residents as of December 2022. Chiyoda Ward is a major economic center in Tokyo prefecture, with a large concentration of government services and private sector companies. The number of census families in 2020 was 37,011, and that of single families was 21,076 [33]. Until 2011, households were required to sort recyclable waste into six categories (plastic packaging, plastic bottle, paper, cans, glass bottles, and cloth). Plastic packaging waste is to be put in a clear bag, which is collected each week without charge.

[8] Residents do not have a choice of collection method; it is determined by the area in which they live.

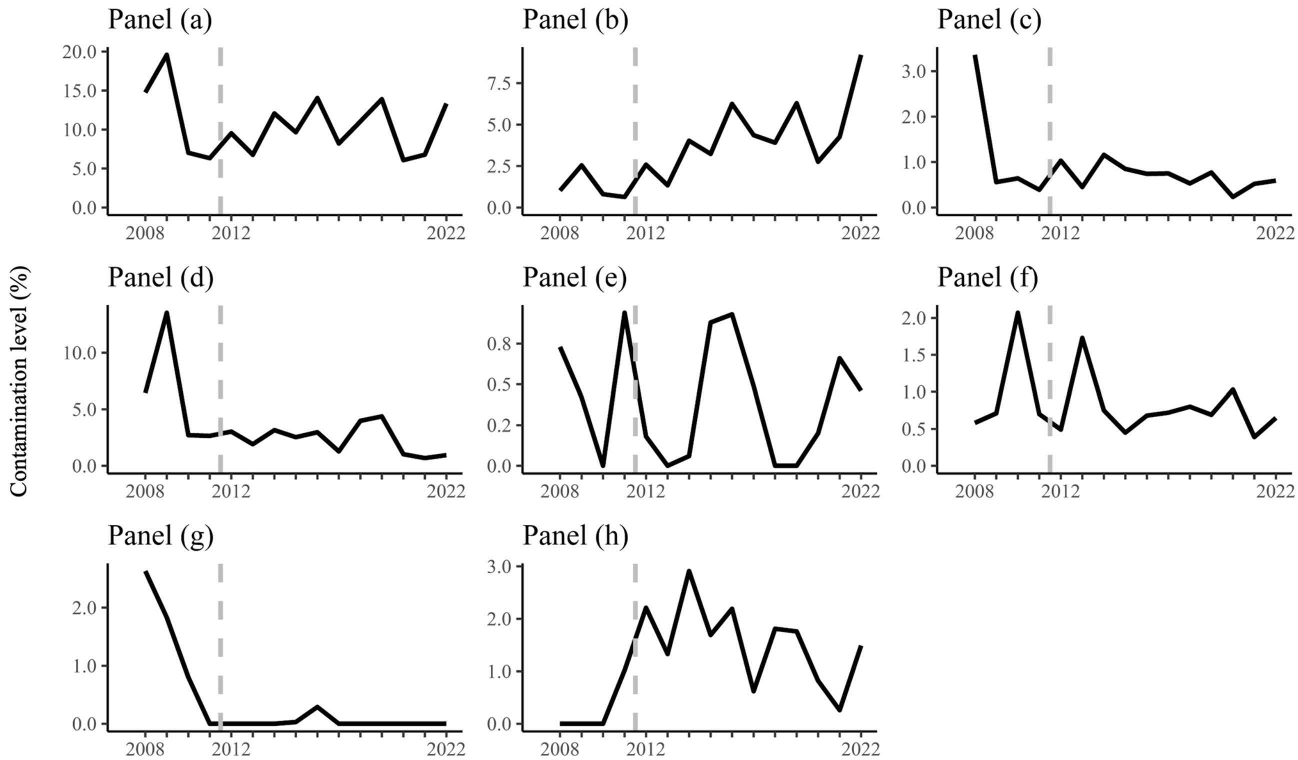


Fig. 3 Assessments of plastic packaging waste contamination after post-collection separation. Figures show the total contamination level (**a**), percentage of plastic product waste mixed with plastic packaging waste (**b**), percentage of containers and packaging waste other than plastic materials mixed with plastic packaging waste (**c**), percentage of dirt adhesion to separated plastic packaging waste (**d**), percentage of plastic bags used for collecting waste mixed with plastic packaging waste (**e**), percentage of plastic bottles mixed with plastic packaging waste (**f**), percentage of business waste (**g**), and percentage of other types of waste mixed with plastic packaging waste (**h**). The gray vertical dotted line represents the moment of intervention

separation began, i.e., when plastic packaging waste and plastic product waste were combined into the same collection category.

Figure 3 shows the quality of recyclables for plastic packaging waste after post-collection separation in Chiyoda Ward. Since 2008, the JCPRA has assessed the contamination of plastic packaging waste separated by municipalities in the post-collection stage.[9] To investigate the contamination of plastic packaging waste separated by municipalities, the JCPRA annually conducts surprise inspections of separated plastic packaging waste in almost all municipalities. The assessment system calculates the contamination levels in plastic packaging waste after post-collection separation, covering the following seven types: total contamination level (Fig. 3a),[10] percentage of plastic product waste mixed with plastic packaging waste (Fig. 3b), percentage of containers and packaging waste other than plastic materials mixed with plastic packaging waste (Fig. 3c), percentage of dirt adhesion in separated plastic packaging waste (Fig. 3d), percentage of plastic bags used for collecting waste[11] mixed with plastic packaging waste (Fig. 3e), percentage of plastic bottles mixed with plastic packaging waste (Fig. 3f), percentage of business waste[12] (Fig. 3g), and percentage of other types of waste mixed with plastic packaging waste (Fig. 3h). The graphs show that the total contamination level (Fig. 3a) and percentage of plastic waste products mixed with plastic packaging waste (Fig. 3b) have increased significantly since 2012. This result is notable because Chiyoda Ward began collecting plastic packaging waste and plastic product waste under the same collection category in 2012. This increase in Fig. 3a, b suggests the negative effect of simplifying plastic waste separation at the collection stage on the quality of recyclables after the post-collection

[9] For details on the guidelines, refer to JCPRA [34].

