Environmental Development 59 (2026) 101447

Contents lists available at ScienceDirect

Environmental Development

journal homepage: www.elsevier.com/locate/envdev

Recycling gains and material losses: A panel analysis of household waste trends in a decade of disruption

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ARTICLE INFO

Keywords:
Waste generation
Household waste
Recycling
Sustainability
COVID-19
Waste management

ABSTRACT

The COVID-19 pandemic significantly altered patterns of household waste generation, revealing complex interplays between consumption behavior, public policy, and environmental sustainability. This study conducts a unique and large-scale empirical analysis of municipal waste generation trends in Hungary, drawing on panel data from 640 municipalities between 2012 and 2023. Using advanced econometric methods, including panel regression models and excess-over-expected framework, this research investigates the differential impacts on selective (recyclable) and non-selective waste streams during a period of intensified social and regulatory transformation. Results indicate that while selective waste collection increased, total waste generation also rose, highlighting a rebound effect in consumer behavior. This suggests that the pandemic encouraged consumers to adopt more conscious waste generation practices, which persisted beyond the crisis. Furthermore, the impact of restrictions and lockdowns varied markedly by municipality type: urban areas saw the greatest increase in selective waste, potentially due to better infrastructure and higher e-commerce activity. However, contamination rates and inadequate recycling practices shadowed these environmental gains. Moreover, the study introduces the innovative use of the COVID-19 Stringency Index to quantify policy intensity and demonstrate its significant correlation with waste surges. These findings challenge assumptions that increased recycling equates to greater sustainability, and underscore the need for robust infrastructure, informed public engagement, and policy integration to avoid unintended consequences. This research not only fills a gap in literature by offering a multi-dimensional analysis of pandemic-era waste behavior but also provides evidence-based insights crucial for shaping circular economy strategies and resilient waste management systems in post-pandemic societies.

1. Introduction

The COVID-19 pandemic fundamentally disrupted societies worldwide. Although the acute phase of the pandemic has ended, its long-term effects remain evident. The emergency measures introduced to contain the virus, including curfews, school closures, travel bans, as well as the longer effects of the pandemic (e.g., fiscal and monetary policy challenges) have significantly altered social behavior, economic activity, and consumption patterns (Behera, 2021; Maró et al., 2025; Zwanka and Buff, 2021). These economic and

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https://doi.org/10.1016/j.envdev.2026.101447
Received 29 May 2025; Received in revised form 23 December 2025; Accepted 1 March 2026
Available online 2 March 2026

social problems and changes, while necessary for public health, have also affected environmental outcomes, particularly in terms of waste generation, and not necessarily in a positive way (Liang et al., 2021; Sarkodie and Owusu, 2021).

Several studies have indicated that consumption may have increased during the pandemic. Concerns over the prolonged impact of COVID-19 prompted individuals to stockpile food supplies (Amaral et al., 2022; Naughton, 2020), while increased stress and sleep disturbances triggered impulsive purchasing behavior, often driven by boredom (Deng et al., 2020; Yu et al., 2022). Collaborative consumption and online shopping have increased significantly as consumers have turned to digital solutions and platforms - habits that many intend to retain even after the pandemic (de Medeiros et al., 2021). In some regions, consumer focus shifted toward essential goods such as staple foods, medicines, and hygiene products (Aday and Aday, 2020; Choo & Rajkumar, 2020). These observations highlight the significant influence of the pandemic on consumer behavior, with implications that extend beyond the short term and may persist well into long-term changes.

However, shifts and changes in consumer behavior are significant not only from an economic and social perspective, but they are also important from an environmental perspective. The surge in demand for disposable masks, gloves and other health-related products has the potential to increase the amount of waste generated, placing additional pressure on existing waste management systems (Adelodun et al., 2021). Furthermore, the rise of online shopping and the widespread use of single-use packaging has exacerbated waste generation, particularly in relation to plastic waste (Aggarwal, 2021). On a more positive note, the pandemic has made people aware of the importance of environmental protection and sustainability, potentially fostering greater ecological consciousness (Brontowiyono, 2021; Ranjbari et al., 2021; Török et al., 2024; Vila and Costa, 2024). This could increase the willingness to participate in selective collection and encourage more conscious consumption behaviors, potentially resulting in higher recycling rates or even reductions in overall waste generation.

Assessing the impact of the current era on both waste generation and environmental awareness is therefore essential for addressing immediate as well as long-term sustainability challenges. Although the literature on this topic is extensive (Adelodun et al., 2021; Yoon et al., 2021; Zhao et al., 2022), most studies adopt a narrow approach and focus, often examining only isolated aspects of the impact of the pandemic; such as changes and shifts in recycling rates or the volume of specific types of waste like medical or hazardous waste (Yoon et al., 2021; Adelodun et al., 2021). Few studies concurrently evaluate changes in household selective and non-selective waste or incorporate relevant microeconomic indicators that influence consumption patterns (Leal Filho et al., 2022), and most typically focus only on the national or regional level. The multifaceted nature of the issue requires a more integrated approach than what such fragmented research can provide.

This study introduces several innovative and unique contributions to the existing literature. First, it is among the first and few large-scale empirical studies to analyze municipal-level panel data on waste generation over a 12-year period (2012–2023), including microeconomic variables like municipal per-capita taxable income. Second, as it was mentioned, unlike most prior studies that only address one type of waste or focus on healthcare waste, this research investigates both selective and non-selective waste at the household level, offering a holistic view of consumption and recycling behavior changes. Third, the use of the COVID-19 Stringency Index applies to a novel methodological framework using the Oxford Stringency Index to quantify government policy impacts and correlate them with shifts in waste generation. This refined approach helps to avoid statistical artifacts that may arise when relying solely on annual data. Fourth, the study introduces and adapts the Excess-over-Expected Waste model, drawing from excess mortality methodologies, to estimate counterfactual scenarios of waste generation in the absence of the pandemic. This provides a robust counterfactual benchmark and allows for a clearer attribution of observed waste surges to pandemic-related behavioral shifts. The results could reveal a rebound effect in waste generation despite improved selective waste habits, highlighting that better recycling does not necessarily equate to less waste, which is critical for circular economy policymaking.

Against this background, the primary objective of this study is to examine how the COVID-19 pandemic and related government stringency measures affected municipal solid waste generation and selective waste collection at the settlement level in Hungary. Using a longitudinal municipal-level panel dataset covering the period 2012–2023, the study aims to disentangle changes in total waste generation, selective waste collection, and recycling rates during and after the pandemic period. Based on this objective, the study addresses the following research questions:

- (RQ1) How did the COVID-19 pandemic influence total municipal solid waste generation at the settlement level?
- (RQ2) Did selective waste collection increase during the pandemic period, and if so, to what extent?
- (RQ3) Did changes in selective waste collection translate into a higher recycling rate, or were increases in total waste generation dominant?

To achieve this, the article is structured as follows. It begins with an introduction to the environmental and behavioral shifts caused by COVID-19, followed by a literature review highlighting gaps in existing research. It then presents the data sources and research design, focusing on 640 Hungarian municipalities. The methodology section details advanced panel regression and excess-over-expected models using the COVID-19 Stringency Index. Results are discussed in terms of changes in waste generation, recycling behavior, and regional differences. The article concludes with implications for sustainability policy and waste management, noting the limitations of the study and outlining potential directions for future research.

