Assessing the impact of source separation solutions for biowaste on residual household waste: An analysis at the French intermunicipal level*

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Abstract

This article analyzes the effectiveness of biowaste source separation by assessing its impact on the quantities of residual household waste collected per capita. Using a difference-in-differences approach, we first examine how solutions implemented by French local authorities, such as home composting and separate biowaste collection, affect residual household waste quantities. We then explore the heterogeneity of these effects across various economic and sociodemographic variables. Finally, we isolate the specific effect of the separate collection of biowaste. We find no significant overall effect of combining different biowaste separation solutions on residual waste quantities in our data. However, our analysis of heterogeneous effects shows that low-density areas experience a greater reduction in residual waste following the implementation of these solutions compared to high-density areas. Our results also suggest that incentive pricing significantly reduces residual household waste, while a high number of tourist accommodations and high population density tend to increase it. When focusing solely on the separate collection of biowaste, our findings reveal a significant average reduction of approximately 25 kg per capita in residual household waste among intermunicipal cooperation entities that have implemented this measure. Based on these results, we suggest ways to improve local public waste management policies.

Keywords: Biowaste; Impact evaluation; Local authorities; Difference-in-differences; Household waste; Incentive pricing.

JEL Classification: C01; Q51; Q53; Q58

1. Introduction

Biowaste constitutes approximately 33% of residual household waste in France (ADEME, 2021b). To reduce the environmental and economic impacts associated with its incineration and landfill when mixed with residual household waste[1], biowaste is targeted by European and French regulations. From January 1, 2024, the French anti-waste and circular economy law (AGEC)[2] requires all local authorities responsible for public waste management services to provide their residents with solutions for the source separation of biowaste. The goal of source separation is to remove biowaste from residual household waste, primarily by reducing its production and encouraging the sorting and recovery of unavoidable biowaste. Local authorities have several options in order to comply with the regulations. They can implement individual composting, collective composting, or separate collection of biowaste. These solutions are complementary, allowing each intermunicipal cooperation entity[3] the flexibility to determine the organizational structure that best suits its needs. In this context, analyzing the effectiveness of these solutions is essential, particularly in reducing residual household waste as biowaste separation becomes more widespread.

The economic literature evaluating local waste management policies has largely focused on the effectiveness of economic instruments, especially incentive-based pricing systems designed to encourage households to reduce waste (e.g., Tsai & Sheu, 2009; Allers & Hoeben, 2010; Gatier, 2016). Research specifically examining the effect of biowaste source separation on residual waste quantities remains limited. A notable example is Alacevich *et al.* (2021), who, using data from household surveys, found that the implementation of biowaste source separation policies in Sweden led to an increase in the separation of dry recyclable waste and a decrease in residual waste. However, to our knowledge, no economic study has examined the impact of composting and the separate collection of biowaste on residual household waste quantities at the intermunicipal level, while accounting for heterogeneity, even though some studies (e.g., Bourdin & Ragazzi, 2018) have shown that policy impacts often vary by region or population. Our study addresses this gap by estimating the effects of implementing biowaste source separation solutions on the quantities of residual household waste collected by

[1] Residual household waste refers to household waste that is not subject to separate collection for recovery. It comprises all household and similar waste, except for glass, packaging and paper, biowaste, bulky waste, and hazardous waste.
[2] Law No. 2020-105 of 10 February 2020 on fighting waste and the circular economy.
[3] *Établissement Public de Coopération Intercommunale* (EPCI) in French.

intermunicipal cooperation entities responsible for waste management in France. We also analyze how these effects vary across different economic and sociodemographic contexts, as well as depending on the presence of incentive pricing systems. Our aim is to explain the extent to which biowaste source separation contributes to reducing residual household waste and to identify ways to improve local public waste management policies.

The article is organized as follows. Section 2 reviews the existing academic literature and highlights the originality of our study. Section 3 describes the difference-in-differences method used to assess the effects of source separation of biowaste on quantities of residual household waste. Section 4 describes the data used for the empirical analyses. Section 5 presents the results, focusing first on the combined effects of source separation solutions for biowaste, then on the specific effects of separate collection on the quantities of residual household waste. Section 6 provides a discussion and suggests ways to improve local public waste management policies, and section 7 concludes.

2. Literature review and contributions

The literature on the evaluation of policies implemented by local authorities responsible for waste management mainly focuses on the effectiveness of economic instruments aimed at encouraging households to reduce their waste. Several evaluation methods have been used, such as the synthetic control method (Bueno & Valente, 2019), matching methods (Gatier, 2016), and the difference-in-differences method (Tsai & Sheu, 2009; Allers & Hoeben, 2010; Carattini *et al.*, 2018; Cheng *et al.*, 2020). For example, Tsai & Sheu (2009) analyzed the effects of incentive pricing on household waste, recycling, and illegal dumping in Taipei (Taiwan), using the difference-in-differences method. They concluded that while incentive pricing reduces waste quantities, its impact on recycling is less significant than suggested by the literature. They also claim that over 60% of the observed reduction in waste can be attributed to increased illegal dumping in neighboring municipalities. Similarly, Allers & Hoeben (2010) used the same method to assess the effect of incentive pricing on household waste in Dutch municipalities. They found that this pricing system reduces both residual household waste and biowaste. Using panel data analysis, Usui & Takeuchi (2014) showed that the introduction of incentive pricing programs encourages participation in recycling activities in Japanese cities. In France, Gatier (2016) used matching methods to show that incentive pricing leads to a 28% reduction in residual household waste and a 33% increase in sorted waste (packaging, newspapers and magazines).

Apart from these analyses based on incentive pricing, some studies have sought to identify the effects of changes in waste collection systems on waste quantities and recycling at the household level. For example, Tucker *et al.* (2001) simulated the behavior of residents in Fylde, United Kingdom. They found that reduced waste collection frequencies changed the recycling habits of 18% of the population. This resulted in environmental benefits and cost savings of 60% from reduced energy consumption and waste collection vehicle emissions. Using propensity score matching and differences-in-differences estimation, Best & Kneip (2019) assessed the causal effect of curbside collection on household recycling participation in Cologne (Germany). They found that curbside collection increased recycling participation by 10-25% for plastics and packaging.