[10] The total contamination level is defined as the sum of the percentage of specific contamination shown in panels B to H.

[11] In Japan, the plastic bags used for collecting waste are not subject to the category of plastic packaging waste.

[12] Business waste is the waste generated by retailers. Plastic packaging waste generated by retailers is classified as industrial waste and is not subject to the category of plastic packaging waste.

separation of plastic packaging waste. Figures 2 and 3 suggest that simplifying plastic waste-separation standards may influence the quantity of plastic packaging waste at the collection stage and the quality of recyclables after post-collection separation.

Methodology

We employ a CIA based on a Bayesian structural time-series approach to estimate and compare the effects of simplifying home-separation standards for plastic waste on the collection volume of plastic packaging waste and the quality of recyclables after post-collection separation with those of a simulated counterfactual. Using estimates with the pre-intervention data and the observed values of the explanatory variables, CIA predicts the response variable without intervention in the post-intervention period. The impact of simplifying plastic waste separation is the post-intervention difference between the observed value of the collection volume and/or quality of recyclables and these unobserved values predicted in the post-intervention period without intervention. We use the 'CausalImpact' package in R (R Foundation for Statistical Computing, Vienna, Austria) [24] and the Markov chain Monte Carlo-based Bayesian methodology to construct a confidence interval (CI) and estimate the causal effect [23, 24, 35]. In this study, we set the number of MCMC model draws to 20,000. The following pair of equations describe the Bayesian structural time-series model:

$$y_t = Z_t^T \alpha_t + \varepsilon_t \varepsilon_t \sim \mathrm{N}\left(0, \sigma_t^2\right) \tag{1}$$

$$\alpha_{t+1} = T_t \alpha_t + R_t \eta_t \eta_t \sim \mathrm{N}(0, Q_t) \tag{2}$$

Equation (1) is the observation equation. y_t is the response variable linked to a vector of the latent state variable α_t at event time t. Equation (2) is the state equation governing the evolution of the state vector α_t through time. Z_t is the output vector, T_t is the transition matrix, R_t is the control matrix, ε_t is a scalar observation error with noise variance σ_t, and η_t is the system error with a state-diffusion matrix Q_t [24].

The response variable of interest is the volume of plastic packaging waste collected per resident. In addition, to indicate the quality of recyclables after post-collection separation, we use the percentage of total contamination, plastic product waste, containers and packaging waste other than plastic materials, and dirt adhesion to plastic packaging waste separated by the Chiyoda Ward authority (as mentioned in subsection "Data"). We use the logarithm of collection volume per capita and the logarithm of the quality of recyclables, respectively. The covariates in our model include the collection volume of plastic bottles per capita and the number of households. Since these control variables were unrelated to the intervention, their relationship with the response variable remained unchanged in the post-intervention period (Fig. 4). Therefore, these control variables can be used to predict the counterfactual state of an outcome. Table 1 presents summary statistics for the main variables used in this study before and after the intervention. The collection volume of plastic packaging waste in the post-intervention period decreased by approximately 9% compared with that in the pre-intervention period. However, in a simple pre-post analysis, the reduction in collected plastic packaging waste can not be interpreted as an intervention effect, as long-term emission trends can not be considered, and a randomized experiment is not available.

