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Estimating the eco-efficiency of urban waste services towards sustainable waste management

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Abstract

Assessing the eco-efficiency of municipalities regarding the provision of solid waste services is a useful tool for improving its sustainability. However, robust, and reliable methods are needed to benchmark the performance of municipalities. Data envelopment analysis (DEA) methods typically used to assess the eco-efficiency of municipal solid waste (MSW) service providers. However, the variables used in the eco-efficiency assessment bear distinct weights for each individual unit, limiting thus interpretation. Therefore, benchmarking the performance of MSW service providers becomes challenging because different conditions are applied. Thus, this study uses a common set weights DEA (DEA-CSW) model assess the eco-efficiency of different municipalities in providing MSW services. Eco-efficiency scores were estimated by integrating total costs, recycled waste and unsorted waste as input, desirable outputs and undesirable outputs, respectively. The empirical application of the model demonstrated that when using DEA-CSW, only one municipality (out of 36) was eco-efficient in managing MSW. The weightings for inputs and outputs were allocated based on the degree of satisfaction estimated for each municipality. Satisfaction ranged from 0.829 to 1.000 indicating that none of the municipalities were heavily penalized based on the eco-efficiency scores estimation when allocating common weights. In conclusion, this study demonstrates that compared to traditional DEA models, the DEA-CSW approach is more adequate at benchmarking the performance of municipalities regarding the provision of MSW services.

KEYWORDS
benchmarking, common weights, data envelopment analysis, eco-efficiency, waste management

1 | INTRODUCTION

Municipal solid waste (MSW) management is a basic common service provided by the public sector (Struk & Boďa, 2022). As people become more environmentally conscious, the effective management of the waste sector is gaining great prominence from municipalities worldwide (Chioatto et al., 2023; Romano et al., 2020; Singh, 2019). Thus,

Abbreviations: AHP, analytic hierarchy process; CRS, constant returns to scale; CSW, common set of weights; DEA, data envelopment analysis; DEA-CCR, charnes, cooper, and rhodes DEA; DEA-CSW, common set of weights DEA; EU, European union; FDH, free disposal hull; GDP, gross domestic product; KPIs, key performance indicators; MSW, municipal solid waste; OECD, organization for economic co-operation and development; OPEX, operational expense; SFA, stochastic frontier analysis; SUBDERE, secretary of regional and administrative development; VRS, variable returns to scale.

improving waste management is one of the targets defined by Goal 11 (Sustainable Cities and Communities) of the Sustainable Development Goals proposed by the United Nations (2015). According to the European Waste Framework Directive (2008/98/EC) and other national and international policies, waste management is prioritized in the following order: prevention, re-use, recycling, energy recovery and disposal. However, the annual amount of waste generated globally is expected to rise to 3.4 billion tonnes by 2050 (Hoornweg & Bhada-Tata, 2012). This expected rise in MSW generation could increase the complexity and tasks involved in MSW management (Taweesan et al., 2017; Tseng, 2011).

Compared to residents in developed nations, those in developing and middle-income countries are more severely impacted by unsustainable MSW management (Ferronato & Torretta, 2019). The World Bank (2022) estimates that over 90% of waste is disposed in unregulated dumps or openly burned in low-income countries. These practices create serious health safety and environmental consequences (Akmal & Jamil, 2021; Haywood et al., 2021). In 2016 5% of global greenhouse gas emissions were generated from solid waste management which contributed directly to climate change. Effective and sustainable MSW management is expensive, often representing 20%–50% of municipal budgets (World Bank, 2022). The effective use of financial resources, without compromising service quality and social and environmental sustainability, represents a major challenge for public management decision-makers (Deus et al., 2022; Guerrero et al., 2013). Consequently, it is important to assess the performance of MSW service provision to improve its efficiency (Halkos & Aslanidis, 2023; Sarra et al., 2017).

The objectives of this study are threefold. The first objective is to estimate and juxtapose eco-efficiency scores for a sample of municipalities using a traditional data envelopment analysis (DEA) model (Charnes, Cooper and Rhodes DEA model -DEA-CCR) (Charnes et al., 1978) and a novel DEA common set of weights (DEA-CSW) approach (Wu et al., 2016). The second objective is to rank the municipalities based on eco-efficiency estimations. The third objective is to scrutinize the impact of common weight allocation on both eco-efficiency scores and the subsequent ranking of municipalities in the provision of MSW services.

Our empirical research was focused on a sample from thirty-six municipalities in Chile. What makes the Chilean scenario noteworthy is that, in contrast to European nations, many Latin American countries are just beginning to establish waste management policies. In fact, the first national regulation promoting solid waste recycling in Chile was only introduced in 2016. As such, the insights from this study can be instrumental in shaping effective MSW management policies that resonate with the ethos of the circular economy and the Sustainable Development Goals. Moreover, the findings from the Chilean study could provide valuable guidance for other middle-income nations embarking on the journey to bolster sustainable solid waste management.