Regarding biowaste, most evaluation studies have concentrated on identifying ecologically preferable recovery solutions by comparing the benefits of various treatment options. The life cycle assessment method has been widely used for this purpose (Krutwagen *et al.*, 2008). For example, Maragkaki *et al.* (2023) applied this method to study biowaste composting in Katerini (Greece), concluding that it offers environmental advantages over landfilling. However, these studies mainly compare the advantages of different treatment methods (industrial composting, incineration with energy recovery, methanization) without considering an essential condition for biowaste recovery: source separation (Angouria-Tsorochidou *et al.*, 2023). De Silva & Taylor (2024) examined the effects of municipal composting services on household waste disposal and landfill emissions in Australia. They found that this measure diverted household waste from landfills and could reduce emissions from landfills by 6-26%. Using individual data from household surveys in California, Sintov *et al.* (2019) showed that home composting policies can help reduce food waste, revealing knock-on effects on household behavior. Similarly, Alacevich *et al.* (2021) found that the implementation of biowaste source separation policies in Sweden led to an increase in the separation of dry recyclable waste and a decrease in residual waste, also based on data from households.

Studies directly analyzing the relationship between biowaste source separation policies and the quantities of waste collected at the intermunicipal level remain rare. We can cite Ek & Miliute-Plepiene (2018), who analyzed the effects of a separate food waste collection policy on the quantities of dry recyclable waste in Swedish municipalities, showing that this policy generated spillover effects and promoted better sorting of packaging waste. However, although empirical research shows that, in general, policy impacts often vary by region or population (Bourdin & Ragazzi, 2018), their study did not account for the economic and sociodemographic heterogeneity of the municipalities analyzed. Moreover, given that a major goal of biowaste source separation is to reduce the quantities of residual waste incinerated or landfilled, it is crucial to assess its direct impact on the residual waste stream.

In the French context, Resse (2007) examined the relevance of local source separation solutions for biowaste, focusing on three French municipalities. This study measured collection performance indicators and waste characterization before and after the implementation of solutions, revealing that the measures adopted in these municipalities reduced the quantities of biowaste in residual household waste. Furthermore, a study by (ADEME, 2022), comparing the average quantities of residual waste in intermunicipal entities that implemented biowaste sorting with the national average, concludes that such intermunicipal entities generally exhibit lower residual waste quantities. Our contribution includes assessing the effectiveness of source separation solutions for biowaste across a diverse range of French intermunicipal cooperation entities, considering both the diversity of available solutions and the heterogeneity of local contexts. For this, we use the difference-in-differences method described in the next section.

3. Methodology

Evaluating public policy requires the comparison of outcomes after implementation with those that would have occurred in its absence. As this counterfactual scenario is generally unobservable, it can be estimated using a control group. This group consists of individuals or entities that did not benefit from the policy, but are comparable to the beneficiaries. Difference-in-differences is one of the most commonly used methods in empirical impact assessment studies in economics (Callaway, 2020). It estimates the impact of a policy by calculating the before-and-after difference in outcomes for the treatment group and then subtracting the variation observed in the control group. This method relies on the "parallel trends" hypothesis, which posits that, in the absence of the policy, the evolution of outcomes would have been similar in both groups (Fredriksson & Oliveira, 2019). The difference-in-differences method has been applied in various contexts to assess the effects of public policies related to waste management (for example, Allers & Hoeben, 2010; Cheng *et al.*, 2020). In our study, the difference-in-differences method is well suited to our research question, which aims to identify the effect of source separation solutions for biowaste on the quantities of residual household waste collected by intermunicipal cooperation entities. The available data on biowaste management policies in France also motivates our estimation strategy. Indeed, while source separation of biowaste will not be mandatory until January 1, 2024, some local authorities have already implemented composting and separate biowaste collection voluntarily or in anticipation of the regulations in recent years. This situation allows us to identify two groups of intermunicipal entities: a treatment group that has adopted the policy, and a control group, which is useful for estimating causal effects using difference-in-differences. Moreover, the availability of data prior to the implementation of biowaste source separation solutions enables us to verify the validity of this method. The canonical difference-in-differences estimator is obtained using the following econometric specification (equation 1):

$$Y_{it} = \alpha + \beta\, Treatment_i + \gamma\, Year_t + \delta\, (Treatment \text{ x } Year)_{it} + \varepsilon \qquad \mathbf{(1)}$$

Y_{it} represents the quantity of residual household waste collected per capita by intermunicipal entity i in year t. $Treatment_i$ is a dummy variable, constant over the years, equal to 1 if the intermunicipal structure i implemented source separation of biowaste. $Year_t$ is a dummy variable equal to 1 for the year after treatment and 0 for the year before. $(Treatment \text{ x } Year)_{it}$ is a dummy variable equal to 1 if intermunicipal structure i is treated in year t. δ is the coefficient of interest, reflecting the Average Treatment Effect on the Treated (ATT).

Several authors, including Allers & Hoeben (2010), Gatier (2016), Agovino *et al.* (2019), Romano *et al.* (2019), Cheng *et al.* (2020), and Romano *et al.* (2022), have demonstrated that economic and sociodemographic factors (such as tourism, population density, income) can explain the levels and differences in the quantities of residual household waste collected by intermunicipal entities. To account for potential heterogeneity, we estimate an extended difference-in-differences model with interaction that allows us to assess how the policy effect varies according to certain characteristics. We include variables that may differ between the treatment and control groups and that are likely to influence the quantities of residual household waste collected. The estimated specification is presented in equation (2):

$$Y_{it} = \beta_0 + \beta_1 Treatment_i + \beta_2 Year_t + \beta_3 (Treatment \text{ x } Year)_{it} + \beta_4 X_i + \beta_5 (Treatment \text{ x } X_i) + \beta_6 (Year \text{ x } X_i) + \beta_7 (Treatment \text{ x } Year \text{ x } X_i) + \varepsilon \qquad \mathbf{(2)}$$

where, X_i represents economic or sociodemographic characteristics (e.g., the number of tourist accommodations, population density, waste pricing systems). β_7 captures how the effect of the policy varies depending on the value (or modality) of X_i. By including these interaction terms, we can determine whether source separation policies for biowaste are more effective in certain areas, depending on specific local characteristics.

In this section, we presented the difference-in-differences method and its extension with interaction terms to assess the impact of source separation solutions for biowaste on residual household waste quantities. The next section describes the data used for the empirical application of this method.