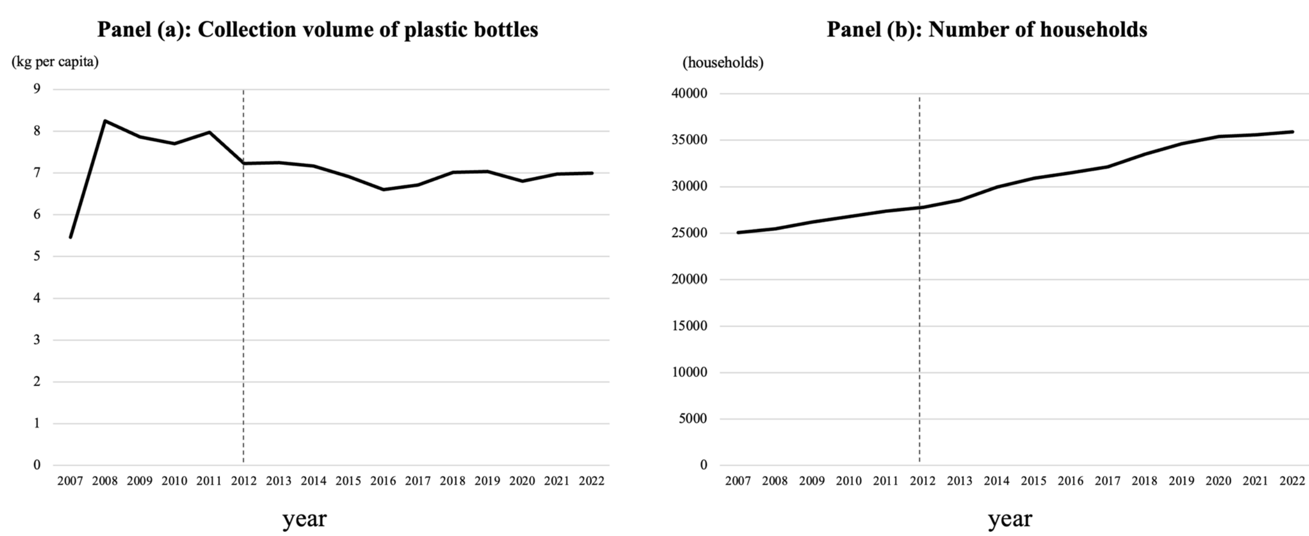


Fig. 4 Control variables. The figure shows the trend in the collection volume of plastic bottles per capita (**a**) and the number of households (**b**) from 2007 to 2022. The gray vertical dotted line represents the moment of intervention

Table 1 Summary statistics

Variable	Unit	Mean	S.D	Min	Max
All (2007–2022)					
Plastic packaging waste	kg/capita	7.937	1.221	6.677	12.026
Plastic bottles	kg/capita	7.119	0.649	5.460	8.249
Number of houses	House	30,412.000	3,810.000	25,039.000	35,889.000
Cross-contamination rate (total)	%	10.609	3.959	6.070	19.600
Percentage of product plastic waste	%	0.838	0.738	0.230	3.360
Percentage of the container and packaging waste other than plastic materials	%	3.547	2.367	0.630	9.210
Percentage of dirt adhesion	%	3.418	3.175	0.690	13.540
Pre-intervention (2007–2011)					
Plastic packaging waste	kg/capita	8.515	2.094	6.677	12.026
Plastic bottles	kg/capita	7.449	1.130	5.460	8.249
Number of houses	House	26,165.200	946.766	25,039.000	27,360.000
Cross-contamination rate (total)	%	11.928	6.381	6.340	19.600
Percentage of product plastic waste	%	1.238	1.419	0.390	3.360
Percentage of the container and packaging waste other than plastic materials	%	1.248	0.876	0.630	2.540
Percentage of dirt adhesion	%	6.335	5.118	2.660	13.540
Post-intervention (2012–2022)					
Plastic packaging waste	kg/capita	7.675	0.492	7.053	8.491
Plastic bottles	kg/capita	6.969	0.206	6.599	7.246
Number of houses	House	32,342.360	2879.848	27,764.000	35,889.000
Cross-contamination rate (total)	%	10.129	2.962	6.070	14.050
Percentage of product plastic waste	%	0.693	0.266	0.230	1.160
Percentage of the container and packaging waste other than plastic materials	%	4.384	2.174	1.340	9.210
Percentage of dirt adhesion	%	2.357	1.271	0.690	4.380

The assessment system for the quality of recyclables after post-collection separation began in 2008; therefore, the descriptive statistics for contamination rates apply from 2008 onward

Data on the collection volume of plastic packaging waste and plastic bottles are obtained from an annual report on MSW from the Tokyo Prefecture from 2007 to 2022 [36]. Data on the contamination levels of separated plastic packaging waste in the post-collection period in Chiyoda Ward from 2008 to 2022 are obtained from disclosure requests to the JCPRA. Data on the number of households are obtained from the e-Stat database of the Official Statistics of Japan [33].

Results

Effects on collection volume

Figure 5 shows the estimation results of the CIA of the collection volume of plastic packaging waste. The gray shaded areas indicate the 95% CI for the prediction, which widens progressively since the predictive strength of the model decreases as it moves away from the intervention year.

The upper panel shows the observed value (solid black line) for the response variable and fitted data (dashed black line), which is a counterfactual prediction for the response variable. Compared with the counterfactual prediction, the collection volume of plastic packaging waste increases after simplifying plastic waste-separation standards, consistent with Dijkgraaf and Gradus's [5] findings. During the post-intervention period, the collection volume of plastic packaging waste had an average value of approximately 2.0, equivalent to approximately 7.7 kg per capita per year. The lower panel (Fig. 5) shows the differences between the counterfactual predictions and the observed values, which are the causal effects of the intervention. The difference between these values is 1.34 (95% CI 0.65, 2.0) on average during the post-intervention period, which is statistically significant at the 1% level. This estimate implies that simplifying plastic waste-separation standards leads to an increase in the collection volume of plastic packaging waste by 2.01 kg per capita per year, on average. These results suggest that the simplified standards for plastic waste separation increase plastic packaging waste-collection volume, indicating that the policy works as intended.