1.1. Theoretical background

The COVID-19 pandemic disrupted not only health systems and economies worldwide but also reshaped environmental behaviors, including consumption and waste generation patterns. Thus, the past few years offer a unique lens through which established theories of consumption, environmental sustainability, and waste generation can be (re-)examined. One central and foundational framework for understanding waste-related challenges is the concept of the circular economy, which challenges the traditional linear "take-make-dispose" approach by promoting waste minimization through reuse, recycling, and sustainable product design (Geisendorf and Pietrulla, 2018; Geissdoerfer et al., 2017). While progress toward circularity had been slow but steady before the pandemic, the crisis introduced temporary setbacks due to heightened reliance on single-use plastics and disposable medical items. Thus, it temporarily disrupted the progress toward circular economy, and in this matter, circularity depends not only on systemic design but also on behavioral and infrastructural readiness. The pandemic also heightened awareness of environmental fragility, suggesting potential for behavioral shifts toward long-term sustainability (Kirchherr et al., 2017). Moreover, the resilience of circular systems is highly contingent on government intervention and institutional flexibility (e.g., waste separation systems), areas where most countries struggled during the pandemic (Rahmandoust et al., 2023). Despite these disruptions, the pandemic also served as a teachable moment for sustainability, bringing to the forefront the fragility of linear economic systems and encouraging shifts in both policy and consumer norms (Kanda and Kivimaa, 2020).

A second theoretical framework relates to consumer behavior theory, particularly the dual-process model of decision-making, which distinguishes between fast, intuitive thinking (System 1) and slower, deliberative reasoning (System 2) (Costa et al., 2022; Evans and Stanovich, 2013; Frankish, 2010). In crisis situations, fear and uncertainty activated fast and emotional thinking, resulting in impulsive consumption behaviors such as panic buying and stockpiling (Costa et al., 2022; Maró et al., 2025; Prentice et al., 2022). These behaviors were further strengthened by media narratives. At the same time, lockdowns and increased time spent at home may have encouraged more deliberate, slower and more rational behaviors, such as improved waste sorting and recycling. Some authors (see e.g., Tripathi et al., 2020) extend this understanding by showing how health-framing and cognitive load influenced compliance with prosocial behaviors. This behavior has parallels in environmental contexts. This duality explains why pandemic-era waste patterns were simultaneously chaotic and adaptive. Together, these theoretical perspectives provide a foundation for understanding how the pandemic has reshaped both systemic waste management processes and individual consumer behaviors, which are further elaborated in the following sections.

1.2. Changing consumption and waste generating patterns

The COVID-19 pandemic has had profound social and environmental consequences that have changed consumption patterns, waste management practices, and broader sustainability efforts globally. Government-enforced lockdowns and restrictions brought significant disruptions to daily life, influencing not only economic activity but also environmental behavior. While some of these changes yielded temporary environmental benefits, such as improved air quality due to reduced industrial operations and traffic (Rodríguez-Urrego and Rodríguez-Urrego, 2020), others have led to increased consumption and waste generation. During the first wave of the pandemic, widespread fear and uncertainty often led to panic buying (Eva et al., 2021; Islam et al., 2021), which resulted in a global increase in the purchase of staple items such as dry and canned goods (Norris et al., 2021; Prentice et al., 2022). Although this behavior diminished in the later stages of the pandemic, it was accompanied by a significant increase in online shopping, driven by lockdowns and closures, resulting in unprecedented levels of e-commerce sales (Arora et al., 2020; Bhatti et al., 2020).

Concerns about health risks drove a sharp increase in the use of single-use plastics, resulting in a substantial increase in plastic waste (Vanapalli et al., 2021; Wibowo et al., 2024). Although these measures helped to reduce the risk of contamination, they have also created serious waste management challenges (Sarkodie and Owusu, 2021). It is estimated that the pandemic produced approximately 1.6 million tons of waste per day, with a considerable share consisting of single-use face masks (Christina et al., 2023). According to Singh et al. (2020), COVID-19-related medical waste volumes increased by up to 300% in certain regions. When waste generation increases at such a scale and speed, existing waste management systems often lack the capacity to respond adequately, creating a direct link between rising waste volumes and improper handling and disposal practices. Furthermore, inadequate disposal of contaminated medical waste not only increased public health risks but also hindered efforts to contain the spread of the virus (Singh et al., 2020). Thus, the pandemic underscored the unsustainability of current linear waste management models, particularly due to the widespread use of disposable plastic materials (Ganguly and Chakraborty, 2024). In some areas, the amount of healthcare waste multiplied during the pandemic, outpacing the available processing capacity (Sarkodie and Owusu, 2021; Wibowo et al., 2024). Under such capacity constraints, waste management systems often resorted to temporary or suboptimal disposal practices, increasing the likelihood of environmental leakage (Sharma et al., 2020; Tripathi et al., 2020). As a result of inadequate waste management, large quantities of improperly disposed materials entered the environment, especially into water and soil, where they degraded into microplastics. These pollutants infiltrated aquatic ecosystems and food chains, posing serious threats to both human health and biodiversity (Sharma et al., 2020).

Moreover, the above-mentioned prolonged closures and the widespread adoption of telecommuting contributed to a rise in non-selective waste, particularly household waste (Cai et al., 2021). The shutdown of offices, schools, and commercial establishments resulted in a shift in waste generation from business and commercial districts to residential areas, placing substantial strain on household waste management systems. In addition, the increased reliance on single-use plastics for food transportation, packaging, and personal protective equipment placed significant pressure on waste collection and processing infrastructure (Iimuro and Tabata, 2024). Selective waste streams, especially recyclable plastics and cardboard, also increased significantly due to shifts in consumption patterns (Adelodun et al., 2021; Leal Filho et al., 2022). This trend was mirrored globally as consumers increasingly relied on courier services to deliver food and essential goods. The rapid expansion of online shopping and food delivery services contributed to these issues, particularly in urban areas where waste management systems were not prepared to handle the surge in packaging waste (Lee and Lim, 2022).

Hungary provides a relevant Central and Eastern European context characterized by rising household consumption prior to the COVID-19 pandemic, alongside comparatively lower recycling rates than the EU average. Previous research documented a steady increase in municipal solid waste generation in Hungary driven by income growth, changing consumption patterns, and expanding retail activity (European Environment Agency, 2025). At the same time, selective waste collection has developed unevenly across municipalities, reflecting differences in local infrastructure, institutional capacity, environmental awareness and behavioral responses (European Environment Agency, 2025; Ráti and Maró, 2025). During the pandemic, shifts toward home-based consumption and increased online shopping were likely to intensify household waste generation (Maró et al., 2025; Sharma et al., 2020), while participation in selective collection may have responded differently across settlement types.

1.3. Challenges of household waste management

The above-mentioned behavioral shifts and changes during the COVID-19 pandemic further complicated waste management and sustainability efforts. While recycling rates improved in certain regions, studies by Richter et al. (2021) and Vargas et al. (2024) revealed that increased contamination of recyclables often compromised the effectiveness of waste separation systems. Olawade et al. (2024) also showed that income levels played a significant role in shaping the quantity of waste generated and the efficiency of its collection during the pandemic. In parallel, the pandemic revealed significant vulnerabilities in waste management systems, particularly in developing countries (Rashid et al., 2025; Vanapalli et al., 2021). In these regions, informal waste collectors play a crucial role in waste management but often lack proper protective equipment and labor rights (Pal and Kashyap, 2025).

For waste collectors, the pandemic represented not only a health crisis but also an economic one, as lockdowns reduced the availability of recyclable materials, severely affecting their income and livelihoods (Hemmesch et al., 2025). The social implications of inadequate waste management extended beyond direct health risks. Waste workers faced heightened exposure to contamination, while their working conditions and wages remained unchanged, further exacerbating existing social inequalities (Ferrara, 2025). Weaknesses in waste management infrastructure were also evident in developed countries, but the challenges were particularly acute in developing countries. Waste collection services were often disrupted or discontinued entirely, triggering local public health crises (Raoufi et al., 2025). Public trust in waste management systems declined, particularly in communities already dependent on fragile or informal infrastructure (Hemmesch et al., 2025).