4. Data and descriptive statistics

4.1. Database and sample

Data on the quantities of waste collected by public waste management services are taken from the "*Collecte*" survey of intermunicipal entities conducted by ADEME and recorded in the SINOE® database.[4] This database allows us to track changes in household waste collection and provides information on composting solutions for biowaste implemented by intermunicipal entities. In addition, a report by ADEME (2022) lists all intermunicipal entities that had adopted separate biowaste collection. From these data sources, we identified 240 intermunicipal entities for which data are available on both residual household waste collected in 2011 and 2021[5], as well as on the implementation of biowaste source separation solutions. Figure 1 shows the evolution of the quantities of residual household waste collected per capita in these 240 intermunicipal entities compared to the national average. The trends appear broadly similar, suggesting that the selected sample is representative of national dynamics and thus relevant for our analysis.

Solutions for sorting biowaste at source implemented by French local authorities include separate collection (via curbside collection with dedicated bins or through voluntary drop-off points), individual composting (by households in private spaces such as gardens, balconies, or yards), and collective composting (in shared neighborhood or residential sites). These solutions are complementary, and intermunicipal entities can combine them to best fit their local context. Figure 2 shows that among the 240 intermunicipal entities in our study sample, 113 had implemented at least one of these three biowaste source separation solutions by 2021, while 127 had not implemented any such solution by 2021.

[4] The survey is sent to approximately 1200 intermunicipal cooperation entities responsible for waste collection and treatment.
[5] We consider these two years to retain as many intermunicipal entities as possible in the study.

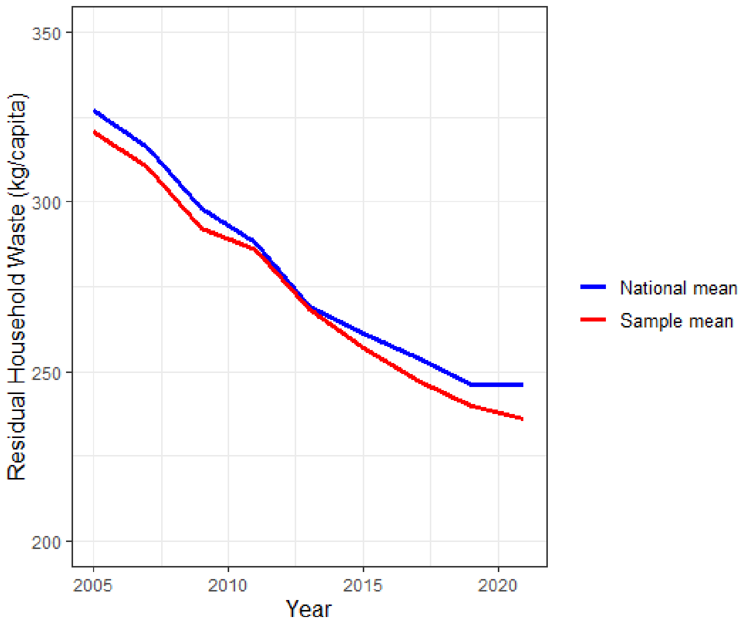

Figure 1 : Evolution of the mean residual household waste collected per capita in the sample and at the national level

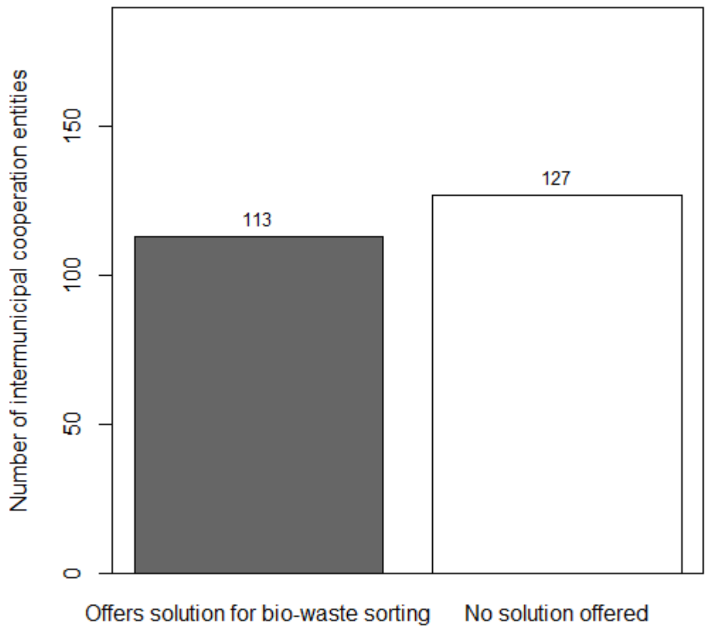

Figure 2 : Distribution of intermunicipal entities by presence of biowaste sorting solutions in 2021

The difference-in-differences analysis is based on two observation years: 2011 (the pre-treatment year) and 2021 (the post-treatment year). It is important to clarify the composition of the treatment and control groups in relation to these two years. The 113 intermunicipal entities that had not implemented any solution in 2011 but adopted at least one solution after that year constitute the treatment group. A graphical representation of the number of solutions implemented by each intermunicipal entity (Figure A.1 in Appendix) shows that among these 113 intermunicipal entities, 6 had implemented both home composting[6] and separate collection, while the remaining 107 offered one solution in 2021. The control group comprises the 127 intermunicipal entities that did not implement any biowaste sorting solution either before or after 2011. Descriptive statistics for these two groups are presented in the next subsection.

4.2. Descriptive statistics

Table 1 presents descriptive statistics on the quantities of residual household waste collected per capita in 2011 and 2021 for both the treatment and control groups, as well as for the total sample of intermunicipal entities studied. Between 2011 and 2021, the average quantity of residual household waste collected per capita decreased across all groups. For example, in the global sample, there was a decrease of nearly 17%, indicating a general reduction in residual waste over the period. Moreover, the data reveal significant variations across intermunicipal entities. In 2021, the minimum quantity collected was 98.74 kg per capita, while some intermunicipal entities exceeded 600 kg per capita.

