Journal of Cleaner Production 323 (2021) 129097

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Assessing efficiency of urban waste services and the role of tariff in a circular economy perspective: An empirical application for Italian municipalities

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ARTICLE INFO

Handling Editor: Cecilia Maria Villas Bôas de Almeida

Keywords:
Circular economy (CE)
Waste management efficiency
Door-to-door collection
Data envelopment analysis (DEA)
Undesirable output
Waste tariff

ABSTRACT

Since the previous decade, there has been an increasing awareness regarding the crucial role of waste management efficiency in ensuring health and environmental protection and the transition toward circular economy objectives. This empirical study investigates the efficiencies of urban waste systems in 78 major Italian towns between 2014 and 2018, taking into account the waste reduction and recycling targets indicated by European circular economy strategy. To this end, we employed the nonparametric approach to measure efficiency, namely the data envelopment analysis (DEA) model. Two DEA models to account for both constant and variable returns to scale were performed. An undesirable output (the total amount of waste collected) was included in the analysis as an input to account for waste reduction targets. Moreover, efficiency scores obtained through the DEA analysis were investigated in relation to relevant variables, along with the already studied variables, such as geographic localization, population density, and the aging index. We also included the tariff paid for waste services and the collection method. The estimated efficiency scores showed significant differences across all the evaluated municipalities, with a promising average growth. We find that the Northern and Central major towns have higher efficiency than the Southern and Island towns. Moreover, efficiency is higher for more densely populated towns and towns with a higher elderly rate. Further, efficiency is higher when the average tariff applied is lower and when door-to-door collection is in force. Finally, the collection method emerges as a crucial issue in ensuring the transition toward circular economy in the urban waste sector.

1. Introduction

According to the World Bank, annual waste generation is estimated to grow by 70% by 2050 (World Bank, 2018), while raw material consumption is projected to double by 2060 (OECD, 2018). In accordance with the European Green Deal, the 2020 EU Circular Economy Strategy Action Plan (CESAP) developed a policy framework to attain a cleaner and competitive economy. With this aim, the plan promotes actions to address economic growth dissociated from resource usage to avoid waste generation and minimize resource extraction from a circular economy (CE) perspective. The Italian law 152/2006 integrated by the Decree 205/2010 implement the Waste Framework Directive (2008/98/EC; EC European Commission, 2008) fixing objectives and strategies as well as the targets for waste recycling and disposal in accordance to the European rules. In addressing European and Italian regulations, waste generation and resource consumption are key issues, by transforming linear value chains in circular value systems (Morseletto, 2020) in a circular, green economy perspective. In this way, the plan, in attaining the first objective of zero waste (Romano et al., 2019, 2020, 2021), implements a set of progressive measures to support and promote an efficient European market for secondary raw materials and for reusable or recyclable products in accordance with the CE model. Following Morseletto (2020), the CE model aims "at the efficient use of resources through waste minimization, long-term value retention, reduction of primary resources, and closed loops of products, product parts, and materials within the boundaries of environmental protection

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https://doi.org/10.1016/j.jclepro.2021.129097
Received 31 March 2021; Received in revised form 5 August 2021; Accepted 17 September 2021
Available online 21 September 2021
0959-6526/© 2021 Published by Elsevier Ltd.

and socioeconomic benefits." (Xideng et al., 2020).

The CE is based on three key factors, also called the 3Rs: "reduce" waste generation, "reuse" products, and "recycle" recyclable materials (Preston, 2012; Birat, 2015; Castellani et al., 2015; Ghisellini et al., 2016; D'Inverno et al., 2020). Although waste reduction is the first pillar of the CE, many studies have indicated that closing the material loops through separate collection is a crucial step toward CE objectives (Corona et al., 2019; Dahlén and Lagerkvist, 2010; Geissdoerfer et al., 2017, Knickmeyer, 2020), as it allows for the reduction of waste disposal in landfills or incinerators (Birat, 2015; Romano et al., 2021).

Recent literature highlights the crucial role of waste management efficiency in ensuring health and environmental protection and the transition toward CE objectives (Agovino et al., 2018; Cerciello et al., 2018; Rhyner et al., 2017). In recent decades, a strand of studies has considered the implications of waste management efficiency in terms of economic, technical, and environmental performance (Rogge and De Jaeger, 2012; Song et al., 2012; Guerrini et al., 2017; Exposito and Velasco, 2018; Romano and Molinos-Senante, 2020; Romano et al., 2020).

Previous works have adopted data envelopment analysis (DEA) to analyze the performances of the waste sector (Marques and Simões, 2009; Benito et al., 2010). The application of DEA enables researchers and regulatory bodies to analyze the efficiency performances of waste services by considering heterogeneity of different factors such as collection modality with door to door collection service widely adopted (Di Foggia and Beccarello, 2021), vehicles, transportation, collection timetables, treatment options, and waste collection and disposal strategies (Yüksel, 2012; Chen and Chen, 2012) addressing issues related to circular economy objectives.

This paper presents a study aimed at investigating performances of the waste sector in major towns of each Italian province considering economic and ecological efficiency. Italy is a prominent case study because it encompasses highly locally-differentiated waste systems due to structural, technical, political, and socioeconomic differences across regions (Agovino et al., 2019). Thus, although the study focuses on the Italian waste sector, it could provide tools and knowledge on issues relevant to assess waste sector analysis in several others countries, since European data and those of the rest of the world indicate that heterogeneity characterizes waste sector of different countries (Kaza et al., 2018).

In contrast to previous waste management studies, which have mainly focused on national, regional, or provincial data, this study analyzes data at the municipal level (NUTS-4) to better account for high local differentiations (Bagliani et al., 2008; Narbón-Perpiñá et al., 2020), focusing on the major towns of each province. Moreover, this scale of analysis allows us to consider collection service variables (door-to-door or street-bin collection) as key factors in waste management services (Yadav and Karmakar, 2019) and their impact on the household recycling rate (Abbott et al., 2011; Starr and Nicolson, 2015; Hage et al., 2018; Andersson and Stage, 2018; Romano et al., 2019).

