IMPACT OF A REGULATORY TARGET AND EXTERNAL FACTORS ON THE WASTE EFFICIENCY OF ITALIAN MUNICIPALITIES

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Impact of a Regulatory Target and External Factors on the Waste Efficiency of Italian Municipalities

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Abstract

Due to increasing consumption and urbanisation, urban waste management and recycling are a primary concern in Italy. Italian waste collection underwent significant reform with the introduction of a sorted collection target of 65% of total collected waste in legislative decree no. 152/2006. In this article, we analyse the effect of this regulatory target on the efficiency of waste collection in 275 Italian municipalities in the years 2016 to 2019. We estimate the coefficients of the cost efficiencies of the sorted and unsorted waste without assuming functional forms for the efficient frontier or the distribution of efficiency. Our findings suggest that municipalities that met the 65% sorted waste target demonstrated higher efficiency as costs increased, while those that failed to meet the target demonstrated higher inefficiency as costs increased. Strong effects emerged for population and urban economic development on the success of waste collection, while only marginal effects were observed for population density and city size. To improve the situation of municipalities that are not meeting the 65% target, we propose several policy measures, including ‘neighbourhood solidarity’.

Keywords: waste collection, Italy, directional FDH, smoothed approximations of nonparametric frontiers, waste economy, waste policy evaluation.

1. Introduction

In Italy and the European Union (EU), municipal waste management has long been a key issue, characterised by the need to find sustainable and cost-efficient ways to dispose of waste with minimal impact on the environment and public health. At the EU level, the Waste Directive 2008/98/EC regulates municipal waste management. In 2018, the EU adopted the Circular Economy Package, which aims at increasing waste recycling and reducing the amount of waste produced. The package includes a 65% recycling target for municipal waste by 2035, a 50% recycling target for plastic packaging by 2025 and the phasing out of landfill use. However, the EU continues to face significant challenges in managing municipal waste. Within this context, Italy has implemented significant structural reforms aimed at improving the nation's waste management.

In Italy, the municipal waste problem escalated in the 1990s and 2000s, due to the closure of several landfills and incinerators, resulting in a national waste crisis manifested in mountains of waste accumulating on city streets. To resolve this situation, reforms to municipal waste management began in 1997 with Law No. 94 on Separate Waste Collection, mandating the separation of organic and inorganic waste. In 2006, Legislative Decree 152/2006 Article 205 (Dl 152/2006-Ministero dell'Ambiente e della Tutela del Territorio e del Mare, 2006) introduced the obligation to achieve 65% sorted waste collection by 2012 (subsequently increased to 70% by Law No. 221 of December 28, 2015, anticipating the EU's 2018 regulations). To meet this goal, various actions and tools were implemented, including door-to-door collection, promotion of recycling culture, support for the circular economy and the imposition of penalties for violations.

According to the Legislative Decree 152/2006, if the minimum target for sorted collection is not achieved at the level of the "Ambiti Territoriali Ottimali" (ATO, geographical areas defined at a regional level, where the collection, treatment and disposal of urban waste are managed in an integrated manner), a 20% surcharge on the landfill tax is imposed, thereby distributing the burden among municipalities in the territory that have fallen short. Decision-makers thus face a trade-off, as they must decide to either reach the target by increasing collection costs or accept the 20% surcharge for landfilling. Italy must reduce or eliminate the overuse of landfills as a form of disposal (Cucchiella et al., 2012), which is the reason for the penalty.

Taken together, the reforms over the past 25 years have led to a significant increase in the proportion of municipal waste subject to sorted collection in Italy, from 9.5% in 1997 to 64% in 2022 (ISPRA, 2022). However, Italy continues to face challenges in meeting the target for sorted waste collection, particularly within certain regions of the country.

The statutory sorted waste target does not account for a fundamental issue that municipalities must address: the cost of waste collection and transport. The management of municipal solid waste typically constitutes a significant portion of the total expenditure of local governments (Sarra et al., 2017). The problem of efficiency in municipal waste management considering both costs and waste collected is often addressed in the literature. As stated by Simões and Marques (2012), that reviewed 107 studies, the most frequently employed method for assessing efficiency in this sector is the nonparametric methodologies. Most of the reviewed studies aimed at determining the relative efficiency in specific countries or regions (e.g., Benito-López et al., 2011; Gonzalez-Garcia et al., 2018 for Spain; De Jaeger et al., 2011 for Belgium; Yang & Zhang, 2011 for Taiwan; Huang et al., 2018 for China; Struk & Boďa, 2022 for the Czech Republic). Moreover, the imposition of a uniform threshold for all Italian cities does not consider the territorial, socio-economic and technical factors (in short external factors to the waste collection process) that may influence progress towards this target. The efficiency analysis literature on Italy is very rich. The literature analyzes this case both at the national level (Lombardi et al., 2021) and at the regional level (lo Storto, 2021 for Puglia region or Romano et al., 2020 for Tuscany region). To analyze municipalities, the literature on Italy employs both nonparametric and parametric methods, as well as a mix of two-stage methods to assess the overall effect of external factors on the efficiency of waste management processes (see Table 1). Among the methods used to assess the effect of external factors on efficiency, Tobit regression (or its variants) as the second step of efficiency analysis is the most common (Agovino et al., 2016; Romano et al, 2021; lo Storto, 2021). Hypothesis testing after the efficiency analysis is another proposed method (Romano & Molinos-Senante, 2021). Parametric methods that incorporate possible external factors (such as geographic ones) inside, such as Spatial Stochastic Frontier (Fusco & Allegrini, 2020) or Geographically weighted regression (Agovino & Musella, 2020) are also other used methods.

Table 1 Methods applied in the existing literature

Reference	**Method applied in the first stage**	**Method applied in the second stage**
Agovino et al., 2017	Multidimensional Scaling Analysis	Cluster analysis (hierarchical)
Agovino et al., 2023	Time Series Dea	
Guerrini et al., 2017	Order - M Conditional And Unconditional (Comparison)	Non parametric regression
lo Storto, 2024	Fuxy DEA	
Lombardi et al., 2021	Data envelopment analysis (DEA)	
Romano & Molinos-Senante, 2020	DEA	Hypothesis test (Mann-Whitney U and Kruskal-Wallis)
Romano et al., 2021	Order-M (Conditional)	Non parametric regression (Nadaraya-Watson estimator)

Romano et al., 2022	Propensity Score Matching	
Sarra et al., 2017	DEA (Scale Efficiency)	Tobit Regression
lo Storto, 2021	DEA	Tobit Regression
Agovino et al., 2018	DEA	Exploratory Spatial Data Analysis +Local Moran Transition Probability Matrix
D'Amato et al., 2015	Econometric Analysis (Max And Minimization Problem With Different Steps)	
Abrate et al., 2015	Stochastic Frontier Model	
Agovino & Musella, 2020	Geographically Weighted Regression	
Agovino et al., 2016	Transition Probability Matrix	generalised ordered probit model
Agovino et al., 2019	Quantile Regression	
Agovino et al., 2020	Panel Analysis	
Di Pillo et al., 2023	Panel Data Model	
Fusco & Allegrini, 2020	Spatial Stochastic Frontier	
Gaeta et al., 2017	Fractional Logit Model	
Greco et al., 2015	Ordinary Least Square Stepwise Regression	
Greco et al., 2018	Ordinary Least Square	
Passarini et al., 2011	Correlation Analysis	

