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Behavioral response to convenience: A natural experiment on door-to-door selective waste collection

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ABSTRACT

This study evaluates the behavioral effects and impact of the curbside double-bin system, which represents a specific form of door-to-door selective waste collection, using a natural experimental design and the COVID-19 pandemic as an exogenous shock. A two-way fixed effects (TWFE) regression model, based on a difference-in-differences (DiD) approach, was applied to municipal-level panel data collected from 93 Hungarian municipalities between 2012 and 2023. The aim of the research is to isolate the causal impact of selective waste collection infrastructure under conditions of external pressure. Municipalities equipped with curbside double-bin systems were found to generate, on average, 11.76 kilograms more selectively collected waste per capita annually, relative to those without such systems, while the volume of mixed waste remained stable. These findings suggest that the presence of convenient waste sorting infrastructure contributed to an increase in overall waste generation, rather than a substitution between waste streams. This outcome has been interpreted as evidence of the Perceived Disposal Ease Bias, whereby the effortlessness of disposal encourages higher material throughput. The results underscore the importance of accounting for behavioral responses when evaluating the environmental effectiveness of waste management policies. It is recommended that convenience-enhancing infrastructure be supplemented with targeted communication and behavioral interventions to ensure alignment with sustainability objectives. To the best of the authors' knowledge, this study represents one of the first empirical applications of a quasi-experimental framework to assess the behavioral implications of selective collection systems under external shocks.

1. Introduction

Over the past decade, significant transformations in waste management and recycling practices have reshaped public attitudes toward environmental sustainability. The global expansion of selective waste collection systems has been accompanied by the development of waste management infrastructure and a heightened awareness of environmental issues (Abbas and Lamri, 2025; Boström, 2021; Ráti and Maró, 2026a). However, a circular economy rebound effect has also been documented in certain contexts (Zink and Geyer, 2017; Mongo, 2021; Metic and Pigosso, 2022), wherein the introduction of selective waste collection has paradoxically coincided with an increase in overall waste generation. This phenomenon reflects a behavioral response in which adequate waste management infrastructure is perceived by consumers as justification for increased consumption (Chen, 2021; Ráti and Maró, 2026b). At the same time, the COVID-19 pandemic introduced unprecedented challenges to waste management systems. Lockdowns, rising online shopping, and the widespread use of protective equipment (e.g., masks and gloves) were associated with significant shifts in both the quantity and composition of household waste (Silva et al., 2021). Although a reduction in overall municipal waste was associated with decreased economic activity, several studies reported increases in selectively collected waste, particularly packaging materials (Ráti and Maró, 2026b; Benson et al., 2021; Lehmann et al., 2021). In addition, heightened environmental awareness was observed during and after the pandemic period, as individuals became increasingly engaged with sustainability-related behaviors (Ganguly and Chakraborty, 2021; Matiiuk and Liobikienė, 2023).

Despite extensive research on household recycling behavior and waste separation practices (Derksen and Gartrell, 1993; Jenkins et al.,

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2003; Arteaga et al., 2023), limited empirical research has explored how behavioral responses to waste management infrastructure evolve under external shocks, such as public health crises. While previous studies have examined the effectiveness of selective waste collection systems under normal conditions, the potential for such infrastructure to induce unintended behavioral consequences during times of disruption remains underexplored. Moreover, while the circular economy rebound effect has been conceptualized theoretically (Zink and Geyer, 2017; Lowe et al., 2024), empirical assessments quantifying its manifestation in real-world municipal waste data remain scarce. This study addresses this gap by applying a quasi-experimental approach that exploits the COVID-19 pandemic as an exogenous shock to evaluate and isolate the behavioral and rebound effects of selective waste infrastructure under externally imposed constraints. The research provides evidence that infrastructure convenience may increase total waste generation, highlighting the behavioral dynamics underlying policy outcomes. Methodologically, the study employs a two-way fixed effects (TWFE) regression model based on a difference-in-differences (DiD) framework (Callaway and Sant'Anna, 2021; Goodman-Bacon, 2021) to assess the causal impact of door-to-door selective waste collection on household-level waste outcomes. This approach improves earlier correlational analyses by addressing concerns of self-selection and unobserved heterogeneity. Moreover, it introduces and empirically tests the concept of the Perceived Disposal Ease Bias (PDEB), a behavioral mechanism explaining how convenience may increase total waste generation rather than merely shifting composition. Thus, the study contributes to the theoretical literature on behavioral distortions in environmental decision-making.

The findings also have clear implications for environmental policy. While selective collection systems are effective in increasing recycling rates, they may also unintentionally encourage overconsumption unless complemented by behavioral nudges and communication strategies (Kirkman and Voulvoulis, 2017; Kollmuss and Agyeman, 2002). Thus, this study assesses how the curbside double-bin system, as a specific form of door-to-door selective waste collection, affects household waste generation under conditions of external pressure. The COVID-19 pandemic is employed as an exogenous shock to isolate the behavioral effects associated with infrastructure-enabled convenience, rather than to evaluate the pandemic's direct consequences. This analytical lens facilitates the examination of the dynamic interplay between individual decision-making and environmental incentives within the context of contemporary waste management (Buheji, 2020; Thøgersen, 2014). By applying a natural experimental design, the study seeks to generate novel empirical insights to inform the development of more effective and behaviorally informed sustainability policies. To achieve these objectives, the remainder of the paper is structured as follows. Section 2 reviews the relevant literature and theoretical background. Section 3 describes the data and empirical methodology. Section 4 presents the results, followed by Section 5, which discusses the findings and their theoretical and policy implications. Section 6 concludes with the key messages of the study.

2. Literature review

2.1. Theoretical background

The conceptual framework of this study is grounded in three interrelated theoretical domains: behavioral economics, the Perceived Disposal Ease Bias (PDEB), and the circular economy rebound effect. Together, these perspectives provide a lens through which the unintended behavioral consequences of selective waste collection infrastructure can be analyzed, particularly under conditions of external shocks. First, behavioral economics offers a critical departure from the classical assumption of fully rational actors in environmental decision-making. Instead of treating individuals as utility-maximizing agents with complete information, behavioral approaches emphasize cognitive biases, heuristics, and context-specific motivators (Kollmuss and Agyeman, 2002; Thøgersen, 2014). In the realm of municipal waste management, decisions related to sorting, recycling, and disposal are often shaped by perceived effort, habits, and moral licensing, rather than by a consistent commitment to environmental values (Derksen and Gartrell, 1993; Schultz et al., 1995; Lin, 2024). The literature has increasingly recognized that infrastructural design, especially the ease and immediacy of waste disposal, can systematically alter household behavior, sometimes undermining broader sustainability objectives (Barr et al., 2003).