Table 1 : Descriptive Statistics for residual household waste quantities

	Quantity of residual household waste collected (kg/capita)					
Year	2011			2021		
Group	Treatment	Control	Total	Treatment	Control	Total
Sample size	113	127	240	113	240	240
Minimum	104.5	86.24	86.24	104.2	98.74	98.74
1st quartile	239.9	231.18	234.59	175.5	187.49	183.24
Median	267.1	261.88	263.87	224.2	234.11	228.26
Mean	282.6	290.70	286.89	228.9	247.84	238.95
3rd quartile	295.5	300.51	299.37	259.9	275.12	270.68
Max	850.5	863.43	863.43	568.2	696.52	696.52

To conduct the heterogeneity analyses in our difference-in-differences framework, we rely on relevant literature and available data to select the following variables: (i) TOURIST-ACCOMMODATION, measured by the number of campsites and the number of available hotel beds. Some authors show that tourism can affect the efficiency of municipal waste management (Caponi, 2022). (ii) DENSITY, representing population density in inhabitants per km². In high-density municipalities, limited space can pose challenges for waste sorting and management

[6] We define "home composting" as the presence of individual composting, collective composting, or both.

(Timlett & Williams, 2009). (iii) INCOME, measured by the median taxable income per consumption unit. This variable is used to capture the standard of living in a given area. Some authors (e.g., Romano *et al.*, 2019) suggest that income influences consumption patterns and, consequently, waste generation. (iv) PRICING-SYSTEM, since the implementation of incentive pricing can influence both waste generation and sorting behavior (Allers & Hoeben, 2010; Gatier, 2016; Romano *et al.*, 2019). Table A.1 in Appendix provides details on the years considered and the data sources for these variables.

Table 2 presents descriptive statistics for the quantitative variables used to perform the heterogeneity analyses, by treatment and control groups. The median values of population density are much lower than the means in both groups, illustrating strong disparities in the distribution of density. The number of tourist accommodation establishments also varies greatly: in the treatment group, it ranges from 0 to 1472, highlighting significant differences in tourism activity among intermunicipal entities. A similar variability is observed across intermunicipal entities for income. For the heterogeneity analyses, all these quantitative variables are divided into two categories: "Low" for intermunicipal entities with values below the median, and "High" for those above the median. This classification allows for comparative analysis across groups.

Table 2 : Descriptive statistics for quantitative variables used to perform the heterogeneity analyses

	TOURIST-ACCOMMODATION		DENSITY (inhabitants/Km^2)		INCOME (euros)	
Group	Treatment	Control	Treatment	Control	Treatment	Control
Minimum	0.00	0.00	7.002	8.187	18,877	20,358
1st quartile	4.00	3.00	35.918	28.292	26,854	26,248
Median	10.00	7.00	78.693	58.327	30,027	28,623
Mean	32.99	17.65	235.410	126.213	31,367	29,539
3rd quartile	28.00	19.50	146.214	134.909	34,786	32,637
Max	1472.00	156.00	10,126.570	1121.320	54,095	45,634

Figure 3 shows the distribution of all intermunicipal entities according to their waste pricing system (the qualitative variable). Three types of pricing systems are distinguished: (i) classic pricing, where the price paid by residents is independent of the amount of waste produced; (ii) incentive pricing, which is calculated based on the quantity of waste generated; and (iii) mixed pricing, where part of the population is subject to classic pricing and the other part to incentive pricing.

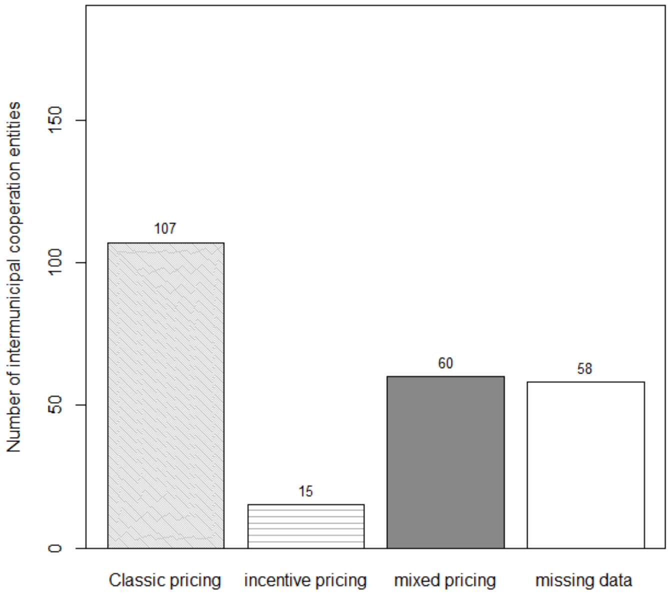

Figure 3 : Distribution of intermunicipal entities by waste pricing system

To assess the specific effects of separate biowaste collection on residual household waste quantities, we retained the same control group but defined the treatment group as only the 53 intermunicipal entities that introduced separate biowaste collection after 2011 (see Figure 4).

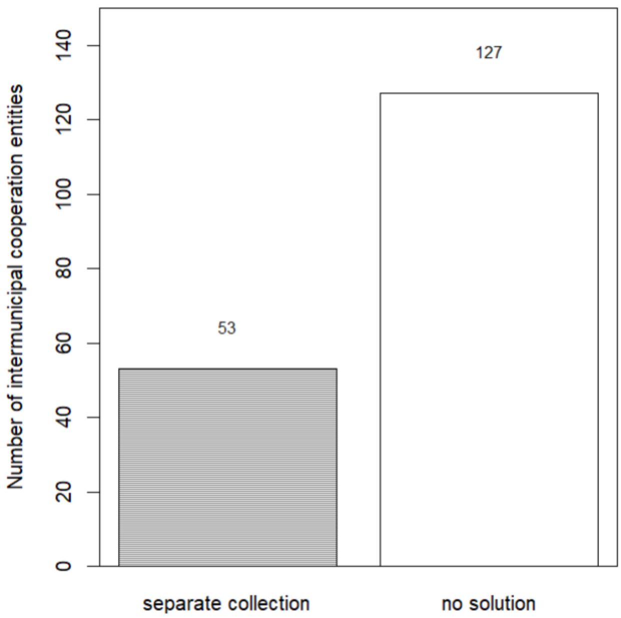

Figure 4 : Distribution of intermunicipal entities according to the presence of separate collection for biowaste in 2021

The next section presents and discusses the results of the empirical application of the difference-in-differences method to these data.

5. Results

This section is divided into two parts. In the first part, we present the effects of source separation of biowaste, which includes the implementation of at least one of the solutions available to French intermunicipal entities (home composting and/or separate collection). In the second part, we specifically assess the impact of separate biowaste collection.