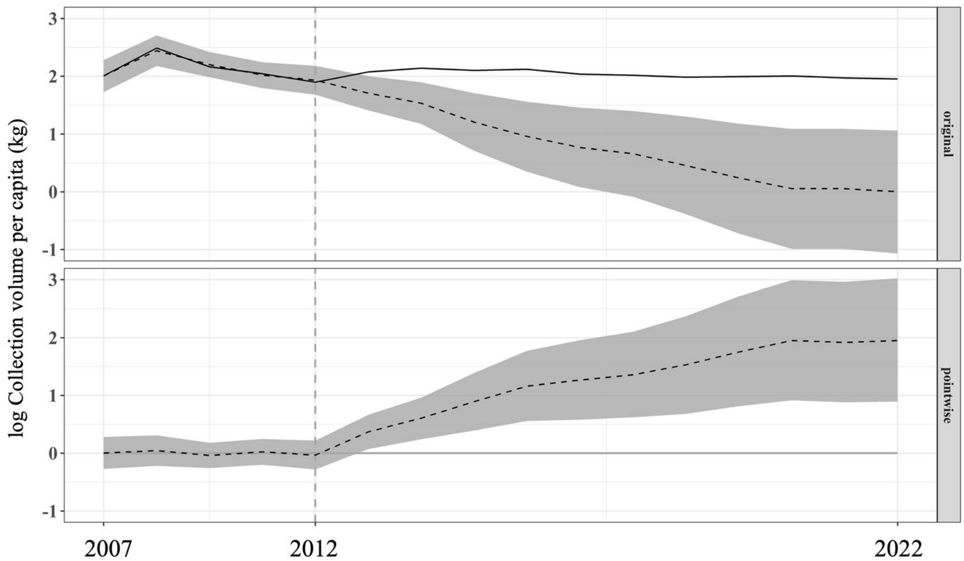


Fig. 5 Estimation results for the amount of plastic packaging waste collected before and after policy intervention. The gray vertical dotted line represents the moment of intervention. The original panel represents the observed data (solid black line) and counterfactual predictions (dashed black line) for the study period. The pointwise panel shows the difference between the observed data and counterfactual predictions. The gray shaded areas indicate the 95% confidence intervals for the prediction

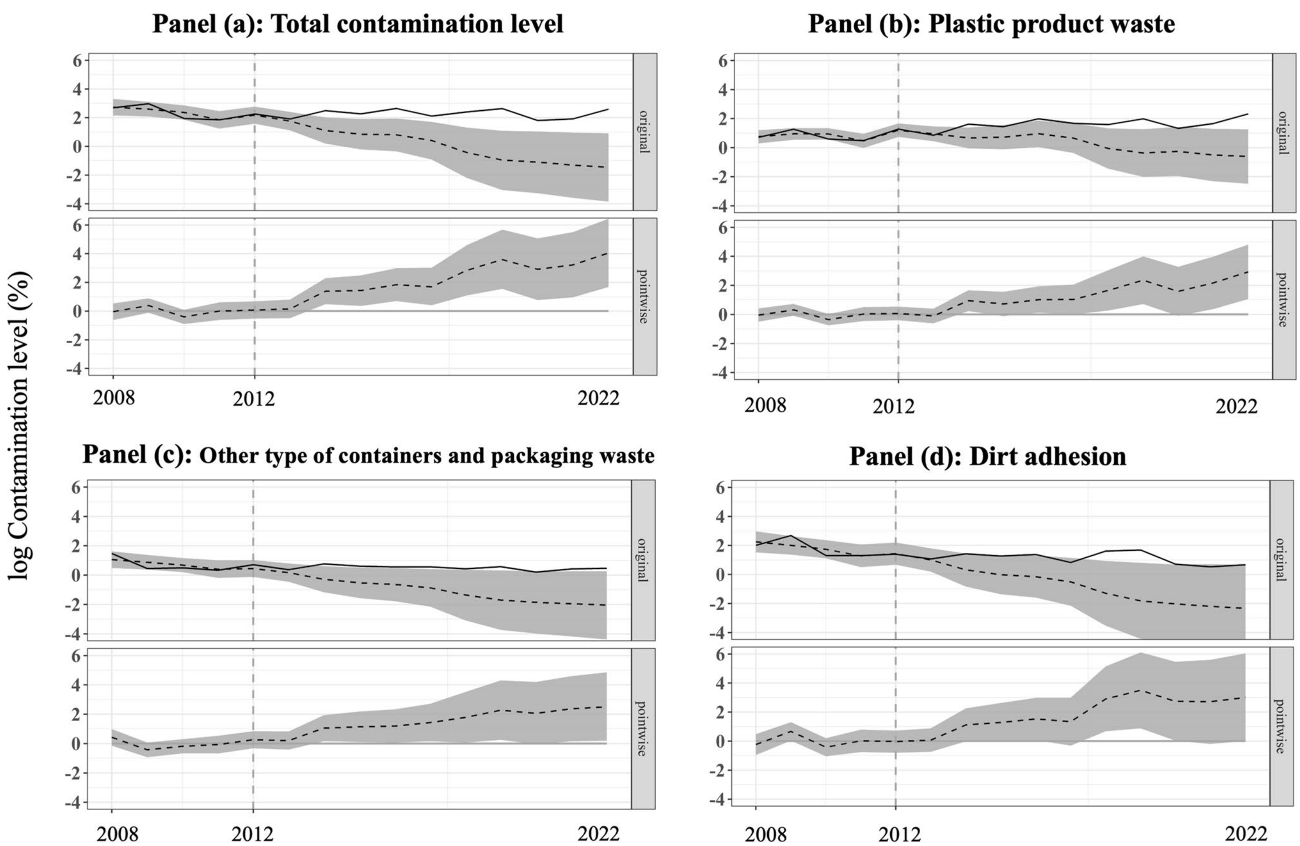


Fig. 6 Estimation results for the quality of recyclables after the post-collection separation of plastic packaging waste. The gray vertical dotted line represents the moment of intervention. The original panels represent the observed data (solid black line) and counterfactual predictions (dashed black line) for the study period. The pointwise panels show the difference between the observed data and counterfactual predictions. The gray shaded areas indicate the 95% confidence intervals for the prediction. The total contamination level of separated plastic packaging waste (**a**), contamination levels of plastic product waste (**b**), other types of containers and packaging waste (**c**), and dirt adhesion (**d**) were analyzed by considering the logarithm after setting the unit to a mixing rate of +1 to prevent a negative value. The assessment system for the quality of recyclables after the post-collection separation of plastic packaging waste began in 2008; therefore, the study period is from 2008 to 2022