This study offers several significant insights. While the DEA methodology has been widely utilized to gauge the efficiency of municipalities in MSW management (Amaral et al., 2022), most scholars have opted for DEA models that inherently assign weights to inputs and outputs. However, this research contends that in specific contexts, particularly when ranking units for regulatory objectives, this inherent feature of the DEA can be a limitation. To address this, we adopted the DEA-CSW model to compute the eco-efficiency scores in MSW management. The study's primary contributions include the computation of eco-efficiency scores using CSW and juxtaposing the rankings of the evaluated municipalities derived from DEA-CCR and DEA-CSW. Focusing on the case study, most existing research has centered on the performance of municipalities in MSW management within affluent European nations. Diverging from this trend, our study scrutinizes the efficacy of MSW management in a middle-income context, thereby shedding light on a distinct operational landscape. As a result, our findings are anticipated to hold significance for other low- to middle-income nations, especially those where national directives geared towards the circular economy are still incipient and weak.

The paper unfolds as follows. Section 2 presents a brief literature review of past studies assessing the performance of MSW management. Section 3 focuses on describing the methodology employed in this study, followed by a discussion of the sample data. Section 4 presents the main results which are discussed in Section 5. Finally, the concluding remarks of the paper are presented in the last section.

2 | LITERATURE REVIEW

The literature reviews conducted by Simoes et al. (2012), Lo Storto (2021) and Amaral et al. (2022) over the last decade showed that many studies have analyzed the performance of MSW service provision. A variety of methodological approaches have been implemented. For instance, key performance indicators (KPIs) were used to monitor and quantify the performance of MSW management by various municipalities and countries (e.g., Bertanza et al., 2018; Deus et al., 2019; Martinho et al., 2017; Velis et al., 2023; Yang et al., 2017). However, KPIs are only partial performance measures. Without a proper aggregation metric, KPI analyses could lead to misinterpretations about the performance of MSW services (Amaral et al., 2022; Ferreira et al., 2020). To overcome this limitation, several studies applied different composite indicators to estimate the performance of units (municipalities, regions or countries) regarding the provision of MSW services (e.g., Agovino et al., 2017; Benedetti et al., 2023; Carvalho & Marques, 2011; Carvalho & Marques, 2014; Deus et al., 2022; Exposito & Velasco, 2018; Gastaldi et al., 2020; Llanquileo-Melgarejo et al., 2021; Marques & Simoes, 2009; Pérez-López et al., 2018; Rogge & De Jaeger, 2012; Sarra et al., 2020). Most of these studies applied frontier methods which allow the relative efficiency of evaluated units to be estimated (Amaral et al., 2022).

Within frontier methods, stochastic frontier analysis (SFA) is a parametric approach that requires the specification of a functional form for production technology. However, this approach takes both inefficiency and noise into account. Consequently, it has poor sensitivity to the imperfect knowledge of data. Hence, SFA has been employed by past research to assess the efficiency of MSW services (e.g., Agovino et al., 2020; Carvalho et al., 2015; Carvalho &

Marques, 2014; Vishwakarma et al., 2012). Non-parametric methods such as free disposal hull (FDH)[1] and DEA do not need to specify any a priori functional form for the production frontier (Sala-Garrido et al., 2022). Moreover, the weights associated with inputs and outputs are endogenously determined by linear and mixed-integer programming models (Cooper et al., 2007). This positive feature of DEA has made it the most popular method for assessing the efficiency of MSW service providers (e.g., Marques and Simoes, 2008; Marques et al., 2012; Halkos & Petrou, 2019; Sarra et al., 2017; Romano & Molinos-Senante, 2020; Salazar-Adams, 2021). The endogenous selection of weights for inputs and outputs reduces the subjectivity of the aggregation process, building the composite indicator (Estruch-Juan et al., 2020). Nevertheless, in traditional DEA models, inputs and outputs weights maximize the efficiency scores for each unit (Alizadeh et al., 2023; Molinos-Senante & Maziotis, 2021). This phenomenon opens the opportunity for these DEA models to apply different weights to each variable (inputs and outputs) being considered when evaluating the efficiency of each analyzed unit. As a result, several authors have argued that cross-municipality comparisons of efficiency with traditional DEA-based composite indicators might be meaningless because performance is evaluated using municipality-specific sets of weights (Castillo-Giménez et al., 2019).