5.1. Effect of source separation solutions for biowaste on residual household waste collected per capita

i) Verification of the parallel trends assumption

Firstly, we tested the appropriateness of using the difference-in-differences method, which relies on the parallel trends assumption between the treatment and control groups prior to the policy adoption (Fredriksson & Oliveira, 2019). To do so, we graphically illustrate the evolution of residual household waste quantities in the treatment and control groups to allow for a visual comparison. Figure 5 shows that the two curves follow similar trends during the pre-treatment period, supporting the validity of the parallel trends assumption.

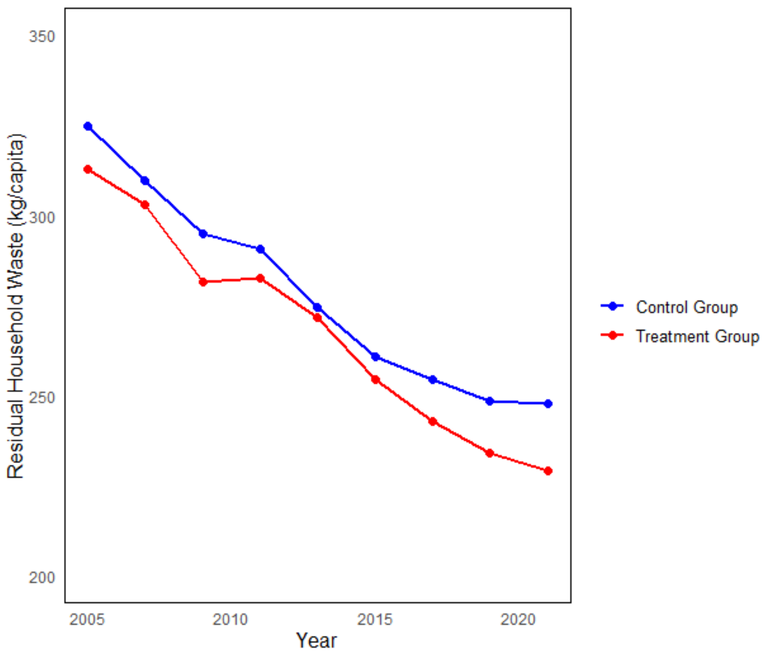

Figure 5 : Trends in residual household waste quantities for treatment and control groups

To confirm this graphical observation, we follow Carattini *et al.* (2018) and conduct a placebo test. Specifically, we introduce a fictitious treatment during the periods prior to policy implementation (2007-2011 and 2009-2011), using the same treatment and control groups as in our main analysis. We then test whether the coefficient of interest (TREATMENT x YEAR), representing the Average Treatment Effect on the Treated (ATT), is statistically significant in these pre-treatment periods. As shown in Table 3, this coefficient is statistically non-significant in both periods, suggesting that there was no significant difference in residual household waste (RHW) trends between the treatment and control groups before the policy was implemented. This validates the use of the difference-in-differences approach in our analysis.

Table 3 : Estimation results for the placebo test of parallel trends (2007-2011 and 2009-2011)

Periods pre-trends	2007-2011	2009-2011
	MODEL	MODEL
Dependent Variable	RHW (kg/capita)	RHW (kg/capita)
ATT	-1.205 (10.39)	5.217 (8.674)
Fixed-Effects:	--------------	-------------
TREATMENT	Yes	Yes
YEAR	Yes	Yes
S.E.: Clustered	by: ID	by: ID
Observations	443	463
R2	0.00956	0.00291
Within R2	7.84e-6	0.00016

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

ii) Difference-in-differences estimation results

The evolution of residual household waste quantities collected per capita (Figure 5) illustrates a gradual decline in both the treatment and control groups between 2005 and 2021. However, after 2011, intermunicipal entities that implemented source separation of biowaste exhibited a more pronounced reduction in residual waste compared to the control group. While this observation suggests a potential effect of biowaste source separation, graphical analysis alone is insufficient to establish causality. The results of the difference-in-differences estimation presented in Table 4 provide a more robust assessment of this effect. In this model, we observe a reduction of 10.81 kg per capita in the coefficient of interest (the ATT), but this result is not statistically significant.

Table 4 : Effect of source separation of biowaste on quantities of residual household waste collected

	MODEL
Dependent Variable	RHW (kg/capita)
ATT	-10.81 (7.398)
Fixed-Effects:	--------------
TREATMENT	Yes
YEAR	Yes
S.E.: Clustered	by: ID
Observations	480
R2	0.06027
Within R2	0.00074

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

To further evaluate this policy, we also assess its effects while accounting for the different variables presented in Table A.1 in Appendix. Specifically, we estimate interaction models for each of these variables to compare the policy effects across different economic and sociodemographic characteristics, as well as according to the waste pricing system.

iii) Results of the heterogeneity analysis of the effect of biowaste source separation on residual household waste collected per capita

This analysis investigates whether the effect of biowaste source separation on residual household waste (RHW) varies depending on the level of tourist accommodation, population density, income and pricing system within intermunicipal entities.

- Interaction model with the tourist accommodation variable

The results presented in Table 5 indicate that intermunicipal entities with a low number of tourist accommodations generally exhibit significantly lower quantities of residual household waste per capita compared to those with a high level of tourism (-43.20 kg/capita on average). This finding is consistent with previous studies (e.g., Caponi, 2022) showing that tourist influxes generate seasonal peaks in waste production, which are reflected in the quantities of waste collected. The triple interaction term (Treatment x Year x TOURIST-ACCOMMODATIONLow) is not statistically significant. This suggests that we cannot statistically differentiate the effect of introducing biowaste source separation policies between areas with low and high levels of tourism activity.

Table 5 : Effect of biowaste source separation on residual household waste by tourist accommodation

	MODEL_TOURIST_ACCOMODATION
Dependent Variable	RHW (kg/capita)
TOURIST-ACCOMMODATIONLow	-43.20* (20.40)
TREATMENT x YEAR	-8.866 (11.04)
TREATMENT x TOURIST-ACCOMMODATIONLow	-15.92 (26.47)
YEAR x TOURIST-ACCOMMODATION_Low	6.064 (9.196)
TREATMENT x YEAR x TOURIST-ACCOMMODATIONLow	-3.430 (14.43)
Fixed-Effects:	---------------
TREATMENT	Yes
YEAR	Yes
S.E.: Clustered	by: ID
Observations	480
R2	0.11844
Within R2	0.06260

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

- Interaction model with the density variable

The results presented in Table 6 show that intermunicipal entities with low population density generally generate significantly lower quantities of residual household waste per capita compared to those with higher density (-59.61 kg/capita on average). In densely populated areas, space for waste sorting, both inside and outside homes, is often limited or even non-existent. Consequently, source separation of waste by households is more challenging in these localities (Timlett & Williams, 2009). Interestingly, the triple interaction term (Treatment x Year x DENSITYLow) is statistically significant and negative (-33.05 kg/capita). This suggests that the introduction of biowaste source separation leads to a greater reduction in residual household waste in low-density areas compared to high-density ones. This finding implies that these solutions are more effective in less densely populated areas, likely due to the greater availability of space, as highlighted in the literature (e.g., Timlett & Williams, 2009). Such conditions facilitate access to composting solutions and encourage higher household participation in source separation efforts. This result may also be linked to the characteristics of populations in different intermunicipal entities: high-density areas tend to attract more transient populations who may be less familiar with local sorting guidelines. Timlett & Williams (2009) also showed that higher population mobility in urban areas poses a major obstacle to effective waste recycling.