Second, the study draws on the concept of the PDEB, a form of behavioral distortion wherein individuals misinterpret infrastructural convenience as an environmental virtue. As described by (Chen, 2021), it could emerge when improved access to recycling or disposal systems reduces the perceived environmental cost of consumption, leading to elevated material throughput. Even in the absence of significant changes in ecological awareness, convenience can trigger behavior that is environmentally counterproductive. When waste sorting becomes effortless due to infrastructure, consumers may feel less compelled to reduce consumption or reuse materials (Zink and Geyer, 2017). Third, the analysis is grounded in the circular economy rebound effect, which refers to the paradoxical outcome wherein efficiency gains in resource use or waste processing incentivize greater consumption overall (Zink and Geyer, 2017; Metic and Pigosso, 2022; Figge and Thorpe, 2019). While the circular economy aims to minimize waste through reuse, recycling, and regeneration, its implementation can unintentionally lower the psychological and financial costs of waste generation. In this context, improvements in collection systems may not lead to lower net waste production but instead create a false sense of environmental responsibility that facilitates increased disposal (Lowe et al., 2024; Guzzo et al., 2024). This effect is particularly relevant when evaluating the success of selective collection infrastructure (Ráti and Maró, 2026c; Ráti and Maró, 2026d), which may boost recycling rates but also reinforce unsustainable consumption patterns. By integrating these three theoretical strands, the present study examines whether the curbside double-bin system, as a specific form of door-to-door selective waste collection, is associated with environmentally beneficial changes in waste separation or with rebound dynamics rooted in convenience-driven biases under conditions of external pressure.

2.2. Inconsistent mechanisms behind waste generation

The identification of the determinants of waste generation has been recognized as a complex and multifaceted challenge. A wide range of studies has emphasized the considerable influence of socio-economic, demographic, cultural, institutional, infrastructural, and policy-related variables on waste generation patterns [see e.g., 31, 32–34]. Demographic characteristics, geographic contexts, income levels, educational attainment, household size, and degrees of urbanization have consistently been identified as key factors shaping waste generation rates and disposal behavior. However, the empirical findings remain frequently contradictory across different contexts. Socio-demographic variables such as gender, age, education, and income have been highlighted as significant predictors of recycling behavior (Saphores et al., 2006). It has been observed that older individuals were more likely to engage in recycling programs (Jakus et al., 1997; Matsumoto, 2011), although other studies failed to find any statistically significant relationship between age and recycling behavior (Werner and Makela, 1998). Gender has also been found to play a pivotal role in household waste management decisions, though the strength and direction of its influence have been shown to vary across different cultural and socio-economic environments. While higher rates of waste separation among women have been shown (Ráti and Maró, 2026c; Ekere et al., 2009), other investigations have reported no significant gender-based differences (Gamba and Oskamp, 1994).

Income has been identified as another critical factor, with higher

income levels generally associated with greater participation in recycling activities (Ráti and Maró, 2026c; Gamba and Oskamp, 1994). However, other studies have indicated that increased income may also correspond with higher overall waste generation (Hidalgo et al., 2019; Khan et al., 2016). It has further been noted that cultural norms and incentive structures may moderate this relationship, as demonstrated in findings where higher income did not necessarily lead to increased waste generation (Zorpas et al., 2017). The relationship between education and recycling behavior has similarly been subject to divergent interpretations (Jakus et al., 1997; Kala and Bolia, 2020). Thus, income and education may increase participation in selective waste collection, but they may also be associated with higher consumption levels and, consequently, greater overall waste generation.

Although it has been demonstrated that larger households tend to generate greater absolute volumes of waste (Rybova, 2019; Rybová et al., 2018), the influence of household size on waste management practices remains inconclusive. In certain cases, larger household units have been observed to adopt more efficient waste management strategies, resulting in reduced per capita waste generation (Van Fan et al., 2025). Cultural norms and socio-economic factors have likewise been shown to exert highly variable effects on waste management behaviors. For instance, significant barriers to effective waste handling have been attributed to infrastructural deficiencies and economic inequality (Jagun et al., 2023). In contrast, it has been found that economic downturns often correlate with a reduction in waste generation, indicating a context-dependent relationship between economic conditions and waste production (Namlis and Komilis, 2019). Although general patterns can be observed in the influence of socio-economic, demographic, and cultural factors on waste generation and management, the findings across the literature remain inconsistent. These discrepancies suggest that waste generation cannot be explained by socio-demographic characteristics alone, but must be interpreted together with the institutional design of waste collection systems, the convenience of infrastructure, and the presence or absence of direct economic incentives.

2.3. Waste management systems and consumer behavior

The evolution of waste management systems over recent decades has been marked by significant transformations in environmental sustainability practices and strategies. Contemporary systems, including collection islands, door-to-door selective waste collection schemes, and municipal waste reduction initiatives, have been implemented with the objective of minimizing adverse environmental impacts and enhancing recycling performance. The global proliferation of modernized waste management structures and the widespread adoption of selective collection systems have been documented (Silva et al., 2021; Sharma et al., 2020; Luhar et al., 2022). A central mechanism behind these changes is convenience. Waste separation at the household level is often perceived as time-consuming, space-demanding, and effort-intensive, which may discourage participation unless suitable infrastructure is provided.

Empirical support for this interpretation has been provided by (Vassanadumrongdee and Kittipongvises, 2018), whose study in Bangkok revealed that the primary obstacles to participation in selective waste collection were identified as the lack of suitable containers (21.9%), insufficient drop-off points (20.4%), and the perceived time burden of sorting waste (19.5%). Convenience has been repeatedly identified in the literature as a critical factor influencing household engagement in waste management (Ráti and Maró, 2026d; Sidique et al., 2010; Timlett and Williams, 2008; Owusu et al., 2013). It has been emphasized that the availability and accessibility of supporting infrastructure are essential to encourage participation (Bernstad et al., 2013). The spatial proximity and placement of collection facilities further influence recycling behavior, as shorter distances and easier access reduce the effort required for source separation (González-Torre and Adenso-Díaz, 2005; Hage et al., 2009; Lange et al., 2014).