Effects on the quality of recyclables after post-collection separation

Figure 6 presents the estimation results for the quality of recyclables after post-collection separation. Figure 6a shows the results for the total contamination level of separated plastic packaging waste. The results show that, compared with the counterfactual prediction, the plastic packaging waste separated in the post-collection stage is more contaminated. The difference between the observed and counterfactual prediction values is 2.36 (95% CI 0.86, 3.78) at a 1% significance level. This estimate shows that simplifying plastic waste-separation standards at the collection stage is associated with a 10.59% increase in the total contamination level of plastic packaging waste separated at the post-collection stage. Figure 6b shows the results for the percentage of plastic product waste mixed with plastic packaging waste. The results show that the difference between the observed and counterfactual prediction values is 1.43 (95% CI 0.29, 2.58) on average during the post-intervention period, at a 1% significance level. This value is equivalent to an approximately 3.18% increase in the percentage of plastic product waste mixed with plastic packaging waste in the post-collection stage. Figure 6c shows the percentage of containers and packaging waste other than plastic materials mixed with plastic packaging waste. We find that simplifying plastic waste-separation standards at the collection stage also increases the percentage of containers and packaging waste other than plastic materials mixed with plastic packaging waste in the post-collection stage. The results show that the difference between the observed and counterfactual prediction values is 1.60 (95% CI 0.18, 3.05) on average during the post-intervention period, at a 5% significance level. This value is equivalent to an approximately 3.95% increase in the contamination levels of the other types of containers and packaging waste. Figure 6d shows that simplifying the home-separation standards for plastic waste increases the percentage of dirt adhesion with separated plastic packaging waste. The difference between the observed and counterfactual prediction values is 2.02 (95% CI 0.19, 3.88) on average during the post-intervention period, at a 5% significance level. This is equivalent to an approximately 6.54% increase in dirt adhesion contamination. These results indicate that collecting several types of plastic waste under the same category creates difficulties in separating them at the post-collection stage.

Robustness checks

The remaining analyses aim to demonstrate the robustness of the results. As a robustness check, we first estimate the same specifications as those in Fig. 5, excluding the 2008 data. The collection volume increased considerably in 2008 (Fig. 2), which may have caused an overestimation of the results shown in Fig. 5. The results, excluding the 2008 data for collection volume, are summarized in Fig. 7. The results show that the difference between the observed and counterfactual prediction values is 0.91 (95% CI 0.34, 1.49) on average during the post-intervention period at a 1% significance level. This value equals approximately 2.48 kg per capita per year in terms of the volume of plastic packaging waste collected after the intervention. Figure 8 plots the estimation results for post-collection separation quality, excluding the 2008 data. We find that, while the percentage of containers and packaging waste other than plastic materials is not significantly different from the counterfactual in Fig. 8c, even if the dataset excluded 2008 data, the yield estimates for

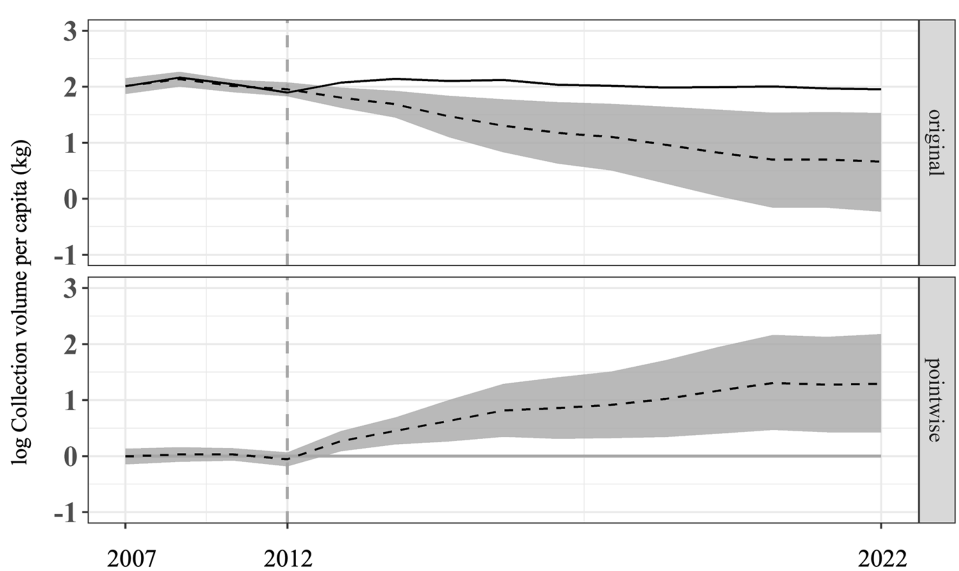


Fig. 7 Results for collection volume with the omitted 2008 data. The gray vertical dotted line represents the moment of intervention. The original panel represents the observed data (solid black line) and counterfactual prediction (dashed black line) for the post-intervention period. The pointwise panel shows the difference between the observed data and counterfactual predictions