The long-term environmental impacts of plastic waste cannot be addressed without the development and implementation of sustainable waste management solutions (Adelodun et al., 2021; Sarkodie and Owusu, 2021; Singh et al., 2025). The innovation and adoption of recyclable and biodegradable materials has gained momentum, driven by growing demand for alternatives that can reduce the environmental footprint of single-use plastics (Najar et al., 2024). Transforming supply chains and upgrading waste management infrastructures are also essential steps towards sustainable development goals (Raoufi et al., 2025). Ultimately, the COVID-19 pandemic highlighted the vulnerability and fragility of global waste management systems, underscoring how overreliance on single-use plastics and inadequate infrastructure have created persistent environmental and societal challenges that demand urgent and systemic solutions.

Such challenges are particularly relevant in the Hungarian context, where structural limitations, fragmented waste management infrastructure, and socioeconomic disparities make the management of household waste especially complex. For example, studies show that higher-income households in Hungary produce more food waste overall, and that income influences waste levels in different food categories (Szabó-Bódi et al., 2018). Moreover, the national plastic recycling rate remains among the lowest in the European Union, reflecting limited collection and recovery systems (Bándy and Élo, 2023; European Environment Agency, 2025). These dynamics underscore the importance of a context-sensitive methodological approach. At the same time, substantial heterogeneity across municipalities in terms of income levels, settlement size, and waste management capacity further complicates household waste management in Hungary (Dusek et al., 2014). The following section therefore introduces the empirical strategy used to analyze municipal-level waste generation and selective collection patterns within this challenging institutional and socioeconomic environment.

2. Data and methodology

2.1. Process of research and presentation of sample

The data employed in this analysis originate from the Hungarian Central Statistical Office (2025), specifically from the Statinfo and T-STAR/TIMEA databases. The dataset possesses both temporal and spatial dimensions, forming a balanced panel structure that enables the investigation of short- and long-term trends in household waste generation. The observational period spans from 2012 to 2023 on an annual basis and includes data from 640 municipalities across Hungary. Sample selection was guided by data availability and quality considerations. Municipalities with fewer than 2,000 inhabitants were generally excluded due to frequent missing observations; however, settlements with complete and internally consistent time series were retained to preserve panel balance. To ensure representativeness and capture heterogeneity in waste generation behaviors, the final sample comprises a diverse set of urban and rural municipalities, stratified by geographic region and settlement size. Given that waste generation is closely associated with economic factors, particularly household income levels (Alzamora et al., 2022; Bandara et al., 2007; Khan et al., 2016), the analysis incorporates per capita taxable income at the municipal level as a key explanatory variable. Descriptive statistics for the main variables are provided in Table 1.

Hungary operates a centralized municipal waste management system in which local governments are responsible for household waste collection, while treatment and disposal services are organized through regional service providers. Household waste collection typically relies on a combination of mixed (residual) waste collection and selectively collected fractions, including paper, plastics, metals, and glass, with coverage and intensity varying substantially across municipalities (Horváth et al., 2021; Ráti and Maró, 2025). Selective waste collection is predominantly based on curbside collection in larger urban areas and on collection points or waste islands in smaller settlements. Although separate collection systems have expanded over the past decade, recycling rates remain below the European Union average, reflecting infrastructural constraints, uneven service provision, and differences in household participation (European Environment Agency, 2025). These institutional characteristics provide an important backdrop for interpreting municipal-level variation in waste generation, and selective collection patterns analyzed in this study.

Furthermore, these significant differences can be attributed to the fact that although the Waste Framework Directive (2008/98/EC), which entered into force in 2008 and allowed Member States until January 1, 2015, to implement separate collection systems. As a result, between 2012 and 2015, several smaller municipalities in Hungary had not yet introduced separate waste collection. Table 2 summarizes the composition of the sample, using the categorization principles most applied by the Hungarian Central Statistical Office (HCSO). The 640 Hungarian municipalities included in the sample exhibit considerable heterogeneity, enabling an analysis that spans settlements of varying sizes and economic conditions. Most municipalities in the dataset are small settlements with fewer than 10,000 inhabitants, representing 75.31% of the total sample. Medium-sized towns, with populations between 10,001 and 50,000, make up 21.56%. Municipalities with populations between 50,001 and 100,000 account for 1.72% of the sample, while those with more than 100,000 inhabitants (excluding Budapest) represent 1.25%. Together, these larger settlements comprise 2.97% of the total sample. Budapest, the capital city of Hungary, represents an additional 0.16% and is treated as a distinct case within the sample.

The analysis of aggregated per-capita waste data from 640 municipalities reveals distinct trends in selective and non-selective waste generation between 2012 and 2023. The volume of selectively collected waste steadily increased from 2012 to 2019, and this upward trend persisted throughout the COVID-19 period. The peak was reached in 2021. Although a slight decline followed, post-pandemic levels have consistently remained above those recorded in 2019. In contrast, the volume of non-selectively collected waste fluctuated annually between 2012 and 2019. A noticeable increase occurred during 2020–2021, likely linked to the pandemic; however, this surge proved temporary, as a significant decline was observed in the years following the pandemic. These developments are illustrated in Fig. 1.

Assessing the impact of the COVID-19 pandemic is challenging due to the annual structure of the available data. Therefore, to assess the impact of the pandemic, the COVID-19 Stringency Index was employed. This index is a composite daily indicator that quantifies the strictness of government-imposed measures, such as school closures, stay-at-home mandates, bans on public gatherings, and mobility restrictions. It is based on a comprehensive database developed by the Blavatnik School of Government at the University of Oxford and is widely recognized for measuring the political and social intensity of the COVID-19 response (Hale et al., 2021). Given the availability of annual panel data, daily Stringency Index values were aggregated to the yearly level using a simple arithmetic average. As epidemiological policy implementation in Hungary was uniform nationwide, the index assumes the same value for all municipalities each year. In addition, several control variables were incorporated into the dataset to strengthen the explanatory power of the model and account for potential confounding effects. Including these controls is a standard and widely accepted practice in quantitative economic research (see e.g., Bakó et al., 2025; Démurger, 2001; Kyriacou et al., 2019). The primary objective of this study, however, is not to evaluate the individual effects of these control variables. Table 3 provides a detailed description of all variables used in the analysis.

2.2. Methods

This study employs panel regression models with two-way fixed effects (TWFE) (Correia et al., 2020; Imai and Kim, 2021) to investigate the impact of recent years on waste generation, with particular emphasis on the quantities of selective and non-selective waste. The panel regression approach facilitates the control of municipality-level fixed effects and time-specific macroeconomic shocks, thereby enabling more accurate estimation of the relationships among variables. This methodology is especially advantageous when working with large panel datasets, as highlighted by Correia et al. (2020), since it mitigates bias from unobserved time-invariant municipal characteristics and allows assessment of the dynamic effects of COVID-19 on waste production.

Model estimation was conducted using the *reghdfe* command in Stata, which efficiently estimates two-way fixed effects (municipality and temporal fixed effects) while avoiding the computational burden of including a large number of dummy variables explicitly (Clarke and Tapia-Schythe, 2021; Correia et al., 2020). This method ensures comprehensive control for both spatial (settlement-specific) and temporal heterogeneity and provides robust standard errors. The municipality fixed effects control for time-invariant factors such as institutional differences, and baseline regulatory frameworks, whereas time fixed effects account for broader macroeconomic shocks and structural policy shifts, ensuring that the estimated impact of COVID-19 is not biased by unrelated

Table 1
Descriptive statistics of the dataset.

Variable	Obs.	Mean	St. dev.	Min	Max
Population (capita)	7,660	12,203.15	68,676.19	144	1,705,300
Taxable income (1000 HUF/capita/year)	7,660	1,219.82	604.78	144	5,102
Non-selective waste (kg/capita/year)	7,660	196.68	63.58	2.03	896.76
Selective waste (kg/capita/year)	7,660	6.67	16.06	0	200.26

Table 2
Settlement type distribution.