Several empirical studies confirm that improved access to collection infrastructure increases participation in source separation. For example, the introduction of selective bins in Hanoi significantly increased the proportion of compostable waste collected (Nguyen et al., 2015). Evidence from US households similarly shows that curbside recycling services positively influence source separation behavior, although the magnitude of the effect varies by waste type (Jenkins et al., 2003). These findings suggest that infrastructure can be a powerful driver of sorting behavior, but they do not necessarily imply a reduction in total waste generation. At the same time, infrastructure alone is rarely sufficient. Poor infrastructural conditions may hinder the transition from waste disposal to resource recovery (Henry et al., 2006; Goulart Coelho et al., 2017; Narayana, 2009), while public engagement, communication, and transparent planning remain essential for effective waste management systems (Kirkman and Voulvoulis, 2017; Rootes, 2009).

The question of which types of infrastructure deployment prove most effective under varying circumstances remains underexplored. A notable contribution in this area has been made by (Struk, 2017), whose study conducted in the Czech Republic demonstrated that both curbside collection and selective island systems significantly increased the proportion of waste that was properly separated. (Struk, 2017) proposed a typology of waste collection systems based on the degree of convenience offered to users. Three principal categories of infrastructure were identified: selective yards, selective islands, and curbside collection. Selective yards involve controlled-access facilities with relatively high logistical costs for users; selective islands provide publicly accessible centralized containers; and curbside collection represents the most convenient household-level option, typically implemented through bins or bags. The findings of Struk (Struk, 2017) suggest that the effectiveness of waste collection infrastructure is closely tied to the balance between service accessibility, operational cost, and user convenience. Municipalities lacking collection infrastructure exhibited the lowest rates of source-separated waste, particularly for recyclable materials such as paper and plastic, while curbside collection was found to be the most effective option for increasing source separation in quantitative terms. These findings are consistent with earlier evidence showing that curbside collection can improve recycling performance and participation rates (Barr et al., 2003; Abbott et al., 2011).

However, an important distinction must be made between convenience-enhancing collection infrastructure and broader policy packages that combine door-to-door collection with direct economic incentives. Empirical research shows that door-to-door schemes, particularly when combined with pay-as-you-throw (PAYT) pricing or related waste-pricing instruments, can reduce residual or total municipal waste while increasing sorted waste collection. Evidence from Italian municipalities is especially relevant in this regard (Barbaglia et al., 2025; Compagnoni, 2020; Di Matteo and Guadagno, 2024). They show that the effects of door-to-door collection and PAYT depend on their interaction and on the wider regional policy context. The introduction of a PAYT threshold tariff and monetary incentives significantly increased the recycling share and reduced total waste per capita, highlighting the role of financial incentives in altering household disposal behavior (Rizzo and Secomandi, 2024; Bucciol et al., 2015; Valente, 2023). In contrast, the present study focuses on the curbside double-bin system as a convenience-enhancing form of door-to-door selective waste collection, without a direct quantity-based financial incentive comparable to PAYT. This distinction is central to the interpretation of the results since PAYT-based systems may, and in many cases do, reduce waste by making disposal financially salient, whereas bin-based curbside collection may primarily reduce the effort cost of source separation and disposal.

In general, door-to-door selective waste collection systems have produced measurable improvements in recycling rates, their implementation may also give rise to unintended behavioral consequences (Wagner and Broaddus, 2016). If convenience is introduced without a

corresponding incentive to reduce the total quantity of waste, households may increase participation in selective collection without reducing overall material throughput. This mechanism is consistent with the PDEB, and the broader circular economy rebound effect, whereby convenient recycling or disposal infrastructure may lower the perceived environmental cost of consumption (Zink and Geyer, 2017; Chen, 2021; Figge and Thorpe, 2019). Under the COVID-19 pandemic, when home-based consumption, online shopping, and packaging-intensive deliveries increased, such convenience-based effects may have become more pronounced (Silva et al., 2021; Benson et al., 2021; Ganguly and Chakraborty, 2021). To accurately capture these heterogeneous behavioral effects, the use of a natural experiment design has been deemed particularly suitable. This methodological approach relies on an exogenous shock that is unrelated to local policy decisions or infrastructural characteristics. Given that the implementation of COVID-related restrictions was exogenous to municipal waste management policies, it provides a quasi-randomized setting in which the presence or absence of selective collection infrastructure can be exploited to isolate causal effects on household waste behavior. By circumventing the issue of self-selection and enhancing internal validity, this framework offers a robust empirical strategy for evaluating the behavioral consequences of environmental interventions.

3. Materials and methods

3.1. Data and research design

A range of selective waste collection methods has been implemented across municipalities in Hungary. Among these, the curbside double-bin system, in which households are provided with two distinct containers, one for plastic and one for paper waste, represents a specific form of door-to-door selective waste collection and is one of the most commonly used approaches. In certain regions, a curbside bag system has also been adopted, whereby designated bags, rather than containers, are distributed to residents for the purpose of selective collection. In addition, selective islands have been installed in some municipalities, particularly within smaller settlements, offering centralized locations for the deposit of recyclable materials. Unlike the curbside double-bin and bag-based systems, selective islands are not considered door-to-door collection systems, as recyclable materials must be transported by residents to centralized collection points.

Based on the above, this study focuses specifically on the curbside double-bin system and evaluates its impact on municipal waste generation by examining changes in aggregated selectively collected waste and mixed waste under conditions of external pressure. The bag-based version of door-to-door selective collection is excluded from the empirical treatment, as previous evidence suggests that it has no measurable effect (Ráti, 2025). In the curbside double-bin system, source separation refers specifically to paper and plastic waste streams, which are collected in two separate household-level containers. Other recyclable materials, such as glass, may be collected through alternative systems, including selective islands, but they are not part of the empirical treatment analyzed here. The data employed in this analysis were obtained from the official repositories of the Hungarian Central Statistical Office (Hungarian Central Statistical Office, 2025), which provide detailed annual waste collection records for a sample of 93 Hungarian municipalities. The HCSO compiles these data based on annual reports submitted by local governments and licensed waste management companies. The quantities of mixed (residual) and selectively collected waste are measured at the point of collection and verified at transfer stations or sorting facilities using truck-mounted weighbridge systems. The data are recorded in kilograms per capita per year, following the European Waste Classification (EWC) scheme. Each operator is legally required to report the total amount of waste collected by category and treatment type (Government Decree 309/2014), allowing consistency and comparability across municipalities. To ensure data reliability, the analysis was restricted to municipalities with verified and consistent reporting, excluding smaller settlements where curbside double-bin system was only partially introduced or inconsistently recorded. As a result, the results should be interpreted as indicative of broader tendencies in waste generation rather than as exact absolute measures.