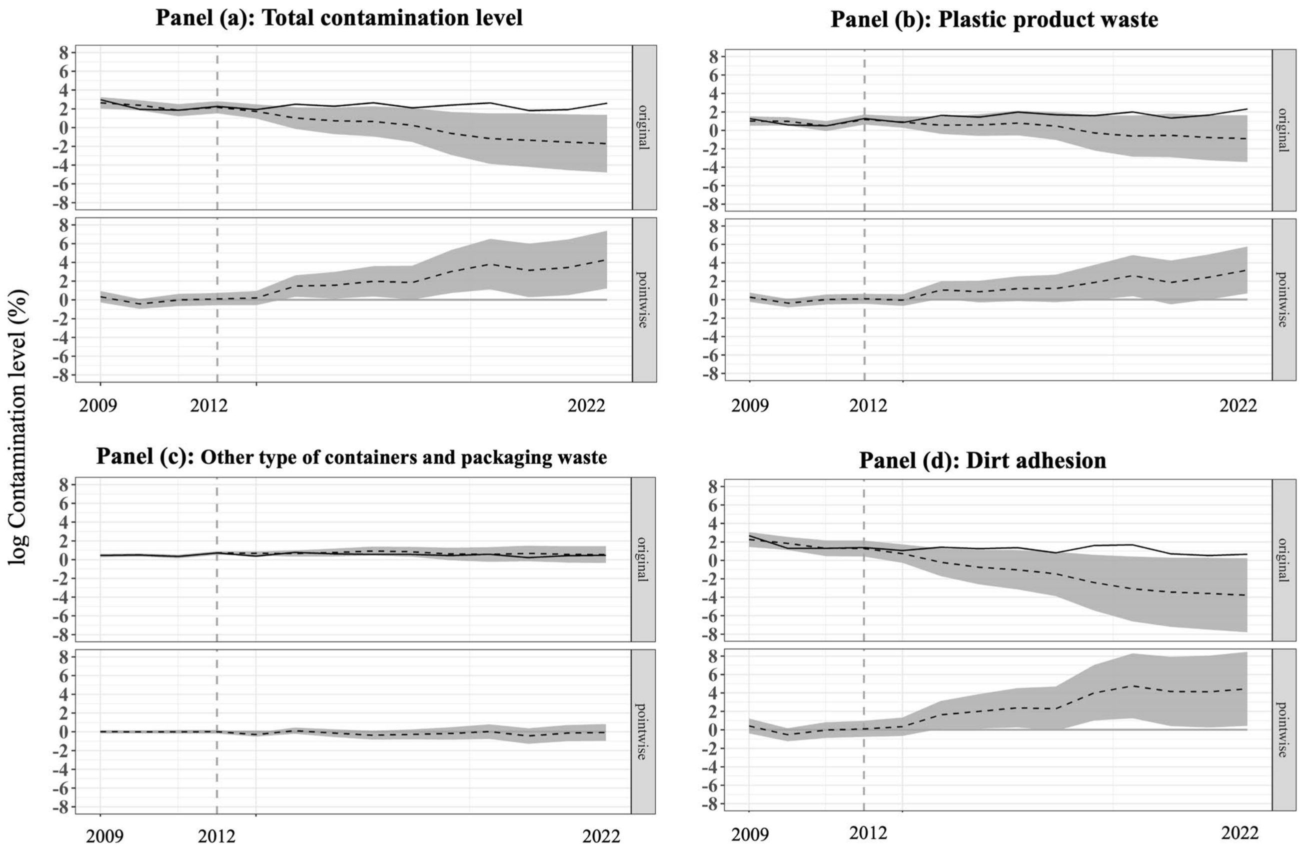


Fig. 8 Results for the quality of recyclables after post-collection separation with the omitted 2008 data. The gray vertical dotted line represents the moment of intervention. The original panels represent the observed data (solid black line) and counterfactual predictions (dashed black line) for the study period. The pointwise panels show the difference between the observed data and counterfactual predictions. The gray shaded areas indicate the 95% confidence intervals for the prediction. The total contamination level of separated plastic packaging waste (**a**), contamination levels of plastic product waste (**b**), other types of containers and packaging waste (**c**), and dirt adhesion (**d**) were analyzed by considering the logarithm after setting the unit to a mixing rate of +1 to prevent a negative value. The assessment system for the quality of recyclables after the post-collection separation of plastic packaging waste began in 2008; therefore, the study period is from 2009 to 2022