Past literature points to several external factors that may influence the efficiency on waste management and collection. These main factors can be summarised as:

- ***morpho-demographic characteristics***, encompassing geographical characteristics such as altimetry (Agovino et al., 2023, Agovino et al., 2018; Di Foggia and Beccarello, 2020; Sarra et al., 2017), population served and population density (lo Storto, 2024; lo Storto, 2021; Agovino et & Musella, 2020; Agovino et al., 2019; Agovino et al., 2016; Fusco & Allegrini, 2020; Greco et al., 2015; Guerrini et al., 2017; Lombardi et al., 2021; Passarini et al., 2011; Romano & Molinos-Senante, 2020), geographical location (Agovino et al., 2018; Agovino et al., 2016; Greco et al., 2015; Abrate et al., 2015) and household characteristics (Guerrini et al., 2017; Sarra et al., 2017);

- ***socio-economic characteristics***, including economic factors such as per capita income and total income or value added (Agovino et al., 2023; Agovino et al., 2017; Gaeta et al., 2017; Sarra et al., 2017; Passarini et al., 2011), population seniority (Romano & Molinos-Senante, 2020), corruption, institution quality and criminal activities (Romano et al., 2022; Romano et al., 2021; Agovino et al., 2020; Agovino et al., 2018; Agovino et al., 2017; Agovino et al., 2016; Di Pillo et al., 2023; D'Amato et al., 2015; Abrate et al., 2015), population education (Agovino et al., 2019) and tourist and non-residence presence (Greco et al., 2018; Guerrini et al., 2017; Sarra et al., 2017);
- ***technical characteristics***, such as road length and city size (lo Storto, 2021; Sarra et al., 2017), collection method (Guerrini et al., 2017) and load capacity and vehicle usage (Guerrini et al., 2017; Greco et al., 2015).

The methods currently used in the literature suffer from some methodological problems. In particular, methods that combine nonparametric efficiency analysis with Tobit regression (Agovino et al., 2016; Romano et al, 2021; lo Storto, 2021) impose the so-called “separability” assumption. This restrictive hypothesis assumes that the external factors do not affect the efficient frontier but only the distance of the observations from the efficient frontier. Hypotheses tests, like the ones used by Romano & Molinos-Senante, suffer from statistical inconsistencies caused by the nature of non-parametric methods like Data envelopment analysis or Free Disposal Hull (see Kneip et al., 2016 for more details).

All existing nonparametric methods summarized in Table 1 do not allow us to obtain point coefficients describing the effect of external factors, unlike our analysis. Parametric models, on the other hand, suffer from several problems: the underlying assumptions of error distribution, the assumed functional form and, the non availability of individual impacts (coefficients) (Greco et al., 2015; 2018). Consequently, our contribution, in addition to providing an extended analysis of the Italian case, is to use for the first time a nonparametric method of efficiency that allows us to evaluate the effect of external factors on efficiency without restrictive assumptions and with the estimation of a coefficient for each municipality analyzed.

The present study aimed to estimate the influence of the regulatory target and external factors on the efficiency of waste collection in Italian municipalities. We employed a recently introduced methodology proposed by Daraio and Simar (2022) to estimate the variation (i.e., sensitivity) of the efficient frontier with respect to inputs, outputs and external factors, without assuming functional forms for the efficient frontier or the efficiency distribution. This was achieved by applying smoothed approximations of nonparametric frontier models. This approach extends the nonparametric conditional approach (see e.g. Daraio and Simar, 2007; Haelermans and De Witte, 2012) allowing the possibility to estimate local coefficients on the impact of the external factors Z.

The study analysed data from 275 Italian municipalities for the years 2016 to 2019, distinguishing between municipalities that achieved the 65% sorted waste target and those that did not. The goal was to understand whether – and to what extent – efficiency differed between these groups and which external factors influenced efficiency in each case.

A work close to ours is the one by Agovino et al. (2016), but they do not analyse the effect of the dl 152/2006 on efficiency. To the best of our knowledge, the relationship between efficiency and the achievement of the dl. 152/2006 target has not yet been explored. In addition, the literature presents conflicting perspectives on the presence of economies of scale (whereby the efficiency of the collection increases in line with population growth) and economies of density (whereby the efficiency of collection decreases in line with population growth), the effect of municipality size and the influence of economic development factors in the Italian context. It is therefore useful and interesting to provide new empirical evidence on the presence of these effects.

The article is organised as follows: Section 2 explains the materials and methods used, Section 3 presents the main results and discussion and Section 4 presents the conclusions. Appendices A, B and C report additional results.

2. Material and methods

2.1. Methodology

Starting with the seminal paper by Farrell (1957), the literature outlines two main approaches for estimating the efficiency of a set of units, based on the inputs (or resources) that are used to produce the outputs (or outcomes): parametric and nonparametric. The *nonparametric approach* is more general and flexible, as it does not specify any functional form for the efficient frontier. It is based on envelopment estimators such as Data Envelopment Analysis (DEA) which assumes convexity and free disposability (i.e. the possibility of destroying or sparing goods/resources at no cost) of the production set based on inputs and outputs; and Free Disposal Hull (FDH), which assumes only free disposability. The *parametric approach*, instead, requires the specification of functional forms for the efficient frontier and the distribution of inefficiency. However, it allows for an estimation of the coefficients of economic interest, i.e., sensitivity parameters that measure variation in efficiency with respect to inputs and external factors; for an overview, see e.g. Fried et al. (2008).

The present study aims at understanding how the investigated municipalities achieve their efficiency and how external factors influence this efficiency. To achieve this, we employed a methodology that was recently proposed by Daraio and Simar (2022) (hereafter DS). The method combines the advantages of both nonparametric and parametric approaches, allowing for the estimation of derivatives, marginal rates of substitutions and other coefficients of economic interest. Importantly, it offers parametric approximation coefficients for the nonparametric frontier. In the present study, we applied this method for the first time in the waste sector, enabling the flexible approximation of nonparametric frontiers to estimate robust coefficients of economic interest without presuming functional specifications for the efficient frontier and the distribution of inefficiency. Our methodology consisted of estimating a nonparametric directional FDH efficient frontier (Daraio et al., 2020; Deprins et al., 1984) and, subsequently, employing a local linear regression to smooth this frontier and derive the coefficients of interest (e.g., derivatives, marginal rates of substitutions).