The dataset includes measurements for both selective and mixed waste streams, reported in kilograms per capita. Selective waste refers to the volume of separately collected recyclable materials, while mixed waste denotes the amount of non-separated municipal waste generated. Given the well-documented influence of income on waste generation (Khan et al., 2016), income was considered as a control variable. However, as individual-level per capita income data were not available, municipal-level taxable income was utilized as a proxy indicator for financial well-being. This substitution allows the assessment of potential relationships between income levels and patterns of waste generation and separation. To account for the potential influence of the COVID-19 pandemic on waste-related behavior and infrastructure use, the dataset spans the period from 2012 to 2023. Descriptive statistics for the variables included in the analysis are presented in Table 1.

The treatment group consists of municipalities that operated a double-bin door-to-door collection system prior to the COVID-19 pandemic, while the control group includes municipalities without such a system. Based on 1116 observations, substantial heterogeneity has been identified within the population of the municipalities included in the dataset. This variation is attributable to the inclusion of both small rural settlements and large urban centers, including Budapest. The smallest municipality within the sample reported a population of only 144 inhabitants, whereas Budapest, the largest city represented, had a population exceeding 1.7 million. In terms of annual personal income tax per capita, the average taxable income was found to be approximately 1.23 million HUF (3455 EUR), with a standard deviation of 569.90 thousand HUF (1598 EUR). These statistics indicate pronounced income disparities across municipalities. The minimum observed value was 151 thousand HUF (424 EUR), while the maximum reached 3.35 million HUF (9410 EUR) per capita annually, highlighting considerable economic heterogeneity that may affect local consumption behavior and patterns of waste generation.

The average annual per capita generation of mixed waste was measured at 206.40 kg, with a standard deviation of 84.27 kg. The observed values ranged from a minimum of 18.44 kg to a maximum of 844.44 kg per capita per year. This wide variation likely reflects differences in urbanization, household consumption, and the availability and quality of local waste management infrastructure. In contrast, the mean annual per capita volume of selectively collected waste was significantly lower, recorded at 30.69 kg, with a maximum of 200.25 kg and a minimum of 0 kg. It indicates that some municipalities lacked selective waste collection systems during at least part of the analyzed period (2012–2023). This variability is likely associated with differences in infrastructural development, public participation, and institutional support for selective waste management. It should be noted that the available municipal-level data report selectively collected waste as an aggregated category and do not provide consistently available fraction-level information. Therefore, the observed increase should be interpreted as an increase in the aggregated selectively collected waste stream. Given the design of the curbside double-bin system, this increase is associated with paper and plastic fractions, especially packaging-related waste. This interpretation is consistent with recent Hungarian evidence (Ráti and Maró, 2026b) showing that pandemic-related changes in household consumption, including the expansion of e-commerce and home delivery, increased packaging-intensive waste streams. However, because the available municipal data does not provide consistent fraction-level information, the present study cannot determine whether the increase was driven primarily by paper, plastic, or other recyclable materials.

The heterogeneity observed in the sample can be attributed to the non-uniform implementation of selective waste collection systems

Table 1
Descriptive statistics of the dataset.

Variable	Obs.	Mean	St. dev.	Control group	St. dev.	Treatment group	St. dev.
Population (capita)	1116	43,740.54	175,569.90	9,925.57	10,206.27	1,464.88	146,655.60
Personal taxable income (thousand HUF/capita/year)	1116	1,229.88	569.90	1,152.66	546.26	1,465.56	576.91
Mixed waste (kg/capita/year)	1116	206.40	84.27	209.34	94.09	197.47	40.93
Selective waste (kg/capita/year)	1116	30.69	33.05	27.63	32.98	40.03	31.52

Note: For reference, 1 EUR ≈ 356 HUF as of May 2026 (Hungarian National Bank). Based on this exchange rate, the average annual per capita personal taxable income corresponds to approximately EUR 3455 across the full sample (HUF 1229,880), EUR 3237 in the control group (HUF 1152,660), and EUR 4116 in the treatment group (HUF 1465,560). The data are reported in HUF in Table 1 to preserve the original units of the source (Hungarian Central Statistical Office).

across Hungarian municipalities. Although the Waste Framework Directive (2008/98/EC) mandated the establishment of separate collection schemes throughout the European Union, full compliance was required of Member States only by January 1, 2015. As a result, during the period between 2012 and 2015, many smaller municipalities in Hungary had not yet implemented any form of selective waste collection. In addition, the lack of a centralized, publicly accessible database systematically documenting the type and timing of selective waste collection systems, such as curbside double-bin, curbside selective bag, and selective island schemes, has posed a challenge to comprehensive data acquisition. As a result, inclusion in the sample was limited to those municipalities for which sufficient and verifiable information was available. Since no national database systematically records the year of introduction of door-to-door selective waste collection systems, data were cross-checked using multiple sources. First, publicly available municipal waste management reports and regional environmental agency publications were reviewed. Second, in cases of missing or inconsistent information, local municipalities and waste management companies were directly contacted by phone to confirm the approximate year when the curbside double-bin system was implemented. These consultations ensured that the timing variable reflects the actual introduction period with reasonable accuracy at the annual level, even if month-level variation cannot be fully captured. Furthermore, this approach allowed for the precise identification of whether the curbside double-bin system had been introduced prior to the onset of the COVID-19 pandemic in 2020.

Based on this classification, the municipalities were divided into two groups: treatment and control. A total of 23 municipalities in which the bin system had already been implemented were assigned to the treatment group, while 70 municipalities without such a system were assigned to the control group. A summary of the group composition is presented in Table 2. Most municipalities included in the sample were classified as small settlements with populations of up to 10,000 inhabitants, or as medium-sized towns with populations ranging between 10,001 and 50,000 inhabitants. In these locations, the curbside double-bin selective waste collection system was generally not implemented.

Table 2
Distribution of the settlements.

Settlement type (population size)	Count (number)	Percentage	Control (number)	Treatment (number)
Small settlement (< 10,000)	45	48.39%	43	2
Medium-sized town (10,001–50,000)	32	34.41%	26	6
Large town (50,001–100,000)	7	7.53%	0	7
County seats and major cities (> 100,000)	8	8.60%	0	8
Capital (Budapest) (Special case) (> 100,000)	1	1.08%	0	1
Total	**93**	**100.00%**		

Note: To ensure data reliability, the analysis was restricted to municipalities with verified and consistent reporting, excluding smaller settlements where door-to-door collection was only partially introduced or inconsistently recorded.

Larger towns, defined as those with populations between 50,001 and 100,000 inhabitants, accounted for 7.53% of the total sample. County seats and major cities with populations exceeding 100,000 inhabitants represented 8.60% of the sample. Budapest, as the capital city and a unique administrative entity, was treated as a special case within the dataset due to its distinct demographic and infrastructural characteristics.