Settlement type (population size)	Count	Percentage
Small settlement (<10,000)	482	75.31%
Medium-sized town (10,001–50,000)	138	21.56%
Large town (50,001–100,000)	11	1.72%
County seats and major cities (>100,000)	8	1.25%
Capital city (>1,000,000)	1	0.16%
Total	640	100%

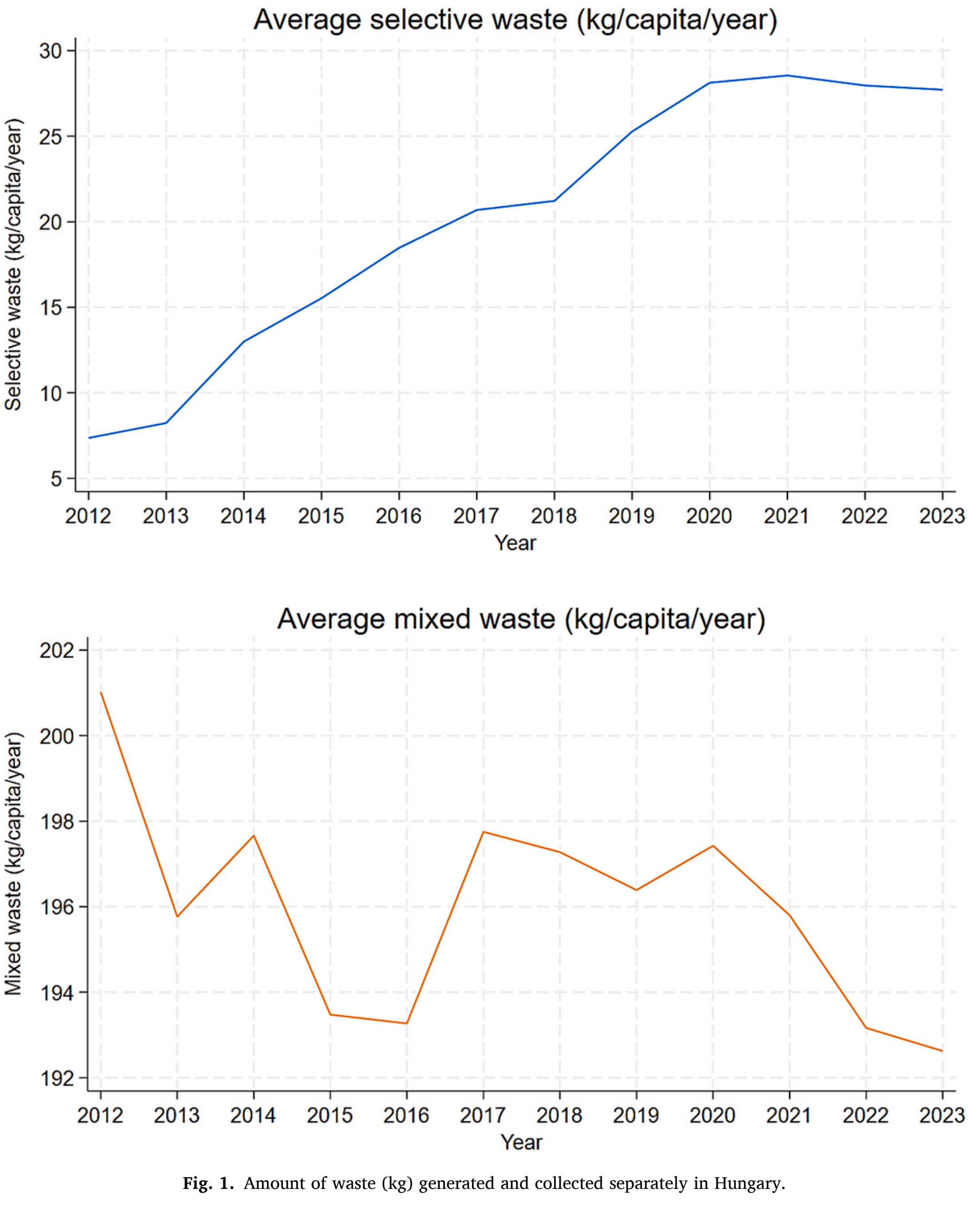

Fig. 1. Amount of waste (kg) generated and collected separately in Hungary.

Table 3
Description of the variables.

Variable	Explanation	Source
Dependent		
Selective_waste	annual selective waste per capita (kg/person/year)	Statinfo (KSH)
Mixed_waste	annual non-selective (mixed) waste per capita (kg/person/year)	Statinfo (KSH)
Total_waste	annual total household waste per capita (kg/person/year)	Statinfo (KSH)
Recycling_rate	share of selectively collected waste compared to total waste (percentage)	Statinfo (KSH)
Independent		
Covid_Stringency	index measuring the strictness of COVID-19 measures	Blavatnik School of Government (University of Oxford)
Taxable_income	annual taxable income per capita (thousand HUF/person/year)	T-STAR/TIMEA (KSH)
Adult	share of population aged 18–59 (% of total population)	T-STAR/TIMEA (KSH)
Elderly	share of population aged 60 and above (% of total population)	T-STAR/TIMEA (KSH)
Internet	number of internet subscriptions per 100 inhabitants	T-STAR/TIMEA (KSH)
Cars	number of passenger cars per 100 inhabitants	T-STAR/TIMEA (KSH)
Pensioners	share of old-age pensioners in the total population (%)	T-STAR/TIMEA (KSH)
Educated_unemployed	share of job seekers with higher education (% of total population)	T-STAR/TIMEA (KSH)
Employment	share of job seekers registered for more than 180 days (% of total population)	T-STAR/TIMEA (KSH)

time trends.

However, the structure of the available data required the application of alternative modeling strategies to better capture the effect of previous years. These include a fixed-effects panel model with a quadratic time trend (Angrist and Pischke, 2009), an interaction model incorporating income levels to assess heterogeneous effects across socioeconomic strata (Gershoff et al., 2007; Hong et al., 2019), and an expected value-based estimation procedure adapted from methodologies commonly used in excess mortality studies (Beaney et al., 2020; Kontis et al., 2020).

2.2.1. *Model 1: Panel regression with quadratic trend and fixed effects*

Model 1 assumes that municipal waste generation follows a non-linear time trend, incorporating additional fixed effects at the municipal level. The inclusion of a quadratic time trend enables the model to capture annual variation without the need for year-specific dummy variables. This specification avoids collinearity between the COVID-19 variable and overall time effects, since the national-level nature of the Stringency Index varies only over time and not across municipalities. As such, the model facilitates estimation of the underlying temporal trend based on pre-pandemic data and allows for the derivation of the counterfactual values (i.e., without the pandemic) for the COVID-19 period. Municipal fixed effects are included to control unobserved, time-invariant characteristics specific to each municipality, such as infrastructure, waste collection systems, and levels of environmental awareness. These fixed effects help eliminate bias from factors that could otherwise distort the estimated effects of COVID-19. Additionally, the model includes income as a key explanatory variable, which has been identified as a determining factor in the volume and composition of consumption. The Stringency Index, which quantifies the severity of governmental restrictions during the pandemic, is also incorporated as a proxy for behavioral changes in households (such as shifts in mobility and consumption patterns) that likely influenced waste generation dynamics.

The baseline regression model is specified as follows (Equation (1))

$$Y_{it} = \alpha + \beta_1 Trend_t + \beta_2 Trend_t^2 + \beta_3 Stringency_t + \mu_i + \mu_{it} \quad (1)$$

where Y_{it} denotes the amount of waste generated, measured either as total municipal waste per capita (in kg/capita/year) or as the recycling rate (i.e., the proportion of selective waste relative to total waste) for municipality *i* in year *t*. The variables $Trend_t$ and $Trend_t^2$ capture linear and quadratic components of the time trend, respectively, $Stringency_t$ represents the national COVID-19 Stringency Index, μ_i denotes municipality-specified fixed effects, and μ_{it} is the idiosyncratic error term.