Table 6 : Effect of biowaste source separation on residual household waste by density

	MODEL_DENSITY
Dependent Variable	RHW (kg/capita)
DENSITYLow	-59.61** (21.02)
TREATMENT x YEAR	4.395 (9.596)
TREATMENT x DENSITYLow	86.76** (29.40)
YEAR x DENSITYLow	9.173 (9.753)
TREATMENT x YEAR x DENSITYLow	-33.05* (16.18)
Fixed-Effects:	----------------
TREATMENT	Yes
YEAR	Yes
S.E.: Clustered	by: ID
Observations	478
R2	0.10251
Within R2	0.04545

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

- Interaction model with the income variable

The results presented in Table 7 indicate that intermunicipal entities with lower median income levels tend to have higher quantities of residual household waste per capita. This result may reflect differences in consumption patterns and waste-related behaviors across income groups (Romano *et al.*, 2019). However, given that this effect is statistically significant at the 10% level, it is difficult to draw strong conclusions about its magnitude. The triple interaction term (Treatment x Year x INCOMELow) is not statistically significant, indicating that we cannot draw firm conclusions about differences in the policy effect between income levels.

Table 7 : Effect of biowaste source separation on residual household waste by income

	MODEL_INCOME
Dependent Variable	RHW (kg/capita)
INCOMELow	36.30. (19.38)
TREATMENT x YEAR	-6.961 (7.857)
TREATMENT x INCOMELow	7.766 (28.14)
YEAR x INCOMELow	-2.598 (8.845)
TREATMENT x YEAR x INCOMELow	-12.60 (15.49)
Fixed-Effects:	--------------
TREATMENT	Yes
YEAR	Yes
S.E.: Clustered	by: ID
Observations	470
R2	0.08885
Within R2	0.03312

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

- Interaction model with the pricing variable

Table 8 presents the heterogeneity analysis by waste pricing system. The coefficient on PRICINGIcentive is negative and significant, indicating that intermunicipal entities using an incentive-based pricing system generally exhibit substantially lower levels of residual household waste (-77.27 kg/capita on average) compared to those applying a classic pricing system (the reference group). This result supports the idea that economic incentives encourage waste reduction, as shown in the literature (e.g., Allers & Hoeben, 2010; Gatier, 2016). However, none of the interaction terms involving the implementation of the biowaste source separation policy are statistically significant, suggesting that we cannot statistically differentiate its effect according to the pricing system.

Table 8 : Effect of biowaste source separation on residual household waste by pricing

	MODEL_PRICING
Dependent Variable	RHW (kg/capita)
PRICINGIncentive	-77.27** (27.63)
PRICINGMixed	11.56 (25.63)
TREATMENT x YEAR	-12.93 (9.148)
TREATMENT x PRICINGIncentive	-36.31 (34.28)
TREATMENT x PRICINGMixed	-15.38 (32.18)
YEAR x PRICINGIncentive	6.416 (15.53)
YEAR x PRICINGMixed	-10.39 (12.62)
TREATMENT x YEAR x PRICINGIncentive	5.372 (34.03)
TREATMENT x YEAR x PRICINGMixed	13.68 (16.12)
Fixed-Effects:	----------------
TREATMENT	Yes
YEAR	Yes
S.E.: Clustered	by: ID
Observations	364
R2	0.14021
Within R2	0.08007

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

In summary, although the heterogeneity analyses provide interesting insights, the global model indicates no significant average effect of implementing at least one biowaste source separation solution on the quantity of residual household waste collected per capita. These results may reflect the highly heterogeneous nature of the policy evaluated in this model, which combines different biowaste source separation solutions rather than representing a single, uniform measure. Therefore, in the next subsection, we specifically assess the effect of implementing separate biowaste collection on residual household waste quantities.

5.2. Specific effect of separate collection of biowaste on quantities of residual household waste collected per capita

As presented in Subsection 2.4.2 on descriptive statistics, to assess the specific impact of separate collection of biowaste on residual household waste quantities, we retained data from 53 intermunicipal entities that implemented this solution (treatment group) and 127 intermunicipal entities that did not implement any biowaste source separation solution (control group). In this model, we control for the variable "HOME_COMPOSTING" to isolate the specific effect of separate collection, since some intermunicipal entities (33 out of the 53 analyzed) implemented both separate collection and home composting. This variable takes the value 1 if an intermunicipal entity implements home composting, and 0 otherwise. As in the previous analysis, we first present tests of the parallel trends assumption before estimating the difference-in-differences model.

i) Verification of the parallel trends assumption

We graphically illustrate the evolution of residual household waste quantities collected per capita in the treatment and control groups to enable a visual comparison. Figure 6 shows that the two curves do not follow similar trends during the pre-treatment period. As the treatment group size is reduced to 53 in this model, this makes visual interpretation more challenging. Several observations are missing prior to the treatment period (2005-2011), which may affect the averages shown in the parallel trends graph.