Descriptive statistics and the distribution of the settlements between control and treatment groups indicate that these groups differ in several observable characteristics. On average, municipalities with the curbside double-bin system have higher personal income and larger populations. Mean values of selective and mixed waste generation per capita are also slightly higher in the treatment group. These observable differences suggest potential sources of bias, which are addressed through a series of robustness checks and the applied fixed-effects methodology presented in the following sections.

3.2. Methodology

The analysis relies on a Two-Way Fixed Effects (TWFE) estimator within a Difference-in-Differences (DiD) framework to identify the causal impact of door-to-door selective waste collection systems on household recycling behavior. This specification accounts for unobserved time-invariant differences across municipalities through municipality fixed effects and for common temporal shocks through year fixed effects, thereby supporting a causal interpretation of the estimated effects. In this study, a structured econometric framework is employed to evaluate the extent to which the presence of curbside double-bin selective waste collection systems influenced municipal waste generation. A single model specification is utilized to identify the effect of infrastructure on waste-related behavioral outcomes under exogenous pressure. The classical DiD methodology is applied, which is traditionally formulated in a two-period context involving a clearly defined pre-treatment and post-treatment phase, as well as delineated treatment and control groups. The causal effect is estimated by measuring the differential change in the outcome variable over time between treated and untreated observational units. The standard DiD estimator, as formalized by (Goodman-Bacon, 2021), is expressed as Eq. (1):

$$\widehat{\delta}_{DiD} = (\overline{\mathbf{Y}}_T, post - \overline{\mathbf{Y}}_T, pre) - (\overline{\mathbf{Y}}_C, post - \overline{\mathbf{Y}}_C, pre) \quad (1)$$

In this formulation, $\overline{\mathbf{Y}}_T, post$ and $\overline{\mathbf{Y}}_T, pre$ denote the average outcomes for the treated group after and before the intervention, respectively, while $\overline{\mathbf{Y}}_C, post$ and $\overline{\mathbf{Y}}_C, pre$ represent the corresponding averages for the control group. This analytical setup is based on the parallel trends assumption, which posits that, in the absence of treatment, the outcome trajectories of both groups would have evolved in a similar manner over time. In the context of the present analysis, however, the treatment, defined as the availability of selective waste collection bins during an exogenous shock (i.e., the COVID-19 pandemic), was not introduced at a uniform point in time. Instead, the dataset spans multiple years and includes municipalities that vary in both the timing and status of treatment exposure. To account for this variation across time and space, a TWFE regression model is employed. This model serves as a generalized extension of the classical DiD approach, allowing for multiple

periods and controlling for unobserved, time-invariant heterogeneity across municipalities as well as common temporal shocks that may influence waste generation patterns (Callaway and Sant'Anna, 2021; Imai and Kim, 2021). The estimated model can be written as follows (Eq. (2)):

$$Y_{it} = \alpha + \beta^1(Bin_i \times COVID_t) + \beta^2 Income_{it} + \gamma_t + \mu_i + u_{it} \quad (2)$$

In this specification Y_{it} represents the amount of waste collected in municipality i during year t, expressed in kilograms per capita. The dependent variable may refer to either selectively or non-selectively collected waste Bin_i is a binary indicator variable equal to 1 if the double-bin selective waste collection system was implemented in municipality i, and 0 otherwise. $COVID_t$ is a dummy variable taking the value of 1 for observations during the COVID-19 period and 0 otherwise. The interaction term $Bin_i \times COVID_t$ represents the primary variable of interest, capturing the differential impact of the selective bin system during the pandemic period. Municipality-level fixed effects μ_i are included to control for time-invariant characteristics specific to each municipality, while year fixed effects γ_t account for temporal shocks that are common across all municipalities. The variable $Income_{it}$ denotes annual per capita taxable income (expressed in thousand HUF) and is included as a control to account for economic differences across municipalities and over time. The term u_{it} represents the idiosyncratic error component.

The identification of the causal effect in this specification relies on the parallel trends assumption, which holds that in the absence of treatment, municipalities with and without the selective bin system would have exhibited similar trends in waste generation. Although differences may exist in baseline levels of waste generation or in responsiveness to external shocks, the inclusion of municipality and year fixed effects is intended to mitigate the influence of such time-invariant and period-specific confounding factors. Under this identifying assumption, the coefficient β^1 can be interpreted as the average treatment effect of the selective bin system during the pandemic period.

The validity of the DiD approach hinges critically on the assumption that, in the absence of treatment, the treated and control groups would have exhibited parallel trends in the outcome variable over time. This condition, known as the parallel trends assumption, constitutes a central identification requirement for causal inference in DiD models. In support of this assumption, Fig. 1 presents the evolution of selectively collected waste in treated and control municipalities during the pre-treatment period. Although baseline levels of waste generation differ between the two groups, their trajectories between 2013 and 2019 reveal similar patterns of increase. This visual evidence suggests that the groups followed approximately parallel trends prior to the intervention, thereby strengthening the plausibility of the parallel trends assumption and enhancing the internal validity of the causal estimates obtained from the DiD specification. Furthermore, the adoption of a natural experiment framework strengthens the credibility of the analysis by exploiting an exogenous shock, namely, the COVID-19 pandemic, that is plausibly uncorrelated with municipal-level waste management policies. Given that the pandemic-related restrictions were imposed externally and simultaneously across all municipalities, the intervention can be interpreted as quasi-random. This exogeneity reduces the likelihood of confounding by unobserved factors and provides a more credible setting for identifying the behavioral impact of selective bin systems on household waste generation.

4. Results

The empirical analysis is conducted using a single TWFE regression model to estimate the impact of curbside double-bin waste collection systems during an exogenous shock. The treatment effect is identified through the interaction of two binary indicators: one denoting the presence of curbside selective waste collection infrastructure, and the other indicating whether the observation period falls within the timeframe of the pandemic. This specification facilitates the estimation of differential changes in waste generation attributable to the implementation of selective bin systems under conditions of external pressure. To control economic heterogeneity across municipalities, annual per capita taxable income is included as a covariate. All estimations were conducted using the *reghdfe* command in Stata 19, applying TWFE specification with robust standard errors clustered by municipality. To control for time-invariant and municipality-specific characteristics (such as geographic, infrastructural, or socio-economic factors that do not vary over time), the models absorbed municipality fixed effects, thereby removing potential bias from unobserved heterogeneity. Year fixed effects were also included to capture nationwide shocks or temporal trends affecting all municipalities equally. As mentioned, standard errors were clustered at the municipal level to account for potential autocorrelation within units over time. This specification ensures that the estimated treatment effect reflects within-municipality variation associated with the introduction of the double-bin system, net of both time-invariant characteristics and common time effects.