In an extended model specification (Equation (2)), additional socioeconomic control variables are incorporated to account for demographic characteristics and infrastructural differences across municipalities:

$$Y_{it} = \alpha + \beta_1 Trend_t + \beta_2 Trend_t^2 + \beta_3 Stringency_t + \beta_4 Income_{it} + \beta_5 Adult_{it} + \beta_6 HighEdWorkers_{it} + \beta_7 Internet_{it} + \beta_8 Cars_{it} + \beta_9 Pensioners_{it} + \beta_{10} Elderly_{it} + \beta_{11} Employment_{it} + \mu_i + \mu_{it} \quad (2)$$

where the additional variables are included to represent demographic and infrastructural characteristics (see Table 3).

2.2.2. *Model 2: Excess over expected*

This approach builds on the methodologies developed in excess mortality research during the era of COVID-19, aiming to estimate counterfactual waste generation levels in the absence of the pandemic (see e.g., Chandra et al., 2024). To predict expected waste generation, both the baseline and extended regression models are re-estimated on data from 2012 to 2019. These models are designed to capture the underlying temporal dynamics and socioeconomic determinants of waste generation prior to the onset of the COVID-19 outbreak.

Using the predicted values $Y_{it}^{Expected}$ for the 2020–2023 period, excess waste generation is calculated as in Equation (3):

$$Excess_{it} = Y_{it}^{observed} - Y_{it}^{Expected} \quad (3)$$

Finally, the estimated excess values are regressed on the same set of explanatory variables that were used to generate the expected values: time trends in the baseline model, and both time trends and socioeconomic as well as infrastructural variables in the extended specification.

2.2.3. Heterogeneity analysis

The impact of the COVID-19 pandemic was unlikely to be uniform across all municipalities; rather, it may have varied depending on the socioeconomic conditions and specific local characteristics of the municipalities. It is therefore essential to explore how the effects differ along social and geographic dimensions. Analyzing such heterogeneity not only enhances the accuracy of empirical assessments but also enables more targeted and effective policy interventions by identifying which population groups or regions were most affected.

Given that the effect of a particular intervention or external shock (in this case the COVID-19 pandemic) may differ substantially between rural and urban populations due to factors such as the size of the settlement, economic development, or demographic composition, it is appropriate to consider the concept of heterogeneous treatment effects (HTE) (Wager and Athey, 2018; Xie et al., 2012). For instance, households in smaller municipalities may face practical barriers to adopting selective waste collection due to insufficient infrastructure or limited access. In contrast, residents of large urban areas are more likely to benefit from convenient access to waste sorting and collection services. Therefore, the impact of the pandemic on waste generation habits can vary significantly across municipalities with differing characteristics. Consequently, the study also investigates the effects of COVID-related restrictions across distinct types of settlements.

A range of statistical methods are available to empirically identify heterogeneous treatment effects. Based on the structure of the data, two interaction models were estimated separately, each including a different interaction term. This approach enables an analysis of how infrastructural, developmental, and other municipal-level differences shaped waste generation patterns during the pandemic. The two interaction models were estimated within a unified regression framework, which can be described as follows (Equation (4)):

$$Waste_{it} = \alpha + \beta_1 Interaction_{it} + \beta_2 Income_{it} + \lambda_t + \mu_i + \mu_{it} \tag{4}$$

where $Interaction_{it}$ denotes the interaction term, specified either as the interaction between income and the COVID-19 Stringency Index ($Income_{it} \times Stringency_t$), or as the interaction between the COVID-19 period and settlement size ($COVID_t \times SettlementType_i$). λt represents the year fixed effects. All other variables retain their definitions provided in the previous model specifications.

This analytical approach contributes to a more nuanced and detailed exploration of the relationship between the pandemic and waste generation. While previous studies have typically analyzed the impact of recent years on waste generation at national or regional level (if addressed at all), the methodology applied here allows for the identification of differences across municipal typologies. By examining interaction effects, the analysis offers a more accurate depiction of the divergent waste generation dynamics observed between urban and rural areas, as well as how these effects vary by income level in response to government-imposed restrictions.

3. Results and discussion

3.1. Results of the panel regression

First, panel regression models are estimated to evaluate the effects of the COVID-19 pandemic on various waste management outcomes, including selective waste generation, non-selective waste generation, total municipal waste generation, and the recycling rate. These models incorporate quadratic time trends and the national COVID-19 Stringency Index and are further augmented by socioeconomic control variables and municipality fixed effects. The results of the initial model are summarized in Table 4.

The estimated coefficients indicate that stricter pandemic-related restrictions were associated with an increase in both selective and non-selective waste generation per capita. Specifically, the COVID-19 Stringency Index exhibits a positive and statistically significant association with mixed waste generation (0.106 kg/capita/year) and selective waste generation (0.017 kg/capita/year), suggesting that periods of more stringent government measures coincided with increased accumulation of waste in both categories. Importantly, while the increase in selective waste is a positive outcome, the rise in non-selective waste did not occur in isolation; rather, it contributed to a statistically significant overall increase in total municipal waste generation (0.123 kg/capita/year). This finding implies that the pandemic placed additional pressure on local waste management systems by amplifying the total volume of waste

Table 4
Results of the panel regression with time trends.

Variable	Mixed Waste	Selective Waste	Total Waste	Recycling Rate
Covid Stringency	0.106*** (0.019)	0.017*** (0.004)	0.123*** (0.02)	0.00003 (0.00001)
Trend	−2.240*** (0.773)	1.375*** (0.144)	−0.865 (0.777)	0.006*** (0.0006)
$Trend^2$	0.158*** (0.059)	−0.048*** (0.009)	0.111* (0.059)	−0.002*** (0.0004)
Constant	201.315*** (1.923)	0.944** (0.476)	202.259*** (1.947)	0.0053*** (0.0018)
Observations	7,660	7,660	7,660	7,660
R-squared	0.681	0.730	0.698	0.737

Notes: Robust standard errors clustered at the settlement level are reported in parentheses. Waste indicators are measured in kilograms per capita per year (kg/capita/year), while the recycling rate is presented as a percentage.

produced.

In contrast, the recycling rate does not show a statistically significant relationship with the COVID-19 Stringency Index. Although the absolute quantity of selectively collected waste increased, this growth was proportional to the rise in total waste, resulting in a relatively stable recycling rate. This outcome suggests that the pandemic did not meaningfully alter recycling behavior or the effectiveness of selective collection systems during the period under study. Overall, the results indicate that the COVID-19 pandemic significantly increased the amount of both selective and non-selective municipal waste. Based on the estimated coefficients, the average COVID-19 Stringency Index of 56.01 in Hungary during 2020 is associated with an increase of approximately 5.94 kg of mixed waste and 0.95 kg of selectively collected waste per capita per year. In total, this corresponds to an estimated additional 6.89 kg of municipal solid waste generated per capita during the pandemic period in 2020.

The extended regression model yielded results that are broadly consistent with the baseline specification but offer greater nuance (see Table 5). The COVID-19 Stringency Index remained positively associated with selective waste generation (0.016 kg/capita/year), mixed waste generation (0.098 kg/capita/year), and total waste generation (0.113 kg/capita/year). Although the estimated coefficients are marginally lower than those obtained from the baseline model, the effects remain substantively meaningful, suggesting that more stringent pandemic-related restrictions were consistently linked to increased waste generation. As in the baseline specification, the recycling rate did not exhibit a statistically significant association with the Stringency Index; however, the estimated trend was slightly negative.