This study employs a DEA approach using publicly available data for the period 2014–2018. DEA allows for an assessment of the economic and ecological efficiency of solid waste management (SWM) in 78 major towns in Italian provinces (NUTS-4) because ecological efficiency combines with economic gains in a win-win strategy for both societies and waste companies (Milanez and Bührs, 2007).

DEA is a convenient technique for efficiency measurement for a variety of reasons. First of all, it is a non-parametric method, which means that the danger of imposing an a-priori wrong functional forms is avoided. In addition, DEA can handle multiple outputs, opposed to the alternative usual parametric approach to efficiency measurement, which is restricted to the single output case. The DEA model approach relies on the principle of output maximization at the smallest amount of input. This principle is based on the assumption that the production process efficiency is related to the balance between the outcome of the desirable output and the inputs used in its production. However, the application of DEA model to environmental efficiency needs to focus on the production of both good (desirable output) and bad (undesirable outputs or externalities). This approach allows considering the waste sector's economic as well as environmental achievements (Korhonen and Luptacik, 2004).

Hence, to assess eco-efficiency we integrate undesirable outputs in the DEA model according to the CESAP targets. Following Wojcik et al. (2017), to assess DEA scores for environmental and economic efficiency, we considered the undesirable outputs as environmental costs, which was accounted as optimizable undesirable outputs and included as inputs in the DEA model, while we considered all desirable outputs as outputs in the model. This approach enables evaluation of the SWM's environmental-technical performances.

The remainder of this paper is outlined as follows. Literature review discussing the previous research on the efficiency estimation of waste management systems is provided in section 2. Section 3 describes the methods and theory employed in this study. The data used are illustrated in Section 4. The results are presented and discussed in section 5, while section 6 concludes the paper.

2. Literature review

Many researchers have examined the efficiency of urban waste management for its importance in welfare, safety, environmental sustainability, affordability, and service quality (Simões and Marques, 2012; Narbón-Perpiñá et al., 2020, Llanquileo- Melgarejo et al., 2021).

As recently highlighted by Halkos and Petrou (2019), DEA has been widely used for efficiency estimation in waste management studies, making it the most applied methodology (Pérez-López et al., 2016; Sarra et al., 2017).

Considering researchers who have implemented DEA to investigate the efficiency of urban waste companies at the municipal level (see for references Gastaldi et al., 2020), the literature shows that the input-output system used has changed, with total cost and total amount of waste collected as the most frequently applied variables. However, a growing number of studies have underlined the need to specifically investigate the separate waste collection targets to provide insight on the effectiveness of European and national legislation. Those studies mainly rely on the efficacy determined based only on a fraction of waste collected separately (e.g., Bosch et al., 2000, used organic waste collected as output). Many of them include the amount of waste collected separately as a desirable output (Rogge and De Jaeger, 2013), while considering the unsorted waste collected as an undesirable output (Sarra et al., 2017; Romano and Molinos-Senante, 2020). Remarkably, to our best knowledge, no study has considered the amount of waste produced as an input (undesirable variable) in the efficiency estimation of waste sector. This variable is usually included as an output.

In studies focusing on efficiency estimation with an aim to provide policy implications, efficiency analysis has been investigated in relation to social and environmental data (for example, see the studies of Sarra et al., 2017 or Guerrini et al., 2017). These include population density (Worthington and Dollery, 2001; García-Sánchez, 2008; Benito-López et al., 2011; Boetti et al., 2012; Tsalis et al., 2018; Romano and Molinos-Senante, 2020), economies of scale of facilities (Llanquileo-Melgarejo, and Molinos-Senante, 2021), population served (Worthington and Dollery, 2001; Garcìa-Sanchez, 2008; Romano and Molinos-Senante, 2020), and geographic area (Simões et al., 2012; Guerrini et al., 2017; Agovino et al., 2018). These studies present contradictory results that call for further investigation.

The literature lacks in-depth analyses of relevant factors, such as the average age of inhabitants, and the few available studies present contrasting results. On the one hand, although elderly people could be keener to correctly separate waste and comply with rules (Tsalis et al., 2018), they influence the municipal waste production and the costs to manage it (Soukopová et al., 2017). On the other hand, Calabrò and Komilis (2019) showed that recycling attitude was not influenced by citizens' age.

The link between efficiency and waste collection methods needs further investigation. A pioneering study by Guerrini et al. (2017), with reference to an Italian area, showed that door-to-door collection favors efficiency and increases its effect from year to year, thereby highlighting a positive experience effect on municipalities and waste utilities performance. Moreover, citizens learn better under door-to-door collection, and they help improve the rules related to it (how to correctly separate waste, when to properly show the waste bin, how to contact the contact center for more information, etc.). Andersson and Stage (2018) found that separate collection of food waste is linked with more recycling of other waste types.

No previous studies have included the tariff paid as a relevant factor that could impact efficiency, even if it is of utmost interest to understand if higher average tariffs paid by households contribute to higher efficiency, or if they are linked with inefficiencies because of sanctions and other penalties that affect waste tariffs in Italy. As highlighted by Marques et al. (2018), "in the waste sector, tariff systems are a relevant and complex topic, especially in environments with low incentives to reduce waste." Municipalities are charged with a penalty if they are unable to meet their expected targets for separate collection rates in accordance with Environmental Code rules (art. 205 Decree 152/2006).

Moreover, recent studies have shown that higher efficient waste management systems also show low tariffs (Minoja and Romano, 2021). This is because of the higher capability to sell separate collected materials (paper, glass, organic, exhaust oils, and plastic) and to avoid the penalties applied to municipalities that were unable to reach the expected targets of separate waste collection.