Formally, we defined the set of technically feasible combinations of inputs (*X*) and outputs (*Y*) as $\Psi = \{(x, y) \in R^{(p+q)} | x \; can \; produce \; y\}$. The efficient boundary (frontier) of this set was the set of efficient combinations of inputs and outputs, such that:

$$\Psi^{\partial} = \{(x, y) \in R^{(p+q)} | (\gamma^{(-1)}x, \gamma y) \notin \Psi, \forall \gamma > 1\}. \quad (1)$$

Various methods may be employed to measure the efficiency of a unit (*x, y*) as the distance from this boundary. In the present study, we applied flexible directional distance measures (see Chambers et al., 1998), defined as $\delta(x, y) = \sup\{\delta | (x - \delta d_x, y + \delta d_y) \in \Psi\}$, where $d_x \in R_+^p$ and $d_y = R_+^q$. Therefore, distance was measured along a path determined by a direction vector $d' = (-d'x, d'y)$ in an additive way, whereby if *(x, y*) lays on the efficient frontier $\delta(x, y) = 0$.

The main steps of the method proposed by DS can be summarised as follows.

[1] From the sample of observations, $X_n = (X_i, Y_i)_{i=1}^n$, compute the nonparametric estimators $\hat{\delta}_i$, I = 1. . .*n* of the directional distances (in our case the FDH estimator; see Daraio et al., 2020, for the Matlab code).

[2] Transform the data using the rotation $\begin{bmatrix} V_i \\ U_i \end{bmatrix}$=$R_d\begin{bmatrix} X_i \\ Y_i \end{bmatrix}$, where R_d is a fixed, non-random rotation matrix, as required for the multivariate case (see DS for details) where V_i and U_i are the new coordinates of the points in the rotated space. V_i replaces X_i and U_i replaces Y_i in the new space.

[3] Project the observed U_i on the nonparametric frontier, providing $\widehat{U}_i^{\partial} = U_i + ||d||\hat{\delta}_i$.

[4] Use the sample $\left(V_i, \widehat{U}_i^{\partial}\right)^n_{i=1}$ to find the best nonparametric approximation of the frontier function φ(v) available for all values of v through local linear approximation. This allows for an estimation of the derivatives and other coefficients of interest at each point, in particular for each observation V_i, i=1…n.): Using $\widehat{U}^{\partial}$ as the appropriate estimator of U^{∂}, estimate the (local) values of $\theta(v) = [\alpha(v)\ \beta'(v)]'$ from the sample $\left\{V_i, \widehat{U}_i^{\partial}\right\}^n_{i=1}$, using the following weighted least squares problem:

$$\left(\hat{\alpha}_n(v), \hat{\beta}_n(v)\right) = argmin_{\alpha,\beta}\left[\sum_{i=1}^{n}\{\widehat{U}_i^{\partial} - \left(\alpha + \beta'(V_i - v)\right)\}^2 K_h(V_i - v)\right] \qquad (2)$$

where $\hat{\alpha}_n(v)$ is the estimated smoothed value of φ(v), $\hat{\beta}_n(v)$ provides an estimate of the first derivatives $\nabla\varphi(v)$, $K_h(V_i - v)$ is a kernel weighting function localizing the value V_i in a neighbourhood of v, and h is a vector of bandwidths determined by least-squares cross validation (see, e.g., Li & Racine, 2007 for details).

The derivatives and coefficients of interest, expressed in terms of v, can be transformed back to the original unit (x,y) by employing the DS method (see DS for details). This methodology allows the approximations of nonparametric frontier coefficients, which represent the coefficients of quantities of interest, to be smoothed without making any assumptions about the functional specifications of the efficient frontier and the distribution of efficiency. It is possible to initially estimate the partial derivatives of efficiency with respect to the inputs (X) and outputs (Y) and to subsequently estimate the partial derivatives of inputs and outputs with respect to external factors. Of note, this methodology does not return a single average coefficient of the derivatives for the entire sample. Instead, it estimates derivatives and calculates local estimates for each unit. Therefore, the evaluation of various derivatives is achieved by visualising their dispersion/distribution, enabling a comprehensive understanding of the overall effects of both the derivative, itself, and individual cases.

2.2. Data

The present study focused on urban waste collection in 275 Italian municipalities from 2016 to 2019. This time span was chosen to ensure that all data were collected consistently and in line with the methodology outlined in the Decree of the Ministry of the Environment and Protection of the Land and Sea of 26 May 2016. From 2020 onward, changes were made to data collection methods that do not allow comparability with previous years (2016-2019), so data from 2020 onward were not considered. Data were collected from the ‘Istituto Superiore per la Protezione e la Ricerca Ambientale’ (ISPRA, 2022) report on municipal waste. The data pertained only to municipalities with at least 10,000 inhabitants, for which information was available for the entire analysis period. The data encompassed the total cost of waste collection and transport, considering only costs related to waste collection, excluding costs of disposal and other activities but including the cost of transportation. ISPRA total cost of waste data are per inhabitant served. The data considered were therefore the waste collection and transport costs per inhabitant multiplied by the number of inhabitants, the tonnes of separated waste and the tonnes of mixed waste in each municipality. Following Guerrini et al. (2017), we aggregated the collection cost items into a single cost value of efficiency, since prices were uniform among the observed units.

The choice of Italian municipalities as units of analysis was mainly driven by the fact that municipalities are responsible for the collection of municipal waste, while other aspects of waste management fall under the purview of different entities. Data were also collected for some of the external factors analyzed in previous literature: population served, territorial size (km^2) and taxable income (considering the fiscal year preceding the year of analysis, e.g., for the year 2019, we referred to 2018 tax income).

In addition, municipalities were classified based on whether they achieved the target set by dl 152/2006 (i.e., 65% separated municipal waste). This choice causes the number of observations in the two groups to vary accordingly over the years, and depending on whether or not 65% of separate collection is achieved, they may be part of one group or the other in one year. The regulatory target is appropriately modelled in our analysis by considering whether or not a municipality belongs to a specific group (target vs non-target) as a discrete external factor. The dataset covered approximately 35% of the entire Italian population. Compared to previous studies such as the one proposed by Lombardi et al. (2021), our study covers approximately 10% more of the Italian population. The municipalities considered are 140 in Northern Italy, 49 in Central Italy and 86 in the South. 178 cities are Coastal and 97 are Non-Coastal. More information on the number of cities by degree of urbanisation and littoral location can be found in Table A.4 in Appendix A.

A primary concern for policymakers is the balance between costs and the attainment of targets. Thus, to assess municipalities' efficiency in balancing collection and transport costs and sorted waste, we employed a model considering the total cost of waste collection and transport as the input (X), tonnes of unsorted waste as a bad output (BY, treated as an input in the frontier estimation) and tonnes of sorted waste as a good output (Y). The use of BY as an input in frontier estimation has an implication in terms of output disposability. When the amount of unsorted waste (i.e., BY) is reduced, the amount of sorted waste (Y) increases. This is a natural result since better sorting reduces unsorted waste. However, if the amount of sorted waste exceeds a certain threshold, collection costs might increase because sorted waste collection might require more effort from the municipality. However, in our analysis, we consider the joint use of X (total cost of waste collection and transport) and BY in the frontier estimation and this takes into account the possible increase in collection cost and allows us to evaluate and identify municipalities that, although they have a high Y (and thus a low BY), also manage to have a low X at the same time. To enhance the calculations, all variables were scaled according to their empirical standard deviation.