Based on these estimates, an average COVID-19 Stringency Index of 56.01 corresponds to an additional 0.90 kg of selectively collected waste, 5.49 kg of mixed waste, and 6.33 kg of total municipal waste generated per capita. The predicted change in the recycling rate remains negligible. Nevertheless, the results suggest that although selective waste generation increased during the pandemic, it was accompanied by a concurrent increase in mixed waste generation, ultimately leading to a net rise in total municipal waste. While the recycling rate remained relatively stable, the significant increase in per capita waste generation represents a negative environmental outcome that underscores the broader pressure placed on municipal waste management systems during the pandemic period.

This pattern is supported by previous studies (Brontowiyono, 2021; Ranjbari et al., 2021). The transition to remote work increased the time spent at home, potentially enhancing attention to selective waste collection. Changes in consumer behavior, such as reduced purchases of non-essential goods and more sustainable consumption habits, also contributed to shifts in waste generation patterns. However, increased waste volumes, even selectively collected, place additional strain on municipal systems, especially in regions lacking processing capacity (Adelodun et al., 2021; Sarkodie and Owusu, 2021). The stability in the recycling rate despite higher selective waste volumes implies that improved participation may not have been accompanied by improvements in waste sorting accuracy or system efficiency. This echoes the rebound effect described by Maier et al. (2023), whereby individuals engage in higher consumption under the perception that waste is being handled sustainably, which paradoxically undermines environmental gains.

3.2. Excess-over-expected method

In the second stage of the analysis, an excess-over-expected framework was applied. Expected waste generation was first estimated using fixed effects panel regressions with quadratic time trends, based on the data from the pre-pandemic period (2012-2019). The difference between the actual observed values and the predicted counterfactual values for the 2020–2023 period was then calculated to derive measures of excess waste generation. These excess values were regressed on the COVID-19 Stringency Index to evaluate how pandemic-related restrictions contributed to the deviations from expected waste generation. The results of the initial model are presented in Table 6.

The regression results on excess waste generation reveal a strong and positive relationship between the COVID-19 Stringency Index and the volume of excess waste. Specifically, a one-unit increase in the Stringency Index is linked to an additional 0.068 kg of

Table 5
Result of the panel regression with time trends and additional controls.

Variables	Mixed Waste	Selective Waste	Total Waste	Recycling Rate
Covid Stringency	0.098*** (0.024)	0.016** (0.007)	0.113*** (0.068)	0.00001 (0.00002)
Income (z-score)	8.932*** (2.566)	0.174 (0.672)	9.105*** (2.644)	−0.001 (0.003)
Trend	−1.065 (1.490)	1.269*** (0.347)	0.2042 (1.494)	0.062*** (0.012)
Trend^2	−0.173** (0.083)	−0.044** (0.0190)	−0.217** (0.085)	−0.002*** (0.0007)
Percentage of adults	−39.715 (127.936)	−40.214 (34.9790)	−79.929 (131.473)	−0.105 (0.130)
Percentage of elderly	−159.533 (117.036)	36.704 (35.3084)	−122.83 (122.053)	0.124 (0.414)
Internet subscription	−25.111*** (9.556)	−1.367 (1.628)	−26.478*** (9.795)	−0.013*** (0.005)
Car ownership rate	67.304** (26.085)	0.202 (6.422)	67.506** (26.532)	0.011 (0.022)
Pensioners	−119.885 (79.625)	44.274 (29.2302)	−75.610 (79.645)	0.151 (0.096)
Educated workers	574.481 (871.752)	−174.90 (312.881)	399.582 (874.29)	−0.923 (3.16)
Local employment rate	138.530* (77.033)	25.995 (28.6697)	164.480 (81.237)	0.076 (0.112)
Constant	279.918*** (96.823)	4.120 (26.404)	284.038 (98.155)	−0.005 (0.094)
Observations	7,660	7,660	7,660	7,660
R-squared	0.688	0.734	0.741	0.739

Notes: Robust standard errors clustered at the settlement level are reported in parentheses. Waste indicators are measured in kilograms per capita per year (kg/capita/year), while the recycling rate is presented as a percentage.

selectively collected waste, 0.354 kg of mixed waste, and 0.421 kg of total waste per capita per year. These results suggest that stricter pandemic-related restrictions led significantly to increases in both selective and non-selective waste streams, with the most pronounced effect observed in total waste generation. The recycling rate exhibited a small but statistically insignificant positive association with the Stringency Index. Based on the estimated coefficients, an average COVID-19 Stringency Index of 56.01 in Hungary corresponds to approximately 3.81 kg of excess selectively collected waste, 19.82 kg of excess mixed waste, and a total of 23.63 kg of additional municipal waste generated per capita on an annual basis.

In the second model specification, the excess values were estimated from pre-pandemic quadratic time trends alongside additional socioeconomic and infrastructural controls. These included indicators of income, age structure, internet access, car ownership, the proportion of pensioners, education level, and local employment rates. The results are presented in Table 7.

The findings confirm a statistically significant and positive effect of the COVID-19 Stringency Index on total waste excess (0.469 kg/capita/year). This suggests that even after accounting for local demographic and infrastructural characteristics, stricter governmental restrictions were associated with a notable increase in municipal waste. Crucially, the model also reveals a divergence between selective and mixed waste patterns. The excess in selectively collected waste remained significantly positive (0.588 kg/capita/year), whereas the excess in mixed waste became negative (−0.119 kg/capita/year). This indicates that, although the pandemic led to an overall increase in total municipal waste, part of this rise can be attributed to a compositional shift from mixed to selectively collected waste streams. Based on these estimated coefficients, an average COVID-19 Stringency Index of 56.01 in 2020 would correspond to approximately 32.94 kg of excess selective waste, a decrease of 6.66 kg in mixed waste, and a net increase of 26.27 kg in total municipal waste per capita on an annual basis.

According to the literature (Ranjbari et al., 2021; Vila and Costa, 2024), individuals' willingness to adopt sustainable behaviors increased during the pandemic, as the crisis underscored the relevance of environmental protection in enhancing societal resilience. Consequently, engagement in environmentally responsible practices - such as waste reduction and selective waste collection - increased markedly. Supporting this, Contreras-Contreras et al. (2023) and Tolppanen et al. (2023) found that the pandemic triggered a broader paradigm shift, fostering stronger support for sustainability initiatives and reinforcing the connection between well-being and the pursuit of sustainable lifestyles, potentially promoting long-term behavioral change. However, this transition toward greater environmental consciousness has also had unintended negative consequences, particularly due to the rise in online purchasing. While digital consumption increased rapidly during the pandemic, it did not recede to pre-pandemic levels afterward. A typical e-commerce delivery may contain up to seven different types of packaging materials, many of which are challenging to recycle. Furthermore, online shopping can generate up to 4.8 times more packaging waste than traditional brick-and-mortar retail (Kim et al., 2022).

Further empirical evidence (Adibfar et al., 2022; Mahpour et al., 2025; Svatosova, 2022) suggests that a significant share of consumers continue to plan and make purchases online even after the acute phase of the pandemic. Official statistics from the Hungarian Central Statistical Office (2025) show that the share of individuals making online purchases within a three-month period rose from 35% in 2019 to 61% in 2022 (and 61.7% in 2024). These trends suggest a lasting shift in consumer behavior. The proportion of online purchases, which are typically associated with higher volumes of packaging waste, has not returned to pre-pandemic levels. Simultaneously, offline (in-store) shopping has also rebounded following the lifting of COVID-related restrictions, further contributing to the overall increase in waste generation. Although much of this waste is now being directed into selective collection systems, the environmental implications remain concerning. Public understanding of proper selective waste disposal practices remains limited in many contexts. As a result, a substantial portion of the waste placed in recycling bins may be non-recyclable. This significantly undermines the effectiveness of selective waste collection systems and reduces the actual recovery of recyclable materials.