3. Methodology

Measuring the waste sector's performance is essential for improving the quality and efficiency of waste services. Many authors have commonly used performance indicators and methodologies to benchmark the efficiency and effectiveness of industry management. Data envelopment analysis, proposed by Charnes et al. (1978, 1981), is an integrated model to identify best practice boundaries for benchmarking purposes; in particular, it is a nonparametric method applied to measure the relative efficiency of a set of independent and homogeneous *z-corresponding* units called decision-making units (DMUs). The Italian case study provides an interesting sample for its highly differentiate waste systems in term of firm dimension and management, markets dimensions, economic factor, social characteristics and urban structures.

In a single input and single output process, we define efficiency as the ratio of the single output to the single input. Generally, in a process with multiple inputs and multiple outputs, the efficiency is given by the ratio of the weighted sum of outputs to the weighted sum of inputs. The choice of weights is challenging. The DEA method uses a particular weighting system for every single DMU.

The maximum efficiency for a DMU k_0 is determined by solving the following fractional problem:

$$\max_{w,v} k_0 = \frac{\sum_{j=1}^{n} w_j y_{jk_0}}{\sum_{j=1}^{m} v_i x_{ik_0}}$$

subject to,

$$\frac{\sum_{j=1}^{n} w_j y_{jk}}{\sum_{j=1}^{m} v_i x_{ik}} \leq 1 \quad k = 1, \ldots\ldots, z \quad w_j, v_i \geq \varepsilon \quad \forall j, i \ , \tag{1}$$

where.

z is the number of DMUs, m is the number of inputs x,
n is the number of outputs y,
w_j is the weight given to output y_j,
v_i is the weight given to input x_i, and
ε is a small positive number.

The above model maximizes the ratio of the weighted sum of outputs to the weighted sum of inputs for DMU k_0, with the restriction that the same ratio for the other units evaluated should not be greater than one, which is the maximum efficiency. The k_0th DMU is efficient relative to other units if its efficiency score is equal to l, and inefficient if less than l. The above non-linear problem can be transformed into a fractional linear programming problem (Charnes et al., 1996). The advantage of this technique is that it produces an aggregate measure of efficiency for each unit using multiple inputs and outputs; the disadvantage is that the efficiency score obtained by each unit is relative, as it depends on the efficiency of other DMUs in the sample. The larger the sample size and the better its completeness and representativeness, the higher is the accuracy of the obtained efficiency estimates.

DEA models can be designed as input-oriented and output-oriented. The former favors the potential improvement of input utilization and the latter analyzes the potential improvement of outputs production by measuring the relative efficiency of a unit in terms of maximal radial contraction to its input levels and maximal radial expansion to its output levels feasible under an efficient operation. Hence, in the input-oriented model, efficiency is estimated by minimizing inputs to produce at least the given level of outputs, while in the output-oriented model efficiency is estimated by maximizing outputs without using more than the given level of inputs.

DEA models can solve linear programming problems for each technology, allowing for both constant returns to scale (CRS) and variable returns to scale (VRS). The former reflects the circumstance where the outputs vary by the same proportion as inputs, while the latter reflects the circumstance where the production technology may exhibit increasing, constant and decreasing returns to scale. Banker et al. (1984) have shown that the CRS model yields an evaluation of overall technical efficiency (Charnes et al., 1981); the efficiency score generated by a CRS model can be separated into two components, one linked to scale efficiency and one linked to pure technical efficiency, devoid of scale efficiencies' effects.

4. Data

This study applies a DEA model to evaluate the economic and environmental efficiency of urban waste management services in a sample of major towns of the Italian province for the period 2014–2018. The Italian waste sector characteristics allow for the verify the effect of a wide set of variables and values due to the deep differentiation existing among Italian towns in term of waste service's environmental targets, markets dimension, management, socio-economic, and technical characteristics. These case study characteristics allow the study and the approach to be applied in several case studies for wider analysis and comparison at national and international level. In accordance with existing studies on the efficiency of waste management (Sarra et al., 2011; Rogge and De Jaeger, 2013; Worthington and Dollery, 2001; Boetti et al., 2012; Simões et al., 2012), total cost data were accounted as inputs, using both cost per inhabitant and cost per kg. Both data were included because they reflect different aspects of waste management: cost per inhabitant is more suited to monitor the fulfillment of the target of waste reduction; indeed, the cost per inhabitant was calculated considering only the number of inhabitants served and living in a municipality and was not affected by the amount of waste produced. These data could affect benchmarking in the case of highly touristic municipalities or municipalities with high rates of commuter workers. In contrast, the cost per kg also considers the amount of waste produced and helps to understand the cost for each kg of waste collected and treated, but it is positively affected in case of an increase in waste production. Thus, it does not consider the waste reduction targets; instead, in benchmarking activities, it could reward and foster an increase in waste produced for collection and treatment, in contrast with the zero-waste framework (Romano et al., 2021). The variables used in our analysis represent technical, economic, demographic and policies characteristics.

➢ Technical and economic characteristics

Two variables were used as outputs: the amount of separate waste collected per inhabitant and the total separate waste collected. Moreover, to consider waste reduction as a main target promoted at the European and Italian levels and to assess the eco-efficiency of waste management systems, we consider an undesirable output, represented by the total amount of waste collected, as an input in the DEA model. On this matter, Gudiputi et al. (2018: 109) affirmed that “Eco-efficiency couples economic and ecological performance of a city with an aim to improve socioeconomic outcomes while reducing environmental burden and waste production.”

Following previous research (Gastaldi et al., 2020; Romano and Molinos-Senante, 2020), data were obtained from the public dataset of the Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA). Following the ISPRA classification, the total cost includes the collection and transport cost of unsorted waste and of sorted recyclable waste, as well as the costs of treatment and disposal of unsorted waste and treatment and recycling of sorted recyclable waste. The total cost also consider street sweeping and washing, administrative, collection and litigation, general management, other costs such as the amortization, and remuneration of capital.