Figure 1 presents a descriptive illustration of X, Y and BY, with a bar plot showing the mean and standard error confidence interval of each factor.

Figure 2 presents a descriptive illustration of the environmental variables analysed, including population, size, population density and total income, with a bar plot showing the mean and standard error confidence interval of each factor. In both Figure 1 and Figure 2, data from all four years (i.e., 2016–2019) are presented. Red bars represent municipalities that did not achieve the regulatory target of 65% sorted waste, while blue bars represent municipalities that met this regulatory target. For more details on the descriptive statistics of both X, Y, BY and the environmental variables see Tables A1, A2 and A3 in Appendix A.

Over the years, the values remained largely consistent, except for an increase in X (total cost of waste collection and transport) among non-target (red) municipalities. This observation can be attributed to differences in population between the groups (as shown in Figure 2), as non-target municipalities tended to be more populous and larger in size, and to have higher total income compared to target municipalities. No significant variation in population density was evident. We used the directional vector d=*median(x,y)*=[(-0.1173, -0.0982); (0.1995)]. The directional vector selected for our analysis has median components, which were chosen because the median is neutral and does not favour any DMUs in advance. Additionally, the median direction is less affected by extreme values than the mean direction as discussed by Fukuyama and Weber (2017). This is particularly useful when comparing heterogeneous DMUs, as is the case in our study.

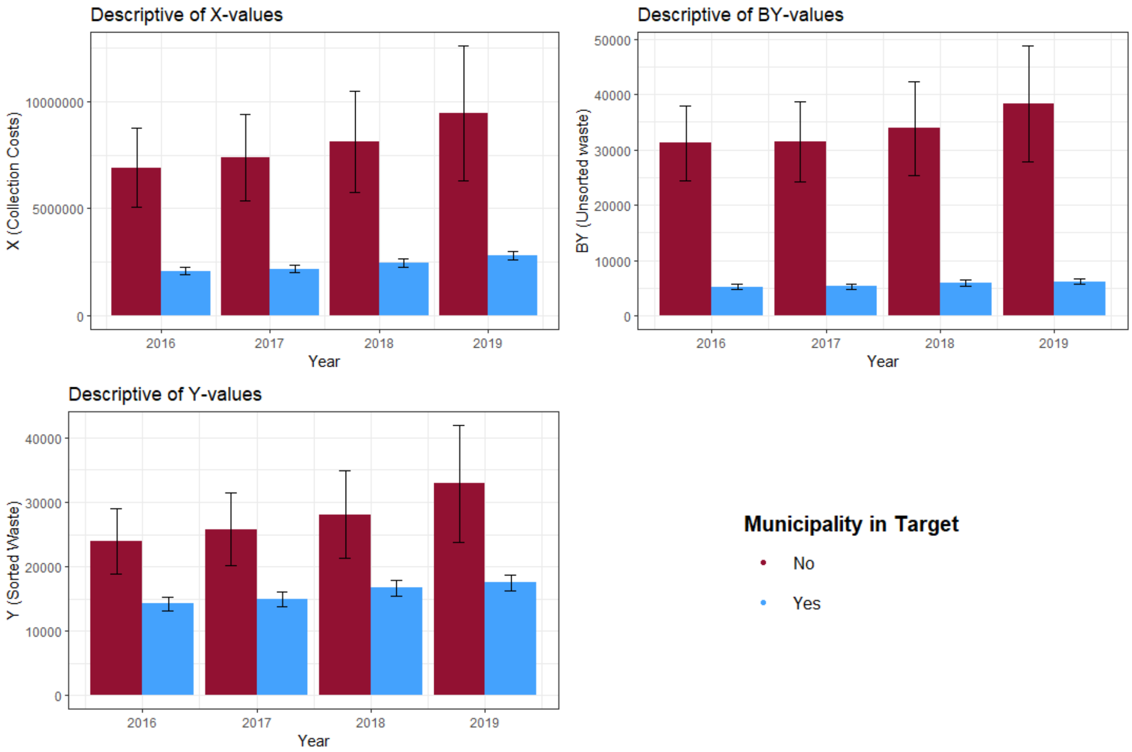

Fig 1 Bar plots illustrating the means and standard error confidence intervals of X (collection cost), BY (unsorted waste) and Y (sorted waste). Colors indicate whether or not municipalities met the regulatory target of 65% sorted waste. Red bars represent municipalities that did not meet the regulatory target, while blue bars represent municipalities that met the target.

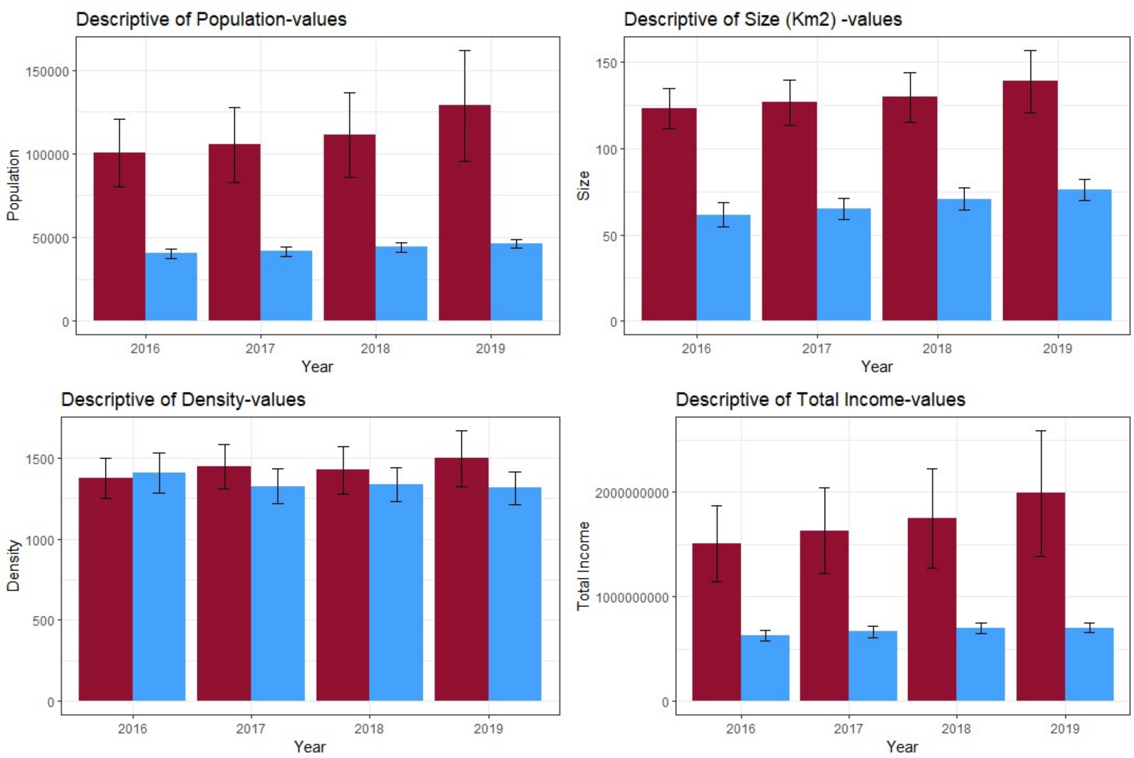

Fig 2 Bar plots showing the means and standard error confidence intervals of the external factors: population, size, population density and total income. Colors represent whether or not the municipality met the regulatory target of 65% sorted waste. Red bars represent municipalities that did not meet the regulatory target, while blue bars represent municipalities that met the regulatory target.