The results of the regression analysis are presented in Table 3, showing the estimated effects of the interaction between the presence of curbside double-bin waste collection infrastructure and the COVID-19 period on municipal waste generation. The coefficient on the interaction term is found to be positive and statistically significant in the case of selectively collected waste. This result indicates that municipalities equipped with curbside bin systems generated, on average, 11.76 kg more selectively collected waste per capita per year during the pandemic period, relative to municipalities lacking such infrastructure. In contrast,

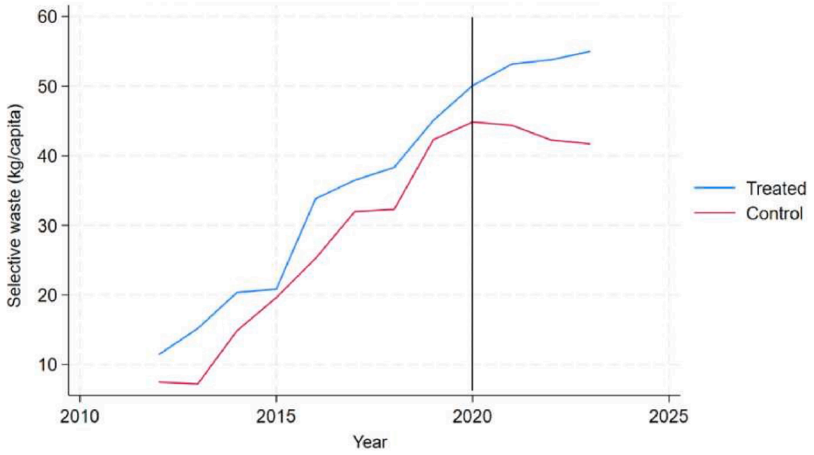

Fig. 1. Parallel (pre-treatment) trends assumption in selective waste.

Table 3
TWFE regression results for selective and mixed waste.

Variables	Selective waste	Mixed waste
Interaction DiD Effect	11.76**	−8.64
	(5.32)	(7.15)
Personal Income (1000 HUF)	−0.0057	0.0068
	(0.0058)	(0.013)
Constant	36.74***	198.75***
	(7.06)	(15.6)
N	1116	1116
R^2	0.401	0.035

Note: Robust standard errors in parentheses. Waste quantities are reported in kilograms per person per year (kg/person/year). * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

the coefficient for mixed waste is estimated to be negative but statistically insignificant, suggesting that the presence of selective bins did not lead to a meaningful change in the quantity of residual (non-separated) waste collected during the shock period. The control variable representing annual per capita income is not found to be significantly associated with either waste category. This suggests that income variation across municipalities does not account for the observed treatment effects, thereby reinforcing the interpretation that the changes in waste generation are attributable to the selective bin infrastructure under external pressure.

To further assess the credibility of identifying assumptions underlying the regression model, a placebo test is performed by introducing a false treatment period that precedes the actual exogenous shock. An interaction term is constructed between the treatment group indicator and a pre-treatment period spanning the years 2016 to 2018. This placebo specification is then estimated using the same TWFE regression framework applied in the main analysis. The rationale for this approach is grounded in the parallel trends assumption: if this assumption holds, no significant differences should be observed between treated and control municipalities during the placebo period, as the treatment (i.e., selective bin infrastructure under COVID-related pressure) had not yet occurred. The results of the placebo regression, summarized in Table 4, lend support to the validity of the parallel trends assumption. The estimated coefficient on the placebo interaction term is found to be small in magnitude and statistically insignificant for both selectively and non-selectively collected waste. In both cases, the 95% confidence intervals include zero, indicating that no differential trends existed between treated and control groups during the pre-treatment period. These findings suggest that the observed effects in the main specification are unlikely to be driven by pre-existing differences in waste generation trends, thereby reinforcing the internal validity and credibility of the causal interpretation.

To further evaluate the robustness of the estimated treatment effects, a leave-one-out sensitivity analysis was conducted. In this procedure, the six largest municipalities (Budapest, Debrecen, Miskolc, Pécs, Szeged, and Győr) were sequentially excluded from the sample, and the TWFE model was re-estimated for each restricted specification. These municipalities were selected due to their status as major urban centers, which may exert disproportionate influence on the estimates owing to their population size or distinctive waste management infrastructures. As reported in Table 5, the estimated coefficients on the interaction term for selectively collected waste remain positive and statistically significant across all model variants. The estimated treatment effects range narrowly between 11.71 and 12.45 kg per capita per year, indicating strong consistency. In contrast, the estimated coefficients for mixed waste remain negative but statistically insignificant throughout all iterations of the analysis. These results suggest that the main findings are not being driven by outlier municipalities. Rather, the positive and significant treatment effect associated with the presence of selective bin infrastructure appears to be stable across varying sample compositions.

Since the double-bin system was primarily introduced in larger municipalities, a potential concern is that the estimated treatment effect captures pre-existing differences in time trends between large and small settlements rather than the true impact of the system. To address this, the baseline two-way fixed-effects model was extended to include population-category–specific year effects, allowing each size group to follow its own time trajectory (de Chaisemartin and D'Haultfœuille, 2022). The results are reported in Table 6. The coefficient on the interaction term remains positive and statistically significant for selective waste, while it is negative and statistically insignificant for mixed waste. This indicates that, even after controlling for size-specific time trends, the estimated increase in selective waste generation (approximately 21.5 kg per person per year) persists, confirming that the observed effect is not driven by heterogeneous developments across settlement sizes but rather reflects the impact of the double-bin system.

Table 4
Placebo TWFE regression results for selective and mixed waste.

Variables	Selective waste (placebo)	Mixed waste (placebo)
Interaction Placebo Effect	1.18	−0.71
	(2.91)	(6.04)
Personal Income (1000 HUF)	−0.0012	0.0035
	(0.0057)	(0.0123)
Constant	32.07	202.17
	(7.01)	(15.17)
N	1116	1116
R^2	0.717	0.844

Note: Robust standard errors in parentheses. Waste quantities are reported in kilograms per person per year (kg/person/year). The placebo regression includes municipality and year fixed effects, clustered at the city level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

5. Discussion

Overall, the findings provide empirical support for the conclusion that the curbside double-bin system, as a specific form of door-to-door selective waste collection, induced a measurable behavioral response under conditions of external pressure. This response is reflected in a significant increase in the volume of selectively collected waste, without a corresponding decrease in mixed (non-selective) waste. More specifically, municipalities equipped with the curbside double-bin system generated, on average, 11.76 kg more selectively collected waste per capita annually than municipalities without such infrastructure, while the estimated change in mixed waste was negative but statistically insignificant. This pattern suggests that the increase in selectively collected waste was not accompanied by clear evidence of substitution away from mixed waste. Multiple studies have documented the complex impacts of the COVID-19 pandemic on municipal waste generation patterns. In many regions, overall municipal waste volumes were

Table 5
Leave-one-out robustness check (Interaction effects only).