Seventy-eight major Italian municipalities were included in the sample. These municipalities account to approximately 25.5% of the Italian population with 15.5 million people. The major towns of each Italian province were classified, according to ISTAT classifications, on the basis of their geographic position: North-West (19 towns), North-East (10 towns), Center (26 towns), South (16 towns), and Islands (7 towns).

Table 1 provides the descriptive statistics of inputs and outputs included in our DEA model for the considered years, and Table 2 reports the Pearson’s correlation coefficients for these variables.

Data show that the separate collected waste per inhabitants (kg) increased during the study period, as did the average total costs (both per kg and per inhabitant). In addition, the variables regarding separate collection waste increased in the considered period, even if the percentage of separate collection reached is still far from the standard level setting the minimum of 65% as indicated by D. Lgs. 152/2006, which implemented the Packaging Waste Directive to Italian law (Guerrini et al., 2017). Moreover, it is possible to note a high cross-municipality variability in waste recycling. Both the total amount of waste collected and total separate waste collected diverge widely between the minimum and maximum values. However, both the minimum and maximum values of the latter have increased.

➢ Demographic and policies characteristics

We also studied several exogenous variables based on previous literature findings (Guerrini et al., 2017; Sarra et al., 2017; Romano and Molinos-Senante, 2020) and the peculiarities of this case. First, we investigated some demographic characteristics of municipalities, such as population density (measured by the ratio of the number of inhabitants per square kilometers of the covered area) and aging index. The latter is the ratio of elderly people of an age when they are usually economically inactive (aged 65 and over) to the number of young people (aged from 0 to 14). In Italy between 2012 and 2020, this index increased steadily, going from 148 to 177. In 2019, Italy was the EU country with the largest portion of elderly population (22.8% of the total population was aged 65 years and older), followed by Greece and Portugal. These data

Table 1
Descriptive Statistics of DEA variables, 2014–2018.

Year		Total cost per inhabitant COST INH	Total cost per kg COST KG	Total amount of waste collected (kg) WASTE	Separate collected waste per inhabitant (kg) SEP INH	Separate collected waste (kg) SEP
2014	Mean	188	35	110,234,960	230	42,517,971
	SD	46	9	214,456,185	106	78,730,494
	Minimum	85	18	10,100,090	28	1,021,119
	Maximum	348	68	1,719,848,194	488	605,042,595
2015	Mean	193	36	109,431,824	240	44,599,705
	SD	43	9	210,885,888	101	84,168,598
	Minimum	86	20	7,997,241	35	3,936,065
	Maximum	352	67	1,681,244,578	439	652,757,606
2016	Mean	192	36	110,691,333	268	49,303,106
	SD	45	9	212,099,081	113	91,771,406
	Minimum	86	15	8,425,439	31	1,948,069
	Maximum	335	64	1,689,206,114	475	709,436,934
2017	Mean	195	37	109,567,461	276	51,205,993
	SD	43	9	211,989,812	114	94,052,703
	Minimum	98	20	8,339,455	33	2,112,020
	Maximum	351	69	1,687,017,240	473	729,050,320
2018	Mean	198	37	111,384,751	302	54,271,552
	SD	46	10	216,857,918	118	97,663,488
	Minimum	97	21	8,986,768	37	2,385,750
	Maximum	362	77	1,728,428,924	542	755,180,757
Total	Mean	193	36	110,262,066	263	48,379,665
	SD	45	9	213,269,776	114	89,644,972
	Minimum	85	15	7,997,241	28	1,021,119
	Maximum	362	77	172,8428,924	542	755,180,757

Table 2
Correlation matrix, 2014–2018.

	SEP INH	SEP	WASTE	COST INH	COST KG
SEP INH	1				
SEP	0.111276215	1			
WASTE	−0.062677286	0.861698867	1		
COST INH	0.058107403	0.245422412	0.232852541	1	
COST KG	−0.188087216	0.106455452	0.101744824	0.734860585	1

were extracted from the Italian National Institute of Statistics (ISTAT) and the publicly available portal comuni-italiani.it.

Second, we considered some of the policies adopted by the municipalities with regard to urban waste service, and we collected data concerning the average tariff applied per year in the municipality (called TARI in Italy) and the waste collection method adopted (street-bin, curbside or door to door). According with Gastaldi et al. (2020), information on the average annual cost paid for the urban waste management service and the collection method was retrieved from the annual reports (called "Dossier Rifiuti") of Cittadinanzattiva, an Italian nonprofit organization. The average annual cost paid was computed by Cittadinanzattiva considering a three-member household living in a house of 100 m^2 and with a gross annual income of EUR 44,200.

Information about the collection method is available only for 2017 and 2018: 37.18% of the observations are related to municipalities that collect waste via door-to-door collection (curbside), while 62.82% of the observations are related to municipalities whose services are managed via a street-bin system. The former requires residents to store their waste in bins outside their doors or gates. The collection crew, after taking out the container, discharges the waste into the waste collection truck, and replaces the container to its place. Where labor costs are high, this method may be more expensive than street-bin collection (Guerrini et al., 2017). The main advantage of the street-bin collection method is to indicate and limit the places from which the waste is transferred to the treatment site or landfill.

The advantage of door-to-door collection is the higher quality of separate waste collected, which allows for a higher recycling rate and provides municipalities and waste utilities with higher revenues from selling recyclables. Furthermore, it fosters the responsibility of households, shopkeepers, and other organizations by increasing their awareness of waste generation, recyclables, and approaches for a more sustainable way of living (Connett, 2013; Calabrò and Komilis, 2019; Tsalis et al., 2018). It also allows for the introduction of the pay-as-you-throw tariff system, which is a tariff method that complies with the polluter-pays principle (Connett, 2013; Romano et al., 2021).

5. Results

In this work, we applied two output-oriented DEA models accounting for CRS and VRS to analyze the impact of scale on the efficiency of the units analyzed. For each municipality considered, the output-oriented DEA efficiency scores are presented in Table 3. Table 4 lists the descriptive statistics for these scores.