3. Results and discussion

In Figures 3–7, the red points and lines correspond to municipalities that did not achieve the 65% target for a specific year (henceforth referred to as *non-target municipalities*), while the blue points and lines represent municipalities that met the 65% target (henceforth referred to as *target municipalities*).

For our initial analysis, we estimated for each municipality the derivative of efficiency with respect to cost (X, Figure 3, panel a), unsorted waste (BY, Figure

3, panel b) and sorted waste (Y, Figure 3, panel c). The local linear regression estimation identified Rome, Brescia, and Reggio Emilia as outliers. To save space we report only the results for 2019 here, while full results for all years are reported in Figures B1, B2 and B3 in Appendix B and look very similar to those of 2019.

In Figure 3, black dotted lines indicate zero, representing unit efficiency. The proximity of points to the dotted line indicates proximity to the efficient frontier, while efficiency scores above zero imply inefficiency. A positive coefficient (i.e., above zero) implies a negative effect on efficiency, as increased X leads to increased inefficiency. Conversely, a negative coefficient (i.e., below zero) implies a positive effect on efficiency, as increased X leads to decreased inefficiency, bringing the unit closer to the efficient frontier. In the present analysis, the relationship between efficiency and cost was found to differ between the two groups. Non-target municipalities (red in Figure 3a) exhibited increasing inefficiency as X rose, moving further from the zero (i.e., optimal) value on the frontier. In contrast, target municipalities (blue in Figure 3a) showed a constant (and almost decreasing) pattern of inefficiency as costs rose.

Figure 3b reveals that an increase in BY was associated with greater efficiency among both non-target and target municipalities up to a certain threshold, after which it hampered efficiency for a small number of municipalities. Figure 3c shows that sorted waste did not strongly influence efficiency, which remained relatively constant for all levels of Y.

These first results suggest that the two groups differed primarily in terms of cost efficiency. Target municipalities (blue in Figure 3a) appeared to benefit from increased X, while non-target municipalities (red in Figure 3a) aimed at minimising X to achieve efficiency.

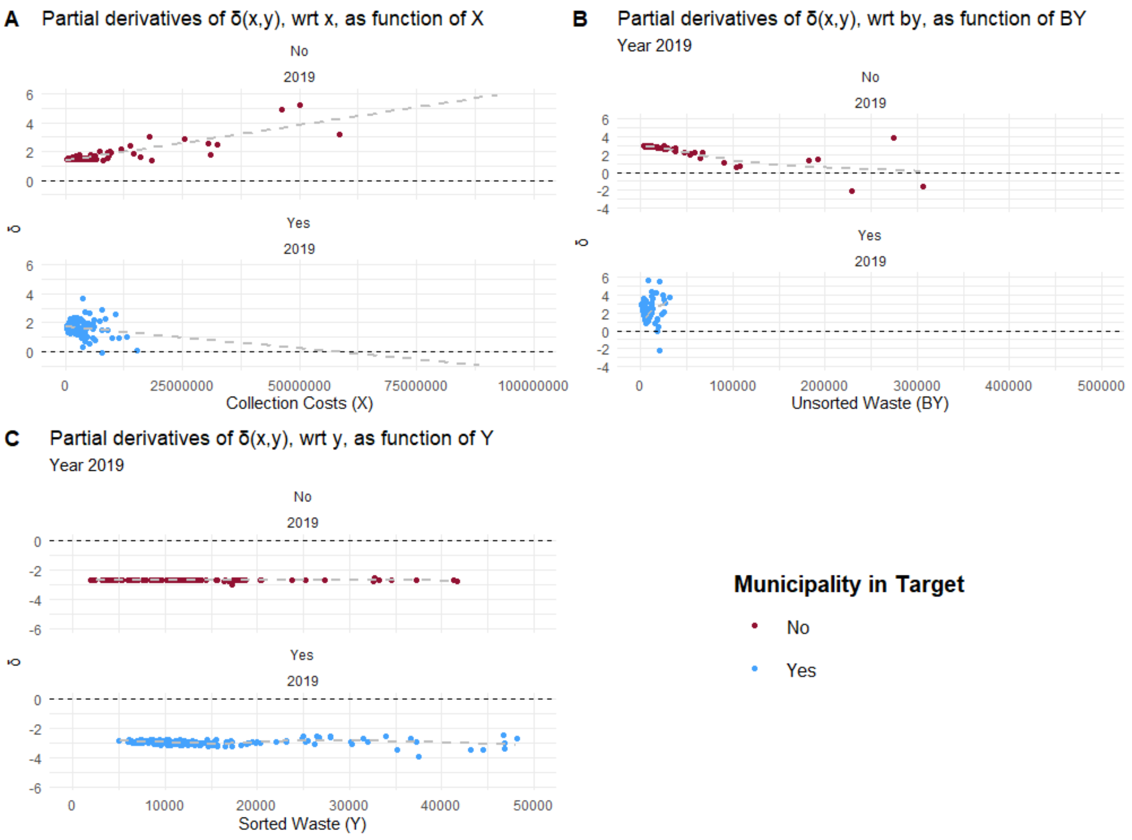

Fig 3 Derivatives of efficiency (one for each municipality) with respect to X (cost, panel a), BY (bad output, panel b) and Y (sorted waste, panel c). Each point represents a municipality. Red points represent non-target municipalities and blue points represent target municipalities. Results for 2019. A loess curve estimated on the points is reported to help the reader view the pattern explained in the main text.

Subsequently, we considered some external factors (Z) that might have affected municipal efficiency: population, size, density and economic development. To analyse the effect of each factor, we estimated conditional efficient frontiers, considering one external factor at a time and calculating the partial derivatives of the input (or output or bad output) with respect to each Z variable at frontier points. To present the overall effect of each of these external factors, we present here the medians and interquartile ranges of the derivatives for the target and non-target municipalities.

As a first analysis of the external factors, we estimated the effects of population (Z) on the input (X) and outputs (BY and Y) to determine whether any economy of scale existed. Thus, we estimated the effect of population (Z) on the cost of collection and transport (input X), BY and Y at frontier points, which means on the efficient frontier of the production process (see Figure 4). The partial derivatives of X with respect to Z summarized in Figure 4 (panel a) are all negative meaning that an increase in population implies a reduction of costs of collection and transport. In addition, municipalities that reached the target (blue line) show a higher reduction of costs than those not in target (Figure 4 panel a). This kind of investigation of economies of scale in efficiency analysis, estimating the impact of Z on the efficient frontier of the production process, has been described at length in Daraio and Simar (2007). A similar trend was observed for BY (Figure

4, panel b). However, there was a direct effect of population (Z) on tonnes of sorted waste (Y) (Figure 4, panel c), with an increase in the former (Z) resulting in an increase in the latter (Y). In all cases, the effects were more prominent in target municipalities (blue points and lines in Figure 4), even though these municipalities tended to have smaller populations relative to non-target municipalities. The results therefore demonstrate an influence of population on costs and quantities of waste collected, highlighting economies of scale. These results are in line with previous studies at regional level (Gaeta et al., 2017; Romano and Molinos-Senante, 2020) and international level (Simões and Marques, 2012).