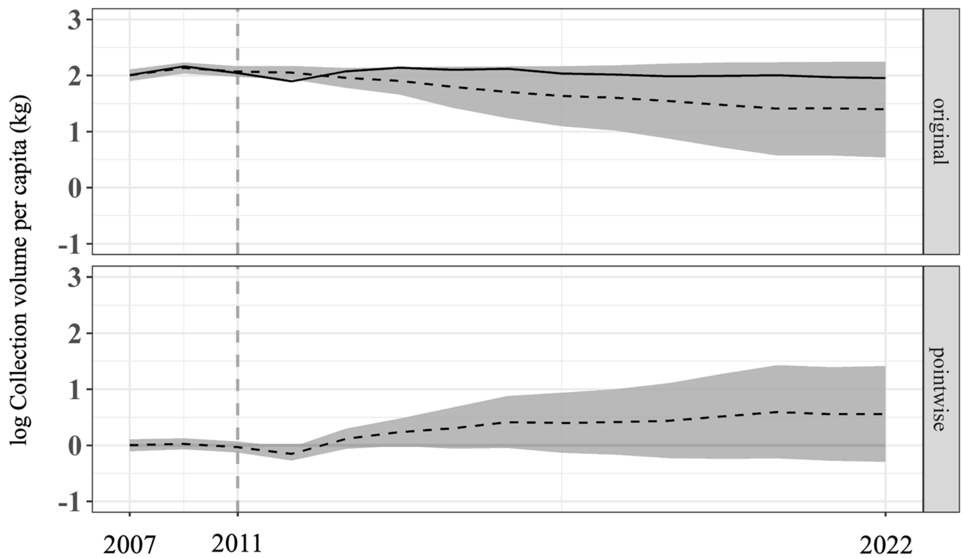
the effect of the intervention are close to the benchmark estimates in terms of the percentage of total contamination (Fig. 8a), plastic product waste (Fig. 8b), and dirt adhesion (Fig. 8d) in separated plastic packaging waste. These results, therefore, provide evidence in favor of the robustness of the results.

Moreover, for completeness, we check the robustness of our findings by changing the intervention period as in the placebo test. Chiyoda Ward began collecting plastic packaging waste and plastic product waste under the same category in 2012. To check the robustness of our findings, we estimate using the year 2011 as the timing of the intervention instead of 2012. Figure 9 shows that the collection volume did not change in the absence of the intervention in 2012. Figure 10 shows the results for the quality of recyclables after post-collection separation, with 2011 used as the intervention period. We also find no evidence of effects on the quality of recyclables after post-collection separation when the intervention period began in 2011 instead of 2012. These results support our benchmark finding that simplifying the plastic waste-separation standards introduced in 2012 led to an increase in plastic packaging waste-collection volume and a decrease in the quality of recyclables after post-collection separation.

Conclusion

This study investigated the effects of simplifying plastic waste separation for households on the amount of plastic packaging waste collection and the quality of recyclables after post-collection separation. Our counterfactuals yielded two main conclusions: first, simplifying waste separation by adding other types of plastic waste to the plastic packaging waste collection category increases the amount of plastic packaging waste collected. This result indicates that

Fig. 9 Results for the intervention period using 2011 for the collection volume. The gray vertical dotted line represents the moment of intervention. The original panel represents the observed data (solid black line) and counterfactual prediction (dashed black line) for the post-intervention period. The pointwise panel shows the difference between the observed data and the counterfactual predictions