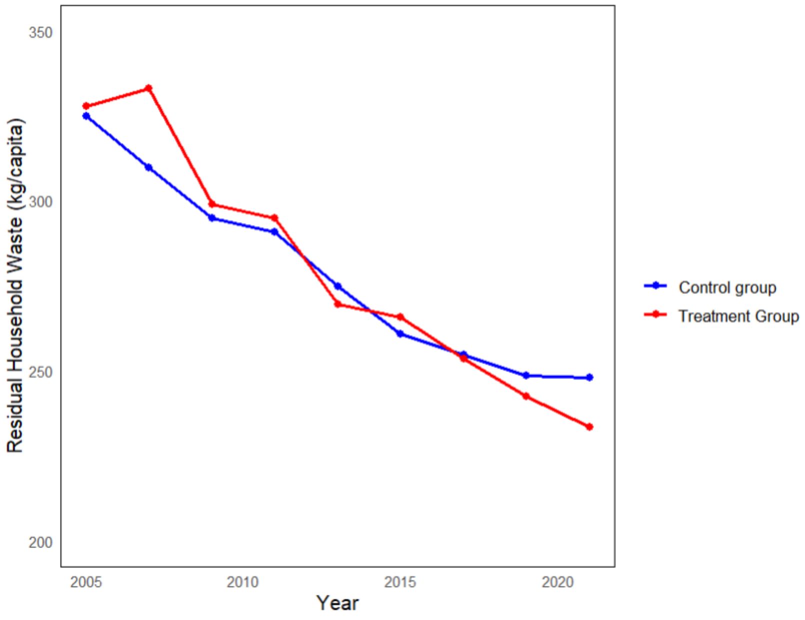

Figure 6 : Trends in residual household waste quantities for treatment and control groups

To ensure we have comparable groups, we performed a matching procedure by pairing each treated observation with its nearest neighbor in the control group, based on the variables presented in Table A.1 in Appendix. Based on the matched sample, we conducted a placebo test to verify whether the average treatment effect on the treated (ATT) was statistically significant during the period prior to policy implementation (2007-2011 and 2009-2011). As shown in Table 9, this coefficient is statistically non-significant in both periods, suggesting no significant difference in trends in residual household waste between the treatment and control groups before the policy was implemented. We can therefore use the difference-in-differences method to assess the effect of separate collection of biowaste using the matched sample.

Table 9 : Estimation results for the placebo test of parallel trends (2007-2011 and 2009-2011)

	2007-2011	2009-2011
Dependent Variable	RHW (kg/capita)	RHW (kg/capita)
ATT	-10.87 (18.21)	-22.12 (13.85)
HOME-COMPOSTING	32.25 (44.24)	33.14 (42.43)
Fixed-Effects:	--------------	--------------
TREATMENT-SEPARATE-COLLECTION	Yes	Yes
YEAR	Yes	Yes
S.E.: Clustered	by: ID	by: ID
Observations	145	147
R2	0.03230	0.01553
Within R2	0.01097	0.01481

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

ii) Difference-in-differences estimation results

The difference-in-differences analysis results presented in Table 10 indicate a significant reduction in residual household waste collected per capita in intermunicipal entities that implemented separate biowaste collection. On average, this reduction amounts to approximately 25 kg per capita. These findings confirm the effectiveness of biowaste source separation in reducing waste destined for landfill or incineration. They are similar to those obtained by Resse (2007) in the French municipality of Nieuil-l'Espoir, who showed that implementing separate biowaste collection diverted 27 kg per capita per year from the municipal waste stream managed by the local authority. Our findings are also consistent with ADEME (2022), which reported that intermunicipal entities with separate biowaste collection systems typically exhibit lower residual waste quantities than the national average.

Table 10 : Effect of separate collection of biowaste on quantities of residual household waste collected

	MODEL_SC
Dependent Variable	RHW (kg/capita)
ATT	-24.95* (11.49)
HOME-COMPOSTING	45.16 (34.79)
Fixed-Effects:	---------------
TREATMENT-SEPARATE-COLLECTION	Yes
YEAR	Yes
S.E.: Clustered	by: ID
Observations	156
R2	0.08494
Within R2	0.03009

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

6. Discussion and perspectives for local public waste management policies

By highlighting the impact of economic and sociodemographic factors on residual household waste quantities, our results confirm the importance of considering these characteristics when designing and implementing local public waste management policies. Our analyses reveal that in densely populated areas, source separation of biowaste is particularly challenging. This is largely due to limited space both within dwellings and in shared outdoor areas, as well as to the characteristics of the population in these areas, which tend to attract more transient residents who may be less familiar with local sorting guidelines (Timlett & Williams, 2009). Our findings also indicate that a high number of tourist accommodations significantly influences waste generation. Tourists are generally unfamiliar with local sorting practices, and the temporary influx of visitors leads to seasonal peaks in waste production (Caponi, 2022), increasing pressure on local waste collection systems. This is reflected in the amount of waste collected per capita, which is calculated based on permanent residents and therefore does not account for tourists. The implementation of incentive-based pricing schemes also has a strong negative effect on residual waste quantities, confirming the effectiveness of economic instruments in promoting waste reduction (Allers & Hoeben, 2010; Gatier, 2016). However, introducing such pricing systems can present several challenges. As noted by Allers & Hoeben (2010) and Tsai

& Sheu (2009), they may lead to illegal dumping. Therefore, their success largely depends on public acceptance.

These findings provide valuable insights for improving local public waste management policies. Our results confirm that the separate collection of biowaste significantly reduces residual household waste, with an estimated reduction of about 25 kg per capita. It is an effective complement or alternative to composting, especially in localities where composting is not feasible due to specific housing types, such as in urban areas. However, implementing the separate collection of biowaste requires a significant degree of logistical organization, raising both economic and environmental concerns. For example, more frequent collections may increase greenhouse gas emissions due to the rise in the number of vehicles on the road (ADEME, 2018). Although the cost of residual household waste management decreases as waste quantities drop, the overall cost of household waste management tends to be higher in municipalities that adopt separate collection of biowaste (ADEME, 2018). This is because the savings from reducing residual household waste do not fully compensate for the new costs involved in managing the biowaste stream. Therefore, to make this policy economically and environmentally sustainable, local authorities could adopt strategies to minimize both the additional costs and environmental impacts of managing this new waste stream. Local authorities can optimize overall waste management by reducing the frequency of residual household waste collection in favor of biowaste collection. In addition to these technical solutions, it is crucial to implement training and awareness campaigns to encourage biowaste sorting practices. Indeed, as emphasized by Ma & Hipel (2016), the lack of public awareness is widely acknowledged as one of the most critical informational barriers to the successful implementation of any municipal solid waste management system. Raising local residents' awareness about the agronomic quality of compost and other products derived from biowaste recovery could further enhance public participation in waste sorting programs. Additionally, local authorities in the tourism sector could benefit from multilingual information sheets that explain local waste sorting guidelines, helping visitors unfamiliar with local systems to properly dispose of their waste. Similarly, local authorities in high-density areas could strengthen public awareness campaigns to promote selective sorting and implement accessible waste separation solutions. They could also introduce incentive pricing to encourage users to modify their consumption behavior and improve waste sorting. Finally, it is essential to underscore that waste prevention remains the highest priority in the waste hierarchy established by the

European Union.[7] Therefore, local authorities could prioritize prevention measures in their policies.