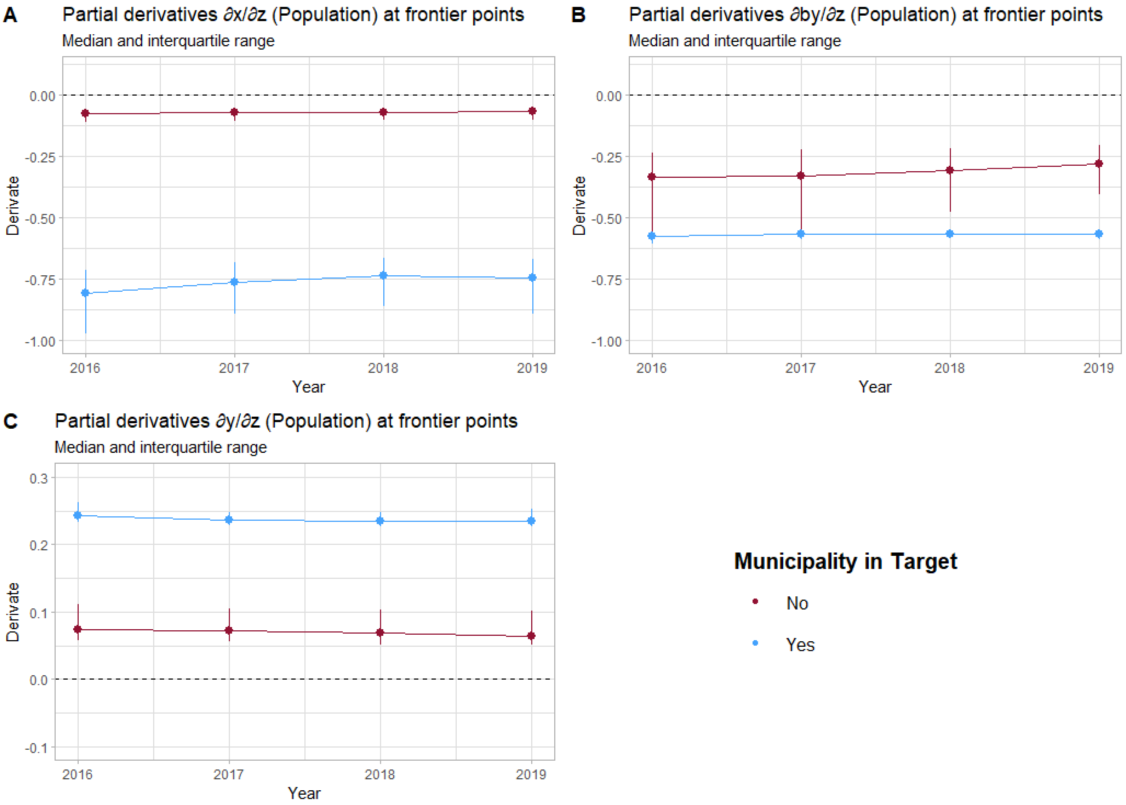

Fig 4 Partial derivatives of the inputs and output at frontier points. Panel a presents the derivatives of X with respect to population (Z). Panel b presents the derivatives of BY with respect to population (Z). Panel c presents the derivatives of Y with respect to population (Z). Points represent the medians of derivatives, and vertical lines represent the dispersions between the first and third quartiles. Red lines and points represent non-target municipalities, while blue lines and points represent target municipalities.

The second factor analysed was municipality size (km^2). Figure 5 displays the results of this analysis. To a limited extent, target municipalities (blue points and lines in Figure 5, panel a) exhibited a decrease in costs (X) as municipality size (Z) increased, with values consistently below 0.1. Rome and Brescia were excluded from the analysis because are outliers. Figure 5, panel b shows a decrease in unsorted waste (BY) with increasing size (Z), while Figure 5, panel c illustrates an increase in sorted waste (Y) with increasing size (Z). Of note, there were almost no discernible effects of size on non-target municipalities (red points and lines in Figure 5). Thus, we can conclude that municipality size had no significant impact on X or the quantity of waste collected. Previous studies have used different methods to examine the relationship between city size and recycling rate. Nevertheless, our findings align with the cumulative evidence from previous research. For instance, Agovino et al. (2016) discovered an inverse correlation between city size and recycling rate. Similarly, Sarra et al. (2017) used Tobit regression to show that area impacts efficiency, while lo Storto (2021) confirmed that size does not influence efficiency.