The DEA model results show significant differences among the units evaluated and small differences for the years considered. As can be seen in Table 3, the efficiency scores vary over time and in relation to geographical location. In particular, the Southern and Island municipalities are always less efficient than the Central and Northern municipalities.

In addition, the ecological efficiency of urban waste systems shows a positive variation during the period considered. Further, the value of the average efficiency score registers an increase from 2014 to 2018 that is equal to 9.2% for CRS specification and 6.1% for VRS specification (Table 4).

This is an encouraging result, probably fostered by the increasing attention of policy makers and citizens to the quality of public services and to regulatory policy aiming at enhancing sustainability and recycling rates, in a CE perspective.

For the CRS efficiency score, we observe a small reduction in 2016 with respect to 2015 (with average efficiency scores equal to 0.658 and 0.660, respectively). However, the number of municipalities with an efficiency score equal to one shows a small reduction from 2014 to 2017. Then, in 2018, the number of fully efficient units is higher with respect to the previous year, even if it is smaller than that in 2014 (Table 4).

To develop policy implications, the efficiency scores obtained through DEA analysis were investigated in relation to relevant external and environmental variables, such as geographic localization, population density, aging index, average annual tariff paid for the waste service (TARI), and collection method.

By focusing on the geographic localization of the urban waste systems evaluated, according to Agovino et al. (2018) and Minoja and Romano (2021) we observed that the municipalities located in the northeast of Italy show the highest average efficiency scores, even if they register a respective loss of efficiency from 2014 to 2018 for both CRS and VRS specifications (3.44% and 2.53%, respectively). In contrast, most Southern and Islands municipalities register very low ratings.

In Southern Italy, only Isernia reported efficient scores (except for 2014); in the Islands macro-zone, only Oristano, which registered a very high increase in efficiency during the study period, is very close to the efficient frontier. However, the average efficiency scores registered in Southern Italian municipalities increased by approximately 39% and 14% for CRS and VRS specifications, respectively (Table 5); this is in accordance with previous studies showing convergence toward best practices in waste management performance (Agovino et al., 2018).

Regarding the demographic characteristics of the municipalities analyzed, we classified the DMUs (major Italian towns) into four groups based on their population density to analyze DEA efficiency scores as a function of urban clusters. We may note that the average behavior of scores is consistent with previous studies and showed a variable trend (Guerrini et al., 2017; Romano et al., 2020a): efficiency increases with population density up to 1500 habitants/km^2, while it decreases for higher population density. In addition, the highest average efficiency scores are registered for population density within the 1000–1500 habitants/km^2 range (Table 6).

The efficiency of urban waste management services shows economies of density up to a certain population density; however, the best clusters are those with over 1,000 inhabitants per km^2, while the worst are the ones with fewer than 500 inhabitants per km^2. This further highlights the impact of the geographic and demographic factors of different territories. In densely populated areas, it is possible to use trucks with more load capacity, thus involving fewer workers and needing fewer trips to treatment plants, landfills, and waste storage centers.

However, for clusters with population densities lower than 1000 habitants/km^2, we observed a higher increase in efficiency during the period analyzed, showing that municipalities and waste utilities are increasingly adopting strategies that increase efficiency in less favorable situations, such as restructuring routes and equipment.

The empirical findings assess a positive correlation between efficiency and elderly people's presence (Table 7) during the entire period considered and for both models implemented (Fig. 1). In accordance with Tsalis et al. (2018), but in divergence with Romano and

Table 3
DEA efficiency scores by Municipalities, 2014–2018.