3.3. *Differences in waste generation across municipalities*

The 640 municipalities included in the analysis exhibit substantial variation in terms of development and (waste management) infrastructure. In the smallest municipalities, dedicated waste collection systems were in some cases absent until 2015. Moreover, the implementation of waste collection infrastructure was not uniform across all municipalities. In the largest cities, the so-called double-bin system dominated, whereby households were provided with separate containers for paper and plastic waste, while landfills and communal collection points ('islands') continued to operate for extended periods. In contrast, smaller municipalities typically implemented either communal collection islands or a door-to-door bag-based collection system. In the latter, residents received transparent bags for sorting different waste types, which were then collected at scheduled intervals. Given the significant differences in

Table 6
Panel regression results on excess waste estimated based on time trends (2020–2023).

Variables	Mixed Waste	Selective Waste	Total Waste	Recycling Rate
Covid Stringency	0.354***	0.068***	0.421***	0.0002
	(0.021)	(0.004)	(0.022)	(0.00017)
Constant	−22.266***	−4.977***	−27.242***	−0.145***
	(0.612)	(0.124)	(0.631)	(0.004)
Observations	2,540	2,540	2,540	2,540
R-squared	0.906	0.962	0.914	0.962

Notes: Waste indicators are measured in kilograms per capita per year (kg/capita/year), while the recycling rate is presented as a percentage.

Table 7
Panel regression results on excess waste estimated based on time trends and additional controls (2020–2023).

Variables	Mixed	Selective	Total Waste	Recycling Rate
Covid Stringency	−0.119**	0.588***	0.469***	0.0001**
	(0.056)	(0.090)	(0.105)	(0.0004)
Income (z-score)	−18.290***	0.309	−17.98***	0.0035**
	(2.493)	(0.356)	(2.52)	(0.0014)
Percentage of adults	−516.460**	59.621*	−456.838**	0.010
	(222.218)	(31.088)	(223.035)	(0.137)
Percentage of elderly	−478.558*	−112.433***	−590.991**	−0.334***
	(258.187)	(27.359)	(262.522)	(0.009)
Internet subscription	38.579**	−2.162	36.417**	0.014
	(17.849)	(2.453)	(18.025)	(0.009)
Car ownership rate	−45.832	3.314	−42.518	−0.351
	(47.855)	(7.317)	(51.399)	(0.023)
Pensioners	275.037	−46.297**	228.74	−0.110
	(171.221)	(19.595)	(173.04)	(0.063)
Educated workers	−587.654	634.028***	46.373	2.178***
	(906.298)	(169.590)	(913.42)	(0.640)
Local employment rate	−172.344	54.209	−118.13	0.194
	(119.616)	(57.139)	(150.78)	(0.169)
Constant	371.899**	−1.139	370.76**	0.051
	(163.372)	(24.321)	(166.35)	(0.102)
Observations	2,540	2,540	2,540	2,540
R-squared	0.913	0.963	0.913	0.963

Notes: Waste indicators are measured in kilograms per capita per year (kg/capita/year), while the recycling rate is presented as a percentage.

the design and effectiveness of waste management infrastructure and collection systems, the analysis explores whether the impact of COVID-related stringency measures varied across different settlement types.

To assess potential heterogeneity in the effects of the pandemic, municipalities were categorized into three groups based on population size: settlements with fewer than 10,000 inhabitants were classified as rural areas, those with 10,001 to 100,000 inhabitants as towns, and those exceeding 100,000 inhabitants as major cities. This classification makes it possible to identify distinct patterns in waste generation and policy responsiveness across settlement types. Estimation results based on interaction terms, using rural settlements as the reference category, are presented in Table 8.

The heterogeneity analysis reveals significant differences in how municipalities of varying sizes responded to pandemic-related restrictions. In this specification, interaction terms between the COVID-19 Stringency Index and settlement type categories were included to examine whether the impact of policy stringency varied across rural areas, towns, and major cities. Rural municipalities, defined as those with populations under 10,000, served as the reference category, while the effects for towns and major cities are captured through corresponding interaction terms. The results suggest that COVID-19-related restrictions had negligible, or in some cases slightly adverse, effects on waste generation in rural areas. In contrast, the impacts were substantially more pronounced in urban municipalities. In towns, the Stringency Index was associated with an increase of 0.069 kg per capita in selectively collected waste and a 0.764 kg per capita rise in total waste. The estimated effects were considerably larger in major cities, where selective waste generation increased by 0.274 kg and total waste by 2.628 kg per capita annually. While mixed waste generation showed a modest increase in rural areas (0.083 kg), it slightly declined in major cities (−0.111 kg per capita), indicating a possible and potential shift toward more effective waste separation practices in urban settings. A similar pattern was observed for the recycling rate, which declined marginally in villages but improved with increasing settlement size, rising in towns and cities relative to rural areas.

Using the average COVID-19 Stringency Index value recorded in Hungary in 2020 (56.01), the estimated pandemic-induced changes in per capita waste generation across different settlement types are as follows:

Table 8
Heterogeneity analysis across the municipalities (2012–2023).

Covid Stringency	Mixed Waste	Selective Waste	Total Waste	Recycling Rate
Village (reference)	0.083***	−0.006	0.021	−0.00025**
	(0.028)	(0.07)	(0.074)	(0.00009)
Towns	0.070	0.069***	0.764***	0.00052***
	(0.056)	(0.022)	(0.226)	(0.00018)
Major Cities	−0.111	0.274***	2.628***	0.0016***
	(0.116)	(0.051)	(0.502)	(0.00039)
Observations	7,660	7,660	7,660	7,660
R-squared	0.688	0.736	0.743	0.770

Notes: The regression models included both quadratic time trends and additional socioeconomic control variables. Waste indicators are measured in kilograms per capita per year (kg/capita/year), while the recycling rate is presented as a percentage.

- **Villages (rural areas):** Mixed waste increased by 4.65 kg. The recycling rate declined slightly (0.014%).
- **Towns**: Compared to villages, selective waste increased by 3.86 kg, total municipal waste rose by 42.79 kg per capita, and the recycling rate improved by 0.029%.
- **Major cities:** Compared to villages, selective waste increased by 15.35 kg, total municipal waste rose by 147.19 kg (and mixed waste decreased by 6.22 kg per capita). The recycling rate improved significantly, with a gain of 0.09%.

These findings underline the importance of accounting for heterogeneity in municipal responses to the pandemic. Urban areas experienced a markedly stronger response in terms of both the volume of waste generated and changes in recycling behavior. This may be attributed to higher levels of consumption and the greater availability and accessibility of selective waste collection. One potential explanation for this pattern is the widespread implementation of the double-bin system, which was primarily adopted by municipalities with populations exceeding 50,000 (Struk, 2017). This system enhanced the efficiency and convenience of waste separation by providing residents with dedicated bins for paper and plastic waste. Additionally, the rapid expansion of e-commerce platforms and food delivery services during the pandemic disproportionately benefited larger urban areas, where such services became more accessible and widely used compared to smaller towns and rural settlements (Kim et al., 2022; Lee and Lim, 2022). As a result, urban residents were exposed to significantly higher volumes of packaging materials and single-use food containers, most of which were disposed of in selective waste bins. In contrast, rural municipalities, mirroring findings in the Global South (Adelodun et al., 2021; Pal and Kashyap, 2025), often lacked adequate infrastructure, leading to higher reliance on mixed disposal channels and lower recycling performance. These patterns also suggest that without equitable access to collection infrastructure, even well-intentioned behaviors may fail to translate into positive environmental outcomes, reinforcing environmental inequality as a latent dimension of pandemic resilience.