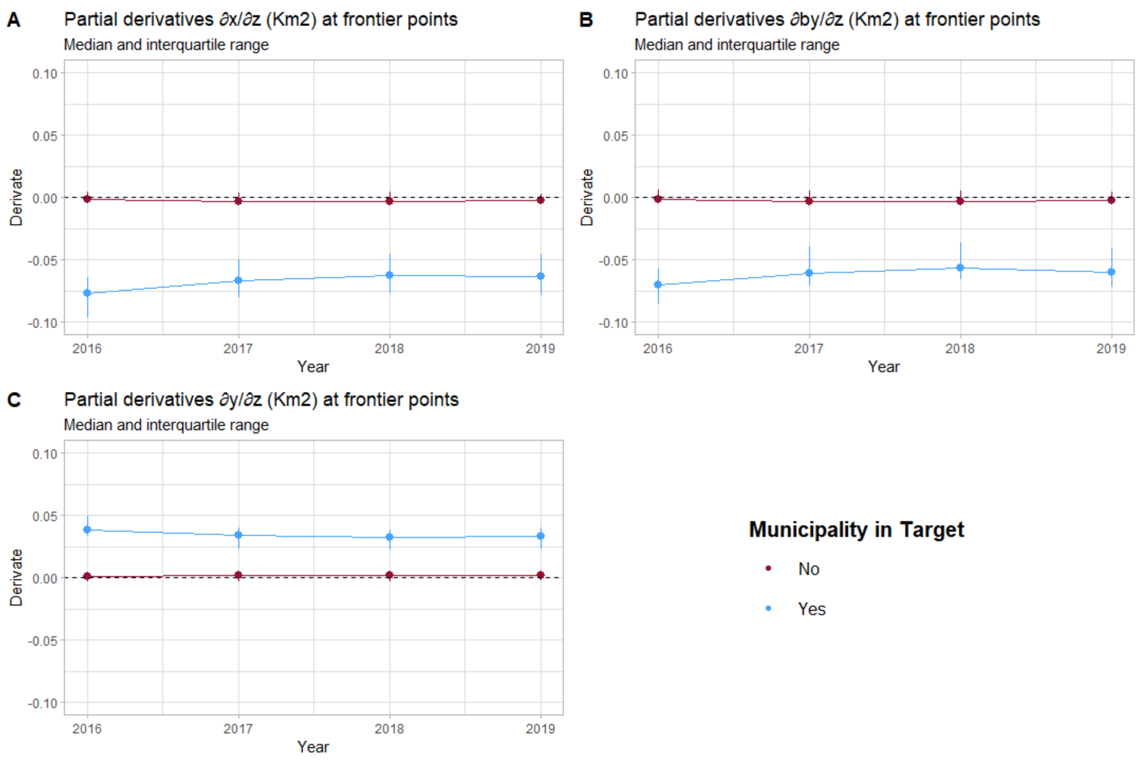

Fig 5 Partial derivatives of the inputs and output at frontier points. Panel a presents the derivatives of X with respect to size (Z). Panel b presents the derivatives of BY with respect to size (Z). Panel c presents the derivatives of Y with respect to size (Z). Points represent the medians of derivatives, and vertical lines represent the dispersions between the first and third quartiles. Red lines and points show non-target municipalities, while blue lines and points represent target municipalities.

Subsequently, we analysed the population density of each municipality to assess whether there was a combined effect of population and size on inputs (X) and outputs (BY and Y). Rome, Parma, Reggio Emilia, and Brescia were excluded from the analysis as they are outliers. The results (Figure 6, panel a) showed an inverse effect of density on X for target municipalities (blue points and lines in Figure 6, panel a), with increased density leading to higher costs. An almost-zero effect on non-target municipalities (red points and lines in Figure 6, panel a) was also observed, with a median interquartile range of nearly 0.2. The same trend applied to BY (Figure 6, panel b): for target municipalities, as density increased, the amount of BY rose. For non-target municipalities, almost no effects were discernible (red points and lines in Figure 6, panel b). Regarding Y (Figure 6, panel c), the values of the partial derivatives were negative for both target and non-target municipalities. Therefore, as density increased, the amount of Y decreased. Although some studies find evidence of density economies in the Italian context, the picture is far from being clear. Lombardi et al. (2021) found a partial effect of density on efficiency in 78 large Italian cities. Romano et al. (2020) and Romano and Molinos-Senante (2020) found evidence of economies of density in Tuscan municipalities, while Passarini et al. (2011) found a negative effect of population density on efficiency in 341 municipalities in Emilia-Romagna. Our study, however, takes a more comprehensive approach, analyzing all Italian municipalities with at least 10,000 residents from all regions of Italy, using a more general approach and considering regulatory targets for the first time. Our results demonstrate that density has almost no effect on efficiency in waste collection. Despite varied results for different regions and methods in previous studies, our results confirm that, at the national level, the effect of density is not well clear.

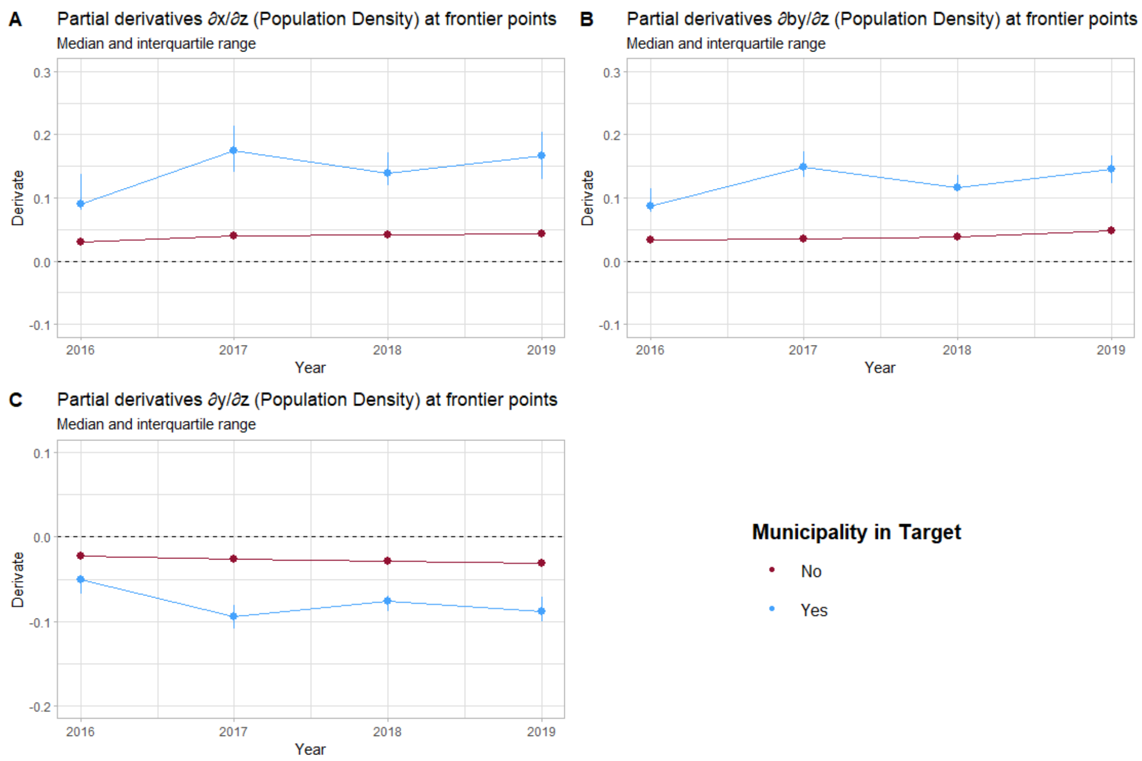

Fig 6 Partial derivatives of the inputs and output at frontier points. Panel a presents the derivatives of X with respect to population density. Panel b presents the derivatives of BY with respect to population density. Panel c presents the derivatives of Y with respect to population density. Points represent the medians of derivatives, and vertical lines represent the dispersions between the first and third quartiles. Red lines and points show non-target municipalities, while blue lines and points refer to target municipalities.

Finally, we evaluated the effect of municipalities' economic development, using total income as a proxy. The results are presented in Figure 7. Negative values for the medians and interquartile ranges of X (Figure 7, panel a) and BY (Figure 7, panel b) suggest that increased economic development had an inverse effect on both factors. Thus, as municipalities' economic development increased, their costs of collection and transport and tonnes of unsorted waste decreased. Although the results were consistent for both target and non-target municipalities, the effect of economic development on the volume of unsorted waste was more pronounced for non-target municipalities (red dots and lines in Figure 7, panel b). At the same time, we observed positive medians and interquartile ranges for the sorted waste (Y) partial derivatives (Figure 7, panel c), denoting a positive effect of economic development on this factor: as municipalities' economic development increased, their tonnes of sorted waste also increased. These results indicate that economic development has a decisive impact on sorted waste collection and transport and the costs incurred from this activity. We obtained similar results for the combined effect of economic development and population using income per capita as the Z variable, but we omit these results to save space. Previous literature had mixed results, as most of the work focused on the impact of income considering only certain variables such as recycling rates. Also, the literature concentrates attention only on specific Italian regions and not at the national level. For instance, Passarini et al. (2011) found no significant correlation between income per capita and waste generation for the 341 municipalities of Emilia Romagna. Sarra et al. (2017), on the other hand, showed that higher per capita income was associated with higher levels of separate collection while Gaeta et al. (2017), using a fractional logit model, demonstrated that income in the Lombardy region had a positive correlation with recycling rates. Our work, therefore, not only generalizes the analysis by not focusing only on a single variable or ratio, but it also generalizes the impact of income (both per capita and total) on the efficiency of waste management at a national level.