Municipality	Area	2014		2015		2016		2017		2018	
		CRS	VRS	CRS	VRS	CRS	VRS	CRS	VRS	CRS	VRS
L'Aquila	South	0.397	0.404	0.429	0.432	0.417	0.427	0.422	0.427	0.428	0.437
Teramo	South	0.77	0.779	0.787	0.791	0.762	0.763	0.727	0.728	0.732	0.735
Matera	South	0.362	0.458	0.299	0.301	0.319	0.325	0.308	0.31	0.327	0.327
Potenza	South	0.267	0.268	0.259	0.261	0.307	0.310	0.569	0.57	0.728	0.73
Catanzaro	South	0.089	0.089	0.132	0.133	0.487	0.491	0.726	0.732	0.768	0.769
Cosenza	South	0.564	0.649	0.659	0.696	0.644	0.685	0.629	0.679	0.704	0.705
Crotone	South	0.239	0.244	0.237	0.237	0.079	0.080	0.084	0.084	0.09	0.09
Reggio c.	South	0.122	0.127	0.226	0.231	0.359	0.367	0.384	0.387	0.477	0.477
Avellino	South	0.585	0.585	0.436	0.438	0.375	0.377	0.366	0.366	0.832	0.84
Napoli	South	0.435	0.435	0.454	0.454	0.533	0.534	0.572	0.578	0.593	0.595
Salerno	South	0.82	0.896	0.811	0.846	0.757	0.798	0.725	0.747	0.696	0.701
Bologna	Center	0.687	0.69	0.748	0.750	0.722	0.724	0.729	0.737	0.761	0.761
Forlì	Center	1	1	0.971	1	0.902	1	1	1	0.79	0.79
Ferrara	Center	0.84	0.84	0.799	0.867	0.778	0.887	0.871	0.941	1	1
Modena	Center	1	1	1	1	0.918	0.968	0.975	0.98	0.909	0.92
Rimini	Center	1	1	0.914	1	0.842	1	0.872	1	0.855	0.951
Ravenna	Center	1	1	1	1	0.903	0.970	0.928	0.94	0.85	0.86
Parma	Center	1	1	1	1	1	1	1	1	1	1
Piacenza	Center	0.918	0.933	0.819	0.941	0.760	0.867	0.928	0.943	1	1
Reggio E.	Center	1	1	0.931	0.943	0.847	0.915	0.94	0.96	1	1
Gorizia	North-East	0.801	0.809	0.818	0.868	0.784	0.793	0.813	0.828	0.819	0.835
Pordenone	North-East	1	1	1	1	1	1	1	1	1	1
Trieste	North-East	0.463	0.467	0.491	0.495	0.524	0.524	0.475	0.475	0.521	0.547
Udine	North-East	1	1	1	1	1	1	1	1	1	1
Frosinone	Center	0.201	0.214	0.208	0.217	0.187	0.208	0.183	0.208	0.554	0.56
Latina	Center	0.44	0.441	0.401	0.405	0.391	0.397	0.289	0.291	0.273	0.273
Roma	Center	1	1	1	1	1	1	1	1	1	1
Viterbo	Center	0.421	0.46	0.634	0.657	0.625	0.699	0.621	0.622	0.628	0.628
Genova	North-West	0.599	0.6	0.583	0.590	0.535	0.538	0.521	0.536	0.5	0.514
Imperia	North-West	0.417	0.44	0.491	0.520	0.445	0.461	0.424	0.458	0.416	0.443
Savona	North-West	0.313	0.319	0.388	0.397	0.512	0.523	0.514	0.526	0.491	0.5
Bergamo	North-West	0.942	0.945	0.909	0.909	0.917	0.918	0.901	0.907	0.864	0.879
Brescia	North-West	0.883	1	0.843	1	0.777	0.819	0.989	0.996	1	1
Como	North-West	0.69	0.698	0.865	0.874	0.885	0.890	0.878	0.881	0.842	0.843
Cremona	North-West	0.704	0.71	0.820	0.822	0.891	0.891	0.892	0.895	0.873	0.874
Lecco	North-West	0.675	0.676	0.730	0.730	0.789	0.799	0.77	0.771	0.765	0.765
Mantova	North-West	0.981	1	0.998	1	0.992	1	0.983	0.988	0.988	1
Milano	North-West	1	1	1	1	1	1	1	1	1	1
Pavia	North-West	0.521	0.527	0.509	0.545	0.659	0.679	0.775	0.801	0.749	0.766
Sondrio	North-West	0.966	1	0.938	1	0.979	1	1	1	0.971	1
Varese	North-West	0.728	0.75	0.759	0.786	0.827	0.854	0.763	0.776	0.775	0.777
Monza	North-West	0.702	0.705	0.744	0.748	0.836	0.843	0.787	0.79	0.752	0.752
Ascoli P.	Center	0.504	0.521	0.538	0.559	0.483	0.493	0.56	0.587	0.754	0.754
Isernia	South	0.255	1	1	1	1	1	1	1	1	1
Asti	North-West	0.827	0.844	0.798	0.809	0.778	0.802	0.809	0.822	0.801	0.803
Biella	North-West	0.77	0.815	0.814	0.845	0.869	0.931	0.903	0.956	0.918	0.982
Torino	North-West	0.82	0.823	0.793	0.798	0.717	0.720	0.751	0.766	0.768	0.777
Vercelli	North-West	0.909	0.943	0.897	0.908	0.810	0.813	0.797	0.81	0.829	0.917
Bari	South	0.484	0.484	0.542	0.548	0.555	0.556	0.583	0.583	0.59	0.611
Foggia	South	0.1	0.101	0.112	0.115	0.171	0.175	0.293	0.293	0.245	0.245
Taranto	South	0.175	0.178	0.255	0.259	0.224	0.226	0.234	0.245	0.253	0.263
Trani	South	0.575	1	0.351	0.360	0.244	0.247	0.24	0.241	0.235	0.235
Nuoro	Islands	0.793	0.837	0.783	0.800	0.695	0.739	0.793	0.861	0.842	0.883
Oristano	Islands	0.793	0.837	0.783	0.800	0.695	0.739	0.793	0.861	0.986	1
Sassari	Islands	0.589	0.595	0.577	0.592	0.619	0.628	0.613	0.619	0.628	0.629
Agrigento	Islands	0.279	0.402	0.193	0.204	0.112	0.115	0.096	0.107	0.639	0.64
Catania	Islands	0.168	0.168	0.150	0.151	0.165	0.174	0.144	0.146	0.116	0.116
Palermo	Islands	0.165	0.172	0.153	0.161	0.121	0.122	0.243	0.249	0.175	0.179
Trapani	Islands	0.301	0.325	0.329	0.370	0.257	0.284	0.171	0.184	0.184	0.184
Arezzo	Center	0.478	0.483	0.527	0.546	0.519	0.546	0.538	0.55	0.512	0.515
Carrara	Center	0.483	0.551	0.471	0.519	0.453	0.480	0.473	0.53	0.454	0.505
Firenze	Center	0.824	0.824	0.823	0.824	0.812	0.820	0.823	0.828	0.817	0.817
Grosseto	Center	0.446	0.472	0.457	0.505	0.448	0.470	0.424	0.467	0.435	0.452
Lucca	Center	0.856	0.9	0.875	0.977	0.968	1	0.944	1	0.938	1
Livorno	Center	0.555	0.577	0.532	0.550	0.551	0.560	0.552	0.56	0.637	0.641
Massa	Center	0.39	0.439	0.469	0.545	0.407	0.517	0.503	0.594	0.408	0.523
Pisa	Center	0.538	0.636	0.559	0.716	0.598	0.779	0.721	0.933	0.727	0.861
Pistoia	Center	0.547	0.548	0.554	0.592	0.515	0.554	0.511	0.522	0.525	0.529
Prato	Center	0.816	0.817	0.733	0.789	0.795	0.891	0.895	0.953	0.945	0.946
Bolzano	North-East	0.911	0.913	0.831	0.832	0.848	0.852	0.807	0.808	0.798	0.807
Trento	North-East	1	1	1	1	0.997	1	0.963	0.965	0.949	0.949
Perugia	Center	0.907	0.919	0.790	0.823	0.803	0.816	0.763	0.795	0.751	0.772
Terni	Center	0.553	0.564	0.502	0.516	0.609	0.620	0.863	0.874	0.863	0.864