Additional control variables could have been considered, particularly those related to the environmental orientation of intermunicipal entities. For instance, Cerqua *et al.* (2024) show that mayors supported by pro-environmentalist parties tend to achieve higher recycling rates, largely due to a stronger commitment to implementing local waste management policies. However, constructing such a variable is difficult in our case. Assigning a political orientation to some of the intermunicipal cooperation entities in our sample is challenging, as they are single-purpose structures (i.e., focused solely on waste management) with no independent fiscal authority. Furthermore, we were unable to include a variable capturing the level of residual waste fees at the intermunicipal level due to data limitations. If such data become available, it would be particularly relevant to incorporate it in heterogeneity analyses, to assess how the level of waste fees paid by households might influence the effectiveness of biowaste source separation policies. Finally, we did not isolate the specific effect of home composting, as detailed data on the actual population covered by this measure are lacking in the SINOE® database for most intermunicipal entities. Moreover, the HOME_COMPOSTING variable is binary and can take the value 'yes' even if only a few composters have been distributed, covering only a small portion of the population. As a result, it is difficult to assess the scale of home composting initiatives and to isolate their specific effect.

7. Conclusion

In this paper, we analyzed the impact of biowaste source separation policies on the quantities of residual household waste collected by French intermunicipal entities, using a difference-in-differences approach. To understand how economic, sociodemographic factors, and pricing systems might influence policy effectiveness, we examined the heterogeneity effects of these variables. We then isolated the specific impact of separate biowaste collection on residual household waste quantities.

Our results show no significant average effect of implementing at least one biowaste source separation solution (home composting or separate collection) on residual household waste quantities when considering all policy combinations. This finding may reflect the highly heterogeneous nature of the policies studied. However, our heterogeneity analyses provide

[7] Directive 2008/98/EC of the European Parliament and of the Council of November 19, 2008.

valuable insights. They show that intermunicipal entities with lower population density achieve a more pronounced reduction in residual household waste following the adoption of biowaste source separation policies, compared to those with very high population density. Our analyses also reveal that a high number of tourist accommodations are associated with higher residual waste quantities, highlighting specific challenges for local waste management in these areas. These findings emphasize the importance of adapting waste management policies to local economic and sociodemographic contexts. Intermunicipal entities with high population density or substantial tourist flows could benefit from targeted strategies that address these specific challenges. Furthermore, implementing incentive pricing systems could encourage households to modify their consumption habits, reduce food waste, and improve sorting practices. When focusing on the specific effect of separate collection of biowaste, our results show a significant reduction of approximately 25 kg per capita in residual household waste, confirming its effectiveness as a waste reduction strategy. Nevertheless, while promoting separate collection, local authorities should also consider strategies to limit the additional economic and environmental costs associated with managing this new waste stream. For example, optimizing service organization by reducing residual waste collection frequencies in favor of biowaste collection could be an effective approach.

This study provides an initial empirical analysis of the effects of biowaste source separation policies on residual household waste quantities across a large sample of French intermunicipal entities, taking into account their heterogeneity. A promising future direction would be to explore, by means of an econometric analysis, the factors that determine household-level participation in sorting and composting biowaste, in order to reinforce the effectiveness of public waste management policies.

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Appendix

Figure A.1 : Distribution of intermunicipal entities by the number of biowaste sorting solutions deployed

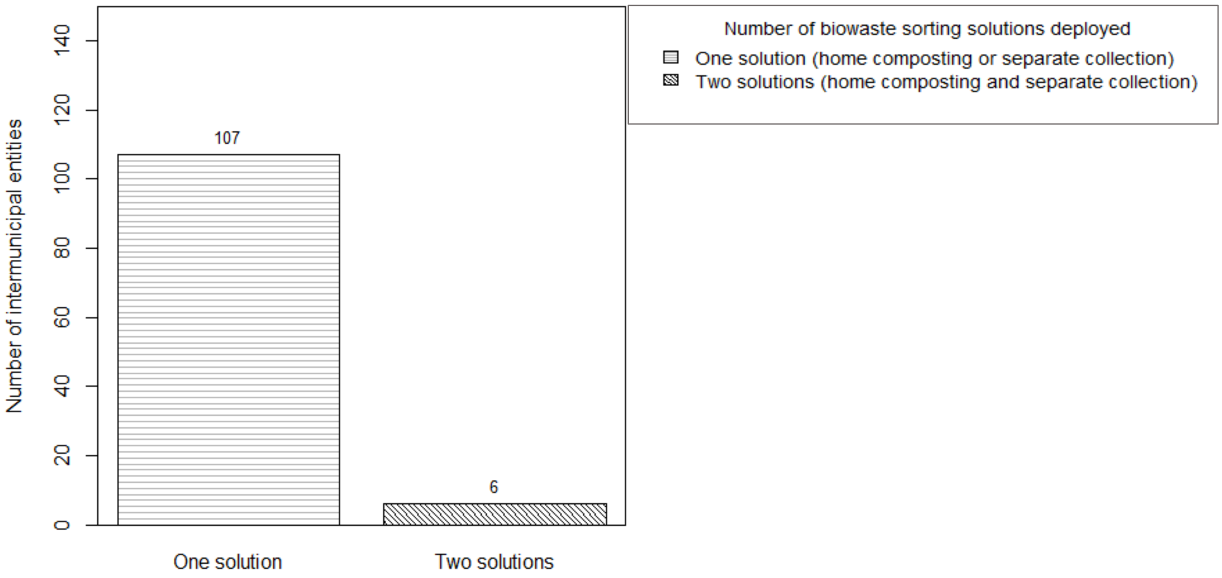

Table A.1 : Definitions of the variables used to perform the heterogeneity analyses

Variable	Description	Years	Source
TOURIST-ACCOMMODATION	Number of tourist accommodation establishments	2011	INSEE
DENSITY	Population density (inhabitants/km^2)	2009	INSEE
INCOME	Income (euros)	2011	INSEE
PRICING	Waste pricing system	2013	SINOE®