Fig 7 Partial derivatives of the inputs and output at frontier points. Panel a presents the derivatives of X with respect to total income (a proxy for economic development). Panel b presents the derivatives of BY with respect to total income. Panel c presents the derivatives Y with respect to total income. Points represent the medians of derivatives, and vertical lines represent the dispersions between the first and third quartiles. Red lines and points show non-target municipalities and blue lines and points represent target municipalities.

4. Conclusions

In the present study, we analysed the efficiency of municipal waste collection in Italy in the years 2016 to 2019, considering municipalities that reached the regulatory target of 65% sorted waste and those that did not. We estimated the coefficients of the cost efficiencies of sorted and unsorted waste without assuming any functional forms for the efficient frontier and the distribution of efficiency, by applying smoothed approximations of nonparametric frontier models (Daraio & Simar, 2022). Our analysis further assessed the impact of population, size, population density and total income on municipalities' efficiency. The findings indicate that Italian municipalities that did not reach the 65% separate waste target experienced a decrease in efficiency as collection and transport costs increased. In contrast, municipalities that met the target demonstrated higher efficiency as costs increased (Figure 3). Contrary to previous research, we found that population density and size had only minimal effects on costs: as municipality size increased, collection and transport costs decreased; and as density increased, costs increased. Additionally, we observed a strong effect of economic development (using the total income as a proxy of this factor) and population, consistent with previous research.

Our results suggest that policymakers should exercise caution when setting targets and penalties that may impose a burden on municipalities in less developed areas, as this may risk triggering a vicious spiral: the lower the level of economic development in a municipality, the fewer collection and transport costs it can sustain, thereby limiting the amount of sorted waste it can collect.

Moreover, the target currently imposed does not differ among cities of different sizes. As we see from the results in Figure 4, population influences the efficiency in the process. To explore this further, we report a descriptive of X, BY and Y in the tables in Appendix C dividing between large cities (cities with more than 200'000 population) and the others. From these tables we can see that large cities struggle to meet the targets, producing more waste (of both types) and incurring higher costs. This may indicate perhaps it is easier for small and medium-sized municipalities to reach the target, and policy implementation should be targeted differently depending on the type of municipality. In addition, target municipalities seem to be more similar than non-target municipalities, and this should be taken into consideration by the regulator who could also apply differentiated targets based on the population of the municipality.

The imposition of a waste disposal penalty in municipalities unable to meet the target for sorted waste collection would only exacerbate this situation. As an alternative, we would recommend that policymakers incentivise cooperation between less economically developed and more economically developed municipalities through resource sharing and joint investment in collection activities as suggested by literature (Bel and Mur, 2009; Bel et al., 2014; Pérez-López et al., 2016; Soukopová et al., 2016).

For instance, municipalities that have already met the target may be encouraged to expand their collection activities to neighbouring non-target municipalities within the same ATO, to reduce costs while simultaneously helping the other municipalities reach the target. Furthermore, “neighbourly solidarity” should be encouraged between less populated municipalities and more populated municipalities, as well as between less economically developed municipalities and more economically developed municipalities, which are proximately situated. More specifically, we propose a form of “neighbourly solidarity” that would extend beyond the mere sharing of collection and transport costs and encompass two critical components: A common fund for investment in joint collection initiatives, such as new waste collection infrastructure; and cost compensation for less economically developed municipalities. In cases where municipalities already share collection management, costs should be distributed considering not only population but also income and performance to the regulatory target. Wealthier and/or larger municipalities should contribute more to the service cost, particularly when they have already reached the target.

Of note, municipalities do not directly provide waste collection services but depend on external waste collectors. Thus, smaller municipalities may already be collaborating with the same waste collector (e.g., through a consortium), which serves as the primary decision-maker. Consequently, close collaboration and dialogue between diverse municipalities and their service providers are essential. Finally, we would like to emphasise that the present findings and their implications refer only to *waste collection*, rather than *waste disposal* (which, in Italy, is managed by the ATO and not the municipality).

To help Italian municipalities improve their sorted waste collection, targets should consider municipalities' population and economic development. To this end, policymakers should consider additional targets beyond the percentage of sorted waste. Such targets could refer to metrics such as tonnes per capita or kilogrammes per income, with further compensation targets set for municipalities that fall below specific thresholds in these categories.

One notable limitation of the present research concerns the study sample, as all the analysed municipalities are in Italy, thereby limiting the generalisability of the results to other countries. In addition, the analysis considered 275 municipalities with populations exceeding 10,000 inhabitants. Thus, a further analysis would be required to consider municipalities with smaller populations. Also, is worth noting that in our analysis, we focused on keeping as many municipalities available to get a national view of the problem. However, waste management practices in Italy exhibit significant regional variation, and this was not a primary focus of our research.

Consequently, this study's limitation concerns the unbalance between the number of municipalities from different regions and regional areas (almost 50% of the municipalities considered are in the North). To consider the heterogeneity due to different regional infrastructures in municipal waste, future specific research on this topic can be developed.

While our article does not provide a comparative analysis of different countries, there is potential for future research to utilize this method to compare municipalities on both a macro and municipal level. This type of analysis could be valuable in assessing the impact of different policies and regulations, such as the waste hierarchy framework in the European Union, on a national and international scale.

As a future development, it would be interesting to expand the analysis by considering additional variables, such as tourism, population seniority, or geo-morphological and geographical location (e.g., coastal or inland location of a municipality). In the present study, in fact, some of this information (such as location) is present but the number of municipalities considered is too low to have meaningful results, while other information, such as the number of tourists, is not available to date. The analysis with the total amount of waste per capita and total cost per capita as variables would be another interesting investigation to carry out in future research. Future research could focus also on the impact of waste collection methods on efficiency. Previous studies (Bel and Warner, 2015; Pérez-López et al., 2021) have hinted that the efficiency of waste collection in municipalities may be impacted by the method of provision. Regrettably, we were unable to incorporate this factor in our research due lack of data. Moreover, it is challenging to generalize waste collection practices in large cities like Rome or Milan as different techniques are employed in different areas. For instance, in Rome, certain sub-regions known as Municipalità rely on street collection, while others use door-to-door collection. Another possible development is the extension of the analysis also to waste disposal and comparing the results with other decision support tools (see e.g. Rigamonti et al., 2013a; Rigamonti et al., 2013b; Rigamonti et al., 2016).

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