3.4. Managerial and policy implications

A shift in consumer habits was observed during the pandemic. A positive development is the increase in the volume of separately collected waste, despite the unknown level of contamination. In contrast, the decrease in non-selective waste has not matched, or has been smaller than, the increase in selective waste, suggesting that the current waste collection systems do not necessarily reduce the overall amount of waste. This discrepancy points to the phenomenon known as the circular rebound effect (Maier et al., 2023), where improved waste sorting infrastructure creates a false sense of environmental responsibility, potentially encouraging increased consumption. Fear of COVID-19 reinforced concerns about climate change and may have had a positive effect on environmental attitudes (Stefkovics and Hortay, 2022). This may have increased the willingness to participate in selective waste collection. At the same time, due to the circular economy rebound effect, people may have felt that by sorting their waste, they were already acting in an environmentally conscious way and contributing to a sustainable economy. Consequently, they might not have perceived the waste they generated as actual waste, and thus, had little incentive to reduce either their consumption or their overall waste production. This is well illustrated by the results summarized in Table 9. Although the coefficients of the COVID-19 Stringency Index of the models used differ, all approaches indicate a significant positive increase in the amount of selective waste and mixed waste. Based on the average COVID-19 Stringency Index (56.01), selective waste increased by an average of 0.9-32.9 kg per capita per year, while total waste rose by 6.3-23.6 kg per capita annually.

This paradox complicates the alignment between recycling and broader sustainability goals. Higher recycling rates may create a false sense of progress, while the absolute increase in waste generation undermines objectives such as resource efficiency, emissions reduction, and long-term circularity. To achieve genuine sustainability, waste prevention and reduced material use must complement recycling efforts; otherwise, the rebound effect risks locking societies into consumption-driven pathways that are incompatible with broader sustainability transitions. Furthermore, the circular economy rebound effect is often associated with the spread of selective waste collection infrastructures. This is consistent with the heterogeneity analysis. Compared to the reference villages – where the selective two-bin system was not available during the pandemic –, the amount of selective and total waste increased substantially in towns and cities (estimated at 42.79, and 147.19 kg per capita of total waste in towns, and major cities; 3.86–15.35 kg of selective waste outside of villages, respectively). For waste management authorities, this implies that technological upgrades in collection infrastructure must be complemented by behavioral interventions and education campaigns aimed at reducing total material throughput, not merely reallocating it between waste streams. Moreover, communication strategies should emphasize the distinction between recycling and absolute waste reduction, addressing the public misconception that increased recycling alone constitutes environmental progress. Local governments should collaborate with NGOs and educational institutions to develop behaviorally informed nudges and incentives, targeting specific demographic groups most prone to rebound effects.

The results also underscore the importance of differentiated waste management strategies based on settlement size and

Table 9
Summary table of the estimated effects of the COVID-19 Stringency Index on municipal waste generation across all model specifications.

Model	Mixed	Selective	Total Waste
Panel regression	0.106***	0.017***	0.123***
Panel regression – extended controls	0.098***	0.016**	0.113***
Excess-over-Expected	0.354***	0.068***	0.421***
Excess-over-Expected – extended controls	−0.119**	0.588***	0.469***

infrastructure availability. Urban municipalities, particularly those equipped with dual-bin systems and curbside collection, achieved higher increases in selective waste, suggesting that logistical convenience is a major driver of recycling participation. In contrast, rural settlements struggled to match this performance, which highlights the critical need to expand and modernize infrastructure in underserved areas. Furthermore, the sharper increase in both selective and total waste in urban municipalities is largely explained by higher consumption levels, particularly during the pandemic when online shopping and home delivery surged, leading to more packaging waste. At the same time, urban areas typically provide more advanced and accessible selective collection infrastructure, which enabled households to channel part of this growing waste stream into recycling.

This pattern reveals that infrastructure readiness is a critical enabler of selective collection, while also highlighting that behavioral readiness alone is insufficient without accessible systems. In rural municipalities, where collection opportunities are more limited, waste increases were less visible in selective streams, underscoring the interaction between infrastructure availability and household waste practices. Thus, policymakers should consider targeted investment in door-to-door collection systems and standardized bin provision in small municipalities, as well as the deployment of mobile collection services where fixed infrastructure is not feasible. Additionally, infrastructural upgrades must be accompanied by training programs for local authorities and waste workers to ensure proper implementation and reduce operational inefficiencies. Investment decisions should be informed by spatially disaggregated data, enabling the allocation of resources to areas with the greatest unmet needs and lowest recycling performance.

Furthermore, the persistent rise in total waste, regardless of improvements in recycling, calls for a broader shift toward consumption-based policies. Strategies such as extended producer responsibility (EPR), eco-design regulations, and packaging taxes could play a vital role in limiting waste generation at the source. Fiscal instruments and tools can further incentivize households to reduce mixed waste. In parallel, municipal governments should adopt performance-based funding schemes that reward waste reduction rather than only recycling rates, thus aligning economic incentives with environmental goals. Policymakers should pilot differential waste tariffs or pay-as-you-throw (PAYT) schemes, particularly in urban areas where waste monitoring technologies can be more easily deployed. These financial mechanisms, if transparently implemented, can foster a stronger link between individual behavior and environmental outcomes, while maintaining social equity through exemptions or subsidies for low-income households.

Finally, this study's insights strengthens the need for integrated data systems and real-time monitoring of waste flows. The pandemic highlighted the fragility and fragmentation of municipal data reporting in many regions. Effective policy requires access to granular, temporally detailed, and standardized waste data to support timely interventions. National governments and the EU should invest in digital infrastructure that enables municipalities to track waste composition and contamination rates, while also providing public transparency dashboards. These steps would enable adaptive waste governance, which is critical for resilience not only during public health emergencies but also in the face of ongoing ecological challenges. Linking waste data with sociodemographic and consumption databases could improve the targeting of interventions and allow for predictive analytics in anticipating future surges in waste generation. Developing standardized indicators across member states would further enhance the comparability and scalability of successful waste management policies within the EU framework.

4. Conclusions

This study provides one of the first large-scale empirical investigations into how the COVID-19 pandemic affected municipal household waste generation and habits across Hungary. Using panel data from 640 municipalities and multiple econometric methods, the analysis captures a nuanced view of pandemic-era waste behavior. The findings reveal a consistent increase in both selective and total waste during periods of stricter COVID-19 restrictions, while the recycling rate remained largely unchanged across settlement types. These results suggest that although engagement in selective collection increased, the overall environmental impact was mixed, as gains in recycling were accompanied by substantial growth in total waste generation.

A key insight of the analysis is that these outcomes were strongly shaped by existing infrastructural and service-related constraints. Differences between urban and rural areas highlight the importance of localized waste management capacities, as municipalities with more developed collection systems were better able to accommodate increased participation in selective collection. At the same time, these infrastructural advantages did not prevent overall waste volumes from rising, indicating that improvements in collection systems alone are insufficient to achieve waste minimization. This interaction between infrastructural capacity and observed waste outcomes helps to explain the apparent contradiction between improved recycling behavior and rising consumption. The findings are consistent with theoretical frameworks such as the circular rebound effect and dual-process consumer behavior models, which suggest that pro-environmental actions, such as increased participation in selective collection, can coexist with, or even encourage, higher levels of material consumption. In this sense, the results illustrate that behavioral engagement in recycling does not automatically translate into reduced environmental pressure when broader consumption patterns remain unchanged.

Despite its methodological strengths, the study faces several limitations. First, waste composition data were not available at a granular level, which restricts deeper analysis of specific material flows (e.g., plastics vs. paper). Second, contamination rates within the selective stream could not be directly measured, which limits the assessment of recycling effectiveness. Third, behavioral variables, such as environmental awareness or perceived risk, were not included, as such data were not systematically available at the municipal level. Thus, future research could build on these findings by incorporating micro-level behavioral surveys to better capture consumer motivations and environmental attitudes during crisis periods. Studies with access to disaggregated waste fractions and contamination levels would allow for more precise assessments of recycling system performance. Additionally, exploring digital waste tracking systems and real-time policy feedback loops could improve the responsiveness of municipal waste governance, not only in pandemic contexts but also in preparation for future sustainability and climate resilience challenges.

CRediT authorship contribution statement

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