City Excluded	Selective Waste	Mixed Waste
Budapest	12.13**	−8.30
	(5.44)	(7.28)
Pécs	12.45**	−6.89
	(5.45)	(7.18)
Debrecen	12.22**	−8.41
	(5.46)	(7.35)
Miskolc	11.71**	−8.75
	(5.50)	(7.38)
Szeged	11.81**	−8.75
	(5.48)	(7.35)
Győr	12.15**	−9.66
	(5.45)	(7.25)
R^2	0.7209 - 0.7224	0.8443 - 0.8456
N	**1104**	

Note: Robust standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 6
Robustness check including size-by-year interaction terms.

Variable	Selective Waste	Mixed Waste
Interaction DiD Effect	21.54**	−15.54
	(10.37)	(15.61)
R^2	0.733	0.852
N	**1116**	

Note: Robust standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

observed to decline because of reduced economic activity (Sarmento et al., 2022). In parallel, a significant increase in selective waste, particularly packaging materials and single-use plastics, was reported, largely attributed to the rise in online shopping and home deliveries (Ráti and Maró, 2026b; Guzzo et al., 2024; Nguyen et al., 2015). In addition, the widespread use of personal protective equipment, such as face masks and gloves, introduced new waste streams into the municipal system (Silva et al., 2021).

Although shifts in consumer behavior during the pandemic (Silva et al., 2021; Benson et al., 2021; Ganguly and Chakraborty, 2021) and the circular economy rebound effect (Zink and Geyer, 2017; Chen, 2021; Figge and Thorpe, 2019) have been examined independently in prior literature, the interaction between crisis-induced constraints and behavioral distortions linked to waste infrastructure remains underexplored. The current study addresses this intersection and gap by providing quasi-experimental evidence on the causal effects of infrastructure-enabled convenience. The interpretation of the mixed-waste coefficient requires caution. Although the point estimate is negative, it cannot be statistically distinguished from zero at conventional significance levels. Moreover, even if the negative point estimate were interpreted as a genuine reduction, its magnitude is smaller than the observed increase in selectively collected waste. Therefore, the results do not support the conclusion that the curbside double-bin system primarily shifted waste from the mixed stream into the selective stream. Instead, they indicate an increase in aggregated selectively collected waste without clear evidence of a corresponding reduction in mixed waste.

5.1. Comparison with existing door-to-door and PAYT evidence

The findings of the present study differ from the evidence discussed above, which shows that door-to-door collection schemes, especially when combined with PAYT tariffs or other waste-pricing instruments, can reduce residual or total municipal waste generation. Several studies report reductions of approximately 10–20%, and in some cases even larger reductions, following the implementation of door-to-door and PAYT-based systems. At first sight, this appears to contrast with the present result. However, this difference should be interpreted considering both policy design and empirical identification. First, evidence shows that door-to-door collection combined with PAYT tariffs, waste-pricing instruments, organic waste separation, or enforcement mechanisms can increase recycling performance while reducing residual or total waste generation (Compagnoni, 2020; Di Matteo and Guadagno, 2024; Bucciol et al., 2015). In these settings, households face a direct economic incentive to reduce unsorted or residual waste. Therefore, the behavioral mechanism differs from the one examined in the present study. PAYT-based systems make disposal financially salient, whereas the curbside double-bin system primarily reduces the effort cost of separating and disposing of recyclable materials.

Second, the identification strategy also differs. Several studies compare the same municipalities before and after the introduction of door-to-door or PAYT schemes (Compagnoni, 2020; Di Matteo and Guadagno, 2024; Valente, 2023). Such before–after designs capture the change relative to the same local baseline and may reflect the combined effects of infrastructure rollout, pricing reform, communication campaigns, organic waste collection, enforcement, and broader local policy change. By contrast, the present study compares municipalities with and without curbside double-bin infrastructure during the same external shock period, using a TWFE/DiD framework and the COVID-19 pandemic as an exogenous shock. Thus, the estimated effect should be interpreted as the differential response of municipalities with convenience-enhancing bin infrastructure relative to municipalities without such infrastructure during a period of externally induced changes in household consumption. This distinction helps reconcile the apparent contrast between the findings of this study and much of the existing door-to-door and PAYT literature. The present study does not suggest that all door-to-door systems increase waste generation. Rather, it indicates that convenience-oriented infrastructure, when not accompanied by direct quantity-based incentives, may increase selective collection without necessarily reducing mixed or total waste. The contrast between these findings and the present results should therefore not be interpreted as a contradiction, but as evidence that different policy mixes activate different behavioral mechanisms. Door-to-door systems combined with PAYT or other direct incentives may encourage waste prevention, whereas convenience-oriented systems without such incentives may mainly increase the ease of disposal and sorting.

5.2. Behavioral interpretation: convenience, rebound and perceived disposal ease

While the PAYT literature emphasizes the waste-reducing effect of combining convenience with direct economic incentives, a separate strand of behavioral and rebound-effect literature suggests that convenience alone may also generate unintended increases in material use and waste generation. The availability of selective waste collection infrastructure may, under certain conditions, increase rather than decrease total household waste generation. Using a DiD design closely comparable to this study, Maier, Geyer (Maier et al., 2023) find that the introduction of curbside recycling in North Carolina increased household solid waste generation by approximately 6 to 10 percent over the 1999–2019 period, which the authors interpret as direct evidence of circular economy rebound at the household level. This finding is methodologically and conceptually aligned with the present analysis, as both studies isolate the effect of selective collection infrastructure operating under a flat-rate service charge, without any direct financial signal targeting waste minimization. Complementary support also comes from (Catlin and Wang, 2013) who show that the mere availability of a recycling option leads consumers to use significantly more resources. Building on this finding, (Sun and Trudel, 2017) develop a utilitarian model in which the positive emotions associated with recycling can outweigh the negative emotions linked to wasting, leading consumers to use larger amounts of resources when recycling is available. (van Doorn and Kurz, 2021) further demonstrate that the "warm glow" produced by participation in recycling initiatives can paradoxically increase rather than reduce waste, indicating that the relationship between convenience and pro-environmental behavior is non-linear.