(*continued on next page*)

Table 3 (*continued*)

Municipality	Area	2014		2015		2016		2017		2018	
		CRS	VRS	CRS	VRS	CRS	VRS	CRS	VRS	CRS	VRS
Aosta	North-West	0.631	0.64	0.783	0.836	0.809	0.814	0.842	0.846	0.839	0.852
Belluno	North-East	1	1	1	1	1	1	1	1	1	1
Padova	North-East	0.811	0.812	0.750	0.765	0.747	0.773	0.699	0.729	0.691	0.708
Venezia	North-East	0.808	0.898	0.758	0.880	0.744	0.861	0.712	0.844	0.712	0.822
Vicenza	North-East	0.937	0.94	0.955	0.990	0.951	0.996	0.981	1	0.941	0.947

Table 4
Summary statistics of DEA efficiency scores, 2014–2018.

	2014	2015	2016	2017	2018
Mean					
CRS	0.648	0.660	0.658	0.684	0.708
VRS	0.681	0.684	0.685	0.705	0.723
Standard deviation					
CRS	0.274	0.264	0.259	0.262	0.246
VRS	0.274	0.270	0.267	0.266	0.248
Minimum					
CRS	0.089	0.112	0.079	0.084	0.09
VRS	0.089	0.115	0.080	0.084	0.09
Maximum					
CRS	1	1	1	1	1
VRS	1	1	1	1	1
Number of DMUs with the highest efficiency score					
CRS	12	10	7	9	11
VRS	17	15	13	12	15

Molinos-Senante (2020), in major Italian towns, the higher presence of elderly people increases efficiency; elderly people could be keener to correctly separate waste because they are retired and have more time to devote to managing waste properly, thereby supporting a higher efficiency of waste services. Moreover, old people could be more proactive in signaling missing services, delays, or other inconveniences to municipalities and waste utilities, thus increasing service quality and diffusing control throughout the territories served.

Regarding the policies adopted by the municipalities analyzed, DMUs were classified based on the tariff applied per year (€) in the municipality (TARI) to analyze the relationship between tariff and recycling rate and to examine whether the eco-efficiency comes with savings in terms of household expenditure, applying the polluter-pays principle. As expected, the results show that there is a negative correlation between efficiency and TARI: as suggested by recent case studies (Minoja and Romano, 2021), efficiency is higher in correspondence with the lower tariff amounts and vice versa (Table 8). Moreover, in the

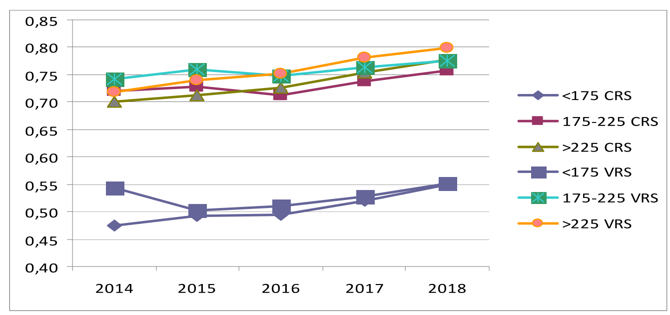

Fig. 1. CRS and VRS efficiency scores: aging index, 2014–2018.

Table 5
Mean efficiency scores by geographic localization, 2014–2018.

Macro-zone	n°	2014		2015		2016		2017		2018	
		CRS	VRS	CRS	VRS	CRS	VRS	CRS	VRS	CRS	VRS
North-West	19	0.741	0.760	0.772	0.796	0.791	0.805	0.805	0.817	0.797	0.813
North-East	10	0.873	0.884	0.860	0.883	0.860	0.880	0.845	0.865	0.843	0.862
Center	26	0.708	0.724	0.702	0.740	0.686	0.738	0.727	0.762	0.746	0.766
South	16	0.390	0.481	0.437	0.444	0.452	0.460	0.491	0.498	0.544	0.548
Islands	7	0.441	0.477	0.424	0.440	0.381	0.400	0.408	0.432	0.510	0.519

Table 6
Mean efficiency scores by density, 2014–2018.

Habitants/km	n°	2014		2015		2016		2017		2018	
		CRS	VRS	CRS	VRS	CRS	VRS	CRS	VRS	CRS	VRS
>1500	24	0.690	0.704	0.693	0.711	0.693	0.706	0.705	0.715	0.727	0.733
1000–1500	9	0.837	0.845	0.847	0.875	0.873	0.910	0.892	0.914	0.871	0.889
500–1000	21	0.635	0.674	0.633	0.661	0.639	0.672	0.685	0.710	0.701	0.726
<500	24	0.547	0.603	0.580	0.606	0.561	0.592	0.585	0.612	0.634	0.648

Table 7
Mean efficiency scores by aging index, 2014–2018.

Aging Index	n°	2014		2015		2016		2017		2018	
		CRS	VRS	CRS	VRS	CRS	VRS	CRS	VRS	CRS	VRS
<175	21	0.475	0.544	0.492	0.502	0.495	0.510	0.520	0.527	0.550	0.552
175–225	33	0.720	0.742	0.728	0.759	0.713	0.748	0.739	0.763	0.758	0.776
>225	24	0.701	0.718	0.713	0.741	0.726	0.751	0.753	0.781	0.778	0.799

cluster with the highest average tariff, a decrease in the efficiency level from 2014 to 2018 emerged, respectively equal to 7.24% and 12.35% for CRS and VRS specifications (Fig. 2).

These empirical results confirm the findings of a previous Italian study (Gastaldi et al., 2020) applied to a more limited interval of time.