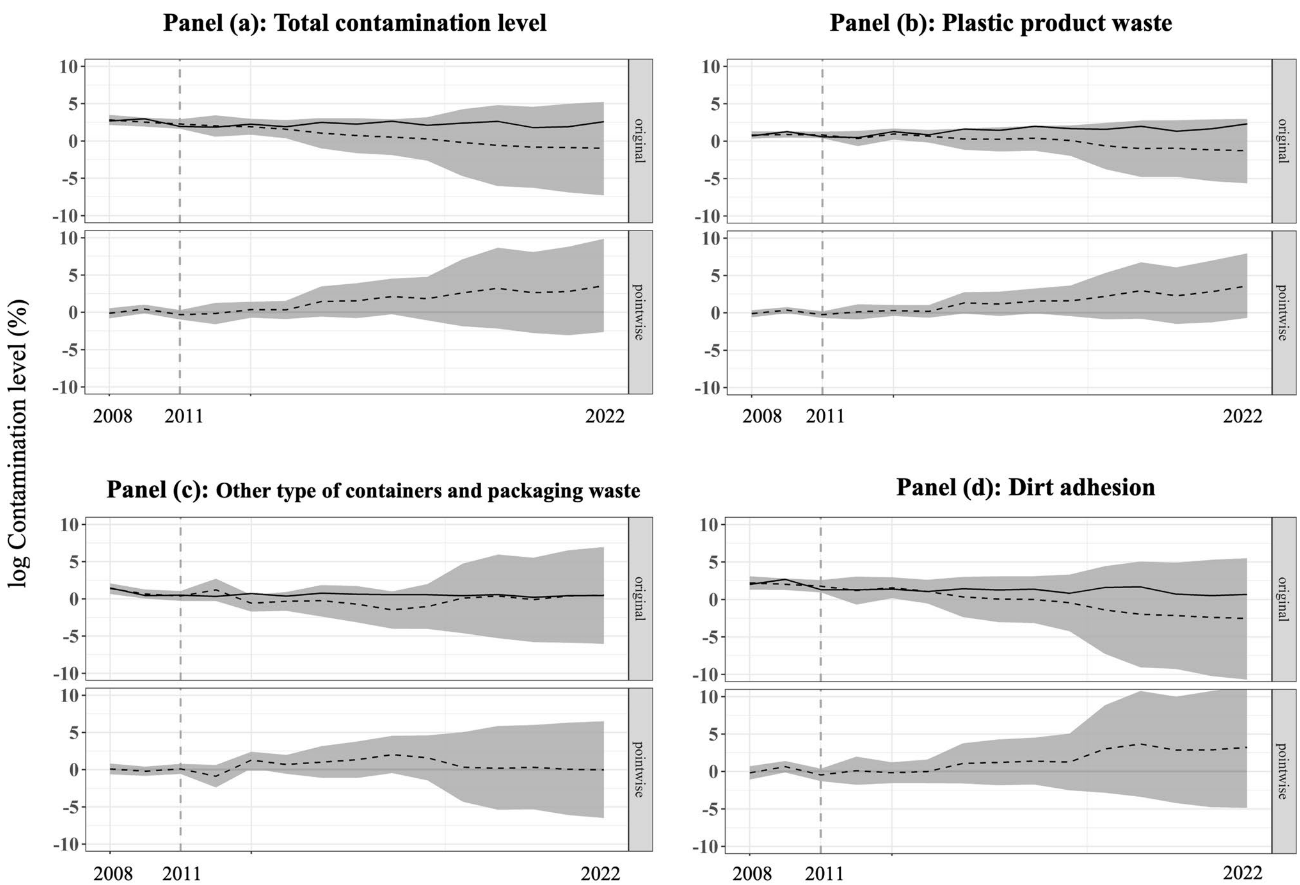


Fig. 10 Results for the intervention period using 2011 for the quality of recyclables after the post-collection separation. The gray vertical dotted line represents the moment of intervention. The original panels represent the observed data (solid black line) and counterfactual predictions (dashed black line) for the study period. The pointwise panels show the difference between the observed data and counterfactual predictions. The gray shaded areas indicate the 95% confidence intervals for the prediction. The total contamination level of separated plastic packaging waste (**a**), contamination levels of plastic product waste (**b**), other types of containers and packaging waste (**c**), and dirt adhesion (**d**) were analyzed by considering the logarithm after setting the unit to a mixing rate of +1 to prevent a negative value. The assessment system for the quality of recyclables after the post-collection separation of plastic packaging waste began in 2008; therefore, the study period is from 2008 to 2022

simplified standards for waste separation induce a decrease in the burden and opportunity cost of waste separation for households and an increase in collection volume. Given the assumption that these results can be accepted as prima facie evidence of a causal effect on the collection volume, our findings demonstrate that simplifying waste separation may improve household behavior regarding plastic recycling and collection volume. Second, reducing the plastic waste collection categories leads to greater contamination of plastic packaging waste separated after collection with other types of plastic waste and dirty plastic packaging waste. This result suggests that simplifying the standards for home separation increases the cost of waste separation for municipalities and recyclers and, consequently, decreases the quality of recyclables after post-collection separation. Our results highlight the magnitude of the burden and opportunity cost of waste separation in recycling [6, 8].

Many policies on post-consumer plastic waste have been implemented worldwide and will continue to be implemented. Adopting a program to simplify plastic waste separation in Japan presents an interesting case study due to the national policy. The MOE, for instance, enacted a new law in 2022 to encourage municipalities to collect and recycle post-consumer plastic product waste, excluding plastic packaging waste.[13] In principle, plastic products are recycled independently at the discretion of each municipality. This law creates a nationwide framework for recycling plastic product waste collected together with plastic packaging waste. However, the plastic waste-separation program can also have some drawbacks. Our results show that simplifying waste-separation programs results in a decrease in the quality of recyclables after post-collection separation. For municipalities with lower recycling capacities, implementing post-collection separation will be more difficult because they have less residual capacity to sort additional plastic product waste from collected plastic waste. Therefore, understanding how waste-separation standards affect not only the collection volume but also the quality of recyclables after post-collection separation is essential for evaluating the effectiveness of recycling policies. Moreover, MSW collection programs involving door-to-door and station collection, which is similar to curbside pick-up and collection points, adopted in Chiyoda Ward, Japan (featured in this study), have been introduced in virtually all most developed countries [2]. Because the waste collection methods addressed in this study are used in many other countries, the results of the present study may also be applicable to them. In addition, the number of studies focusing on these collection schemes for MSW and recycling has increased worldwide (e.g., the Netherlands [5], Denmark [37], Germany [38], Spain [39], Sweden [40], and the US [41, 42]). Given the recent global interest in plastic recycling and collection programs, the effects of simplifying waste-separation standards on the volume of plastic waste collection and the quality of recyclables embody policy relevance beyond the national scope.

Due to data limitations, we are unable to examine the impact of simplifying waste separation on the production volume and quality of recycled plastic products. Investigations into the precise mechanism underlying the relationship between waste-separation standards at the collection stage and recycled plastic products could provide crucial knowledge for predicting recycling volume. Moreover, our results indicate that simplifying plastic waste separation leads to greater contamination of plastic packaging waste separated after collection. Simplifying separation categories may facilitate recycling where separation and cleaning facilities have adequate capacity; however, where these facilities have inadequate capacity, simplification of the separation categories may inhibit recycling. Therefore, understanding the impact of simplifying plastic waste separation on the recycling volume is important. Future research could address this question if more detailed data on recycled plastic products become available after the recycling process.

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Data availability All data used in this study are available from the authors upon request. For more information, please refer to the Data Statement page.

Declarations

Conflicts of interest The authors declare no conflicts of interest relevant to the content of this article.

[13] Most municipalities, however, do not collect and recycle plastic product waste at present because of a reverse fee trade with recycling companies to recycle collected plastic product waste and because of a lack of financial support from the central government.

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