The contextual conditions of the COVID-19 period are also relevant in this regard. Goods received via express delivery consume up to 4.8 times more packaging material than goods purchased in conventional retail settings (Kim et al., 2022), which may further amplify the rebound observed in municipalities equipped with door-to-door infrastructure during the pandemic, when online retail expanded significantly. Taken together, these findings provide convergent empirical and experimental support for the PDEB mechanism, and strengthen the interpretation that infrastructural convenience, when introduced in isolation, can lower the perceived environmental and effort costs of disposal and thereby contribute to a net increase in total waste generation. This interpretation is consistent with the broader theoretical framework of the circular economy rebound effect (Zink and Geyer, 2017; Figge and Thorpe, 2019).

5.3. Managerial and policy implications

The findings of this study suggest that curbside double-bin waste collection systems, while effective in increasing recycling volumes, may induce unintended behavioral responses that elevate total waste generation. As a result, infrastructure-based interventions must be carefully calibrated to avoid counterproductive environmental outcomes. First, it is recommended that selective collection infrastructure be implemented in conjunction with behavioral communication strategies. The presence of easily accessible collection systems may lower perceived environmental costs and weaken intrinsic motivations to reduce waste. Therefore, informational campaigns that emphasize waste prevention, not just separation, should be designed and delivered alongside infrastructure rollout. Messaging should counteract the perception that recycling alone constitutes environmentally responsible behavior and instead reinforce waste minimization as the primary objective.

Second, waste composition monitoring should be institutionalized to detect rebound effects in real time. Although increases in selectively collected volumes may be viewed as positive indicators, they may conceal broader patterns of material overuse or contamination. Routine audits of waste streams, particularly in newly serviced municipalities, are necessary to assess whether infrastructure is producing net sustainability gains or simply shifting public perceptions. These insights can inform adaptive adjustments in service design. Third, policy frameworks should move beyond infrastructure provision and incorporate regulatory and fiscal mechanisms that discourage overconsumption. Volume-based pricing schemes (e.g., PAYT systems) and restrictions on single-use packaging may be deployed to limit the behavioral rebound associated with perceived convenience. In parallel, municipalities should be incentivized to invest not only in physical infrastructure, but also in data-driven behavioral insights and community engagement tools.

Finally, it should be acknowledged that infrastructure effectiveness is context-dependent, and policies must be tailored to local socioeconomic conditions. In municipalities where environmental awareness is low or participation in waste sorting remains limited, additional investments in education and transparency may be required before infrastructure can yield meaningful behavioral shifts. In summary, while selective collection systems play an essential role in advancing circular economy objectives, their success ultimately depends on the alignment of infrastructural, psychological, and regulatory dimensions. Without an integrated approach, well-intentioned systems risk reinforcing unsustainable consumption patterns rather than mitigating them.

6. Conclusion

This study has provided novel empirical evidence on the behavioral impact of the curbside double-bin system, as a specific form of door-to-door selective waste collection, under conditions of external disruption. By leveraging the COVID-19 pandemic as an exogenous shock, a quasi-experimental framework was applied to isolate the effect of infrastructure-enabled convenience on household waste generation. It has been demonstrated that the introduction of the curbside double-bin system was associated with a statistically significant increase in selectively collected waste, while no corresponding reduction was observed in mixed waste. Although the point estimate for mixed waste is negative, the relatively high variability of the underlying data does not allow us to distinguish it from zero at conventional significance levels. Even under the assumption that this point estimate reflects a genuine reduction, its magnitude is smaller than the observed increase in selective waste, implying a net increase in total municipal solid waste – a pattern consistent with the rebound mechanism and the PDEB described above. This finding suggests that convenience-enhancing infrastructure may lead not only to improved sorting, but also to an overall rise in waste generation. The results contribute to the broader literature on the circular economy rebound effect by offering causal support for the PDEB. Infrastructure that simplifies disposal processes may unintentionally encourage overconsumption and reduce perceived environmental costs. As such, selective waste collection systems, although successful in raising recycling participation, may generate counterproductive behavioral responses if implemented in isolation. To conclude, a significant gap in the literature has been addressed by analyzing the behavioral implications of infrastructure-driven convenience in the context of an exogenous shock.

Despite the study's strengths, several limitations must be acknowledged. First, the classification of municipalities was based on the confirmed presence of the curbside double-bin system during the pandemic period, without access to precise information regarding the exact timing of system implementation. This limitation constrains the ability to evaluate dynamic treatment effects and may affect the generalizability of the results. More specifically, the timing of infrastructure rollout could only be identified at the annual level. Since official datasets do not include detailed records of the exact implementation dates, local municipalities and waste management providers were contacted to validate the reported years of introduction. While these confirmations suggest that the recorded timing is broadly accurate at the annual level, month-level uncertainty remains possible. Future research could address this limitation by using administrative or operational data sources with finer temporal resolution.

Second, the dataset does not contain detailed information on waste composition or contamination levels, restricting the analysis of substitution patterns between recyclable and non-recyclable waste streams and the assessment of overall environmental effectiveness. Official municipal datasets in Hungary, and in many European countries, only report total quantities of selectively and residually collected waste, without distinguishing between clean and contaminated fractions. As a result, the present analysis captures quantitative rather than qualitative aspects of waste management performance. These limitations do not invalidate the main empirical finding, but they narrow the scope of its interpretation. The results should therefore be understood as evidence of an increase in aggregated selectively collected waste associated with the curbside double-bin system, rather than as proof of changes in specific recyclable fractions or sorting quality. Since the available data do not provide consistent fraction-level or contamination-level information, the study cannot determine whether the increase was driven primarily by paper, plastic, glass, or other recyclable materials, nor can it assess the actual material recovery rate. Future research could combine administrative datasets with field-level composition audits or life-cycle assessment (LCA) approaches to evaluate how behavioral responses translate into actual environmental outcomes.

Third, qualitative aspects of citizen engagement and sorting quality could not be incorporated. These factors may influence the true environmental effectiveness of selective collection systems and are therefore relevant for a deeper evaluation. Further research is warranted to disentangle the mechanisms underlying the circular economy rebound effect, and to explore how recycling-oriented infrastructure may alter household disposal behavior beyond mere sorting. Based on the above, the present findings should be interpreted as indicative of a behavioral response at the level of municipal waste quantities, while more detailed composition-based analyses are needed to confirm the underlying material mechanisms. A more comprehensive understanding of these behavioral dynamics could inform the design of complementary policy instruments aimed at mitigating overall waste generation, while preserving the environmental benefits associated with higher recycling rates.

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CRediT authorship contribution statement

Zalán Márk Maró: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **József Ráti:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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