Furthermore, efficiency results in relation to the collection method used were examined. Confirming previous findings (Guerrini et al., 2017), our empirical results show that MSW systems that have adopted door-to-door collection register the highest efficiency scores for both CRS and VRS models throughout the study period (Table 9). This result supports the idea that although door-to-door collection is more labor-intensive, it is able to increase municipalities' and waste utilities' efficiency in managing urban waste collection and treatment because it increases the quality and quantity of recyclables and fosters citizens' awareness of sustainable waste practices (Tsalis and Komilis, 2018). According to Connett (2013), door-to-door collection favors source separation and is effective in achieving high separate collection rates, even beyond required targets (Romano et al., 2020b; Minoja and Romano, 2021; Romano et al., 2021).

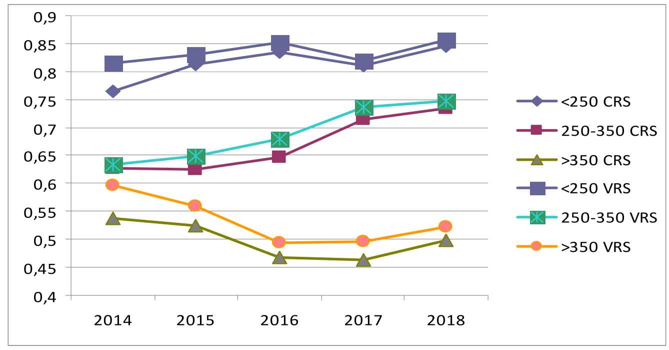

Fig. 2. CRS and VRS efficiency scores: TARI, 2014–2018.

Table 9
Mean efficiency scores by waste collection methods, 2017–2018.

	n°	2017		2018	
Methods		CRS	VRS	CRS	VRS
Street-bin system	49	0.603	0.624	0.632	0.649
Door-to-door	29	0.822	0.841	0.836	0.847

6. Conclusion

In this work, we analyzed the performance of municipal waste systems in Italy by focusing on 78 major Italian towns in each province for a period of 5 years (2014–2018). Within a CE framework, we implemented two output-oriented DEA models that also consider undesirable output represented by the total amount of waste collected. We evaluated technical efficiency accounting for constant and VRS assumptions to evaluate the ability of these municipalities to maximize their outputs; that is, the amount of separate waste collected per inhabitant and the total separate waste collected. Moreover, we considered both demographic variables and other external variables related to the policies adopted by municipalities and waste utilities to analyze their relationship with the efficiency estimates obtained through DEA analysis. This approach allows to assess weaknesses and strengths of waste management by indicating which improvements are needed to reach efficiency in term of circular and green economy, and providing, ended, information to policy makers in order to address tailored actions to better support the transition toward a circular and green economy system. From the theoretical perspective the model shows the effectiveness of the tool in evaluating both economic and environmental efficiency of the firms. This approach provides the necessary support for monitoring and evaluating progress toward the European and national circular and green economy targets.

The results reveal significant differences among the units evaluated, mainly due to the geographic localization. In particular, we note that many Southern and Islands municipalities register very low efficiency scores. In contrast, we also observe that efficiency scores increase during the observed period and that the ecological efficiency of major Italian towns' urban waste systems registers a positive, even if quite small, variation during this period.

The municipalities located in the northeast of Italy show the highest average efficiency scores, confirming previous findings.

By analyzing the efficiency results obtained with reference to the demographic characteristics of the municipalities analyzed, the efficiency of urban waste management services shows an economy of density up to a certain population density (1,500 habitants/km^2) and that DEA scores are higher in the presence of a higher elderly rate. Such findings can be used by municipalities to more precisely target territories and age groups that hold the potential to enhance the efficiency of municipal SWM. For example, establishing information campaigns that target ad hoc clusters of citizens who are less involved in separate collection, or defining routes and determining the best equipment to serve less densely populated areas, could help increase the efficiency rate of major towns. Finally, regarding the policies adopted by the Italian municipalities analyzed, the obtained results show that, in the period under observation, the efficiency levels are higher with a lower tariff level and with a door-to-door waste collection service. The collection method emerges as a crucial issue in ensuring the transition toward circular economy in the urban waste sector.

The study has some limitations. First, the sample focuses only on Italian provinces. Since the Italian case study provides evidences of a highly differentiated waste sector it enables the study implementation to a wider analysis, so that future studies could undertake comprehensive international comparisons among European countries by exploring services, geographical and regulatory characteristics, thus highlighting the existing differences among European waste systems with stronger policy implication. Other limiting factors of the study are linked to data quality and availability. In fact, it would be interesting to include additional variables that affect municipality performance, and to introduce other performance indicators along with waste production and separate waste collected. Finally, a comparative evaluation with the alternative method of efficiency measurement, represented by Stochastic Frontier Analysis, can be made.

CRediT authorship contribution statement

Ginevra Virginia Lombardi: Supervision, Data curation, Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing, Software, Validation. **Massimo Gastaldi:**

Table 8
Mean efficiency scores by TARI, 2014–2018.

	n° 2014	n° 2016	n°2017	n° 2018	2014		2015		2016		2017		2018	
TARI/year €					CRS	VRS	CRS	VRS	CRS	VRS	CRS	VRS	CRS	VRS
<250	24	23	25	26	0.764	0.815	0.813	0.830	0.834	0.851	0.811	0.820	0.845	0.856
250–350	36	36	34	31	0.626	0.635	0.626	0.650	0.647	0.680	0.715	0.737	0.735	0.747
>350	18	19	19	21	0.537	0.596	0.524	0.559	0.467	0.494	0.463	0.497	0.498	0.522

Data curation, Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing, Software, Validation. **Agnese Rapposelli:** Data curation, Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing, Software, Validation. **Giulia Romano:** Data curation, Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Software, Validation.

Declaration of competing interest

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

Acknowledgments

The Authors acknowledge the support of Jlenia Corizzo in data collection. Giulia Romano acknowledges the financial contribution of the University of Pisa – PRA 2018 project.

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