When efficiency results are used for regulatory purposes, flexible weights have two notable shortcomings. First, the discriminatory power of traditional DEA models is limited. For instance, several units (municipalities) can be identified as efficient, hindering the ranking of units (Huang et al., 2011). Second, different sets of weights are used to estimate efficiency scores. Consequently, assessment results, and thus the ranking, of units are, sometimes, not acceptable to others. This issue is particularly relevant when municipalities with the best efficiency scores are used to identify the best MSW management practices and policies. To our knowledge, these limitations have only been considered by Castillo-Giménez et al. (2019) and Giannakitsidou et al. (2020) when evaluating the performance of MSW management. Castillo-Giménez et al. (2019) combined DEA and multicriteria decision-making techniques to improve the discriminatory power of the DEA model, while maintaining a common weighting scheme for the four variables considered in the assessment. The authors focused on ranking 28 European countries based on their waste treatment performance. The estimated composite indicators included four variables related to waste treatment options: namely, landfill, incineration, recycling and composting & digestion. Of note, the composite indicator estimated by Castillo-Giménez et al. (2019) did not integrate any economic related variables, and so did not estimate economic efficiency. Giannakitsidou et al. (2020) also did not integrate economic variables when evaluating the environmental and circular economy performance of 26 European countries. Thus, while both studies considered the shortcomings related to flexible weights in DEA models, they only focused on environmental and circular economy performance, and did not consider the relevance of economics in MSW management.

This study aimed to fill the current knowledge gap in ranking municipalities regarding MSW management, taking both environmental and economic performance (eco-efficiency) into account. In doing so, a novel DEA-CSW from Wu et al. (2016) was applied. Grounded in the satisfaction degree concept, this model assesses the performance of all municipalities under a unified framework, given that the weights assigned to variables (inputs and outputs) remain consistent across municipalities. Furthermore, the application of the DEA-CSW technique enables the identification of a singular best-performing unit, enhancing the distinguishing ability inherent in conventional DEA models.

3 | MATERIALS AND METHODS

3.1 | Methodology for eco-efficiency estimation

The method used in this study encompassed two primary steps. In the first step, a standard DEA model that assigned flexible weights to variables was employed to estimate an eco-efficiency score for each municipality evaluated (as discussed in Section 3.1). The subsequent step centered on gauging eco-efficiency using a common set of weights (detailed in Section 3.2). Through this process, the maximum and minimum eco-efficiency goals for municipalities were determined. A satisfaction degree for every municipality was then computed, and based on these, the conclusive eco-efficiency scores using common set of weights were computed (Figure 1).

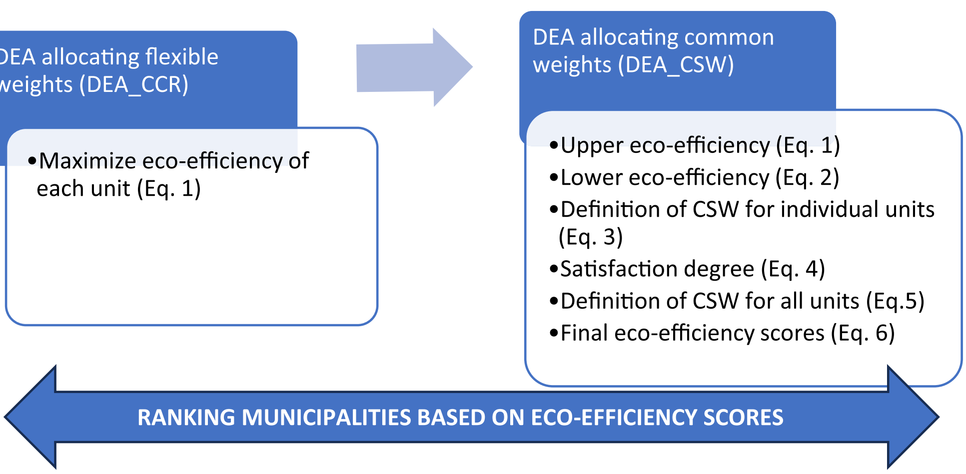

FIGURE 1 Methodological steps to assess eco-efficiency of municipalities.

The methodological approach adopted in this study aligns with previous research that has assessed eco-efficiency in the management of MSW in Chile and various other countries (e.g., Alizadeh et al., 2023; Delgado-Antequera et al., 2021; Guerrini et al., 2017). Conversely, some studies have opted for parametric methods, such as SFA, in their evaluations (e.g., Agovino et al., 2020; Castillo-Giménez et al., 2019). Nevertheless, it is a novel approach since there are no previous studies assessing the eco-efficiency of municipalities using the DEA-CSW method.

DEA is a data-oriented non-parametric method that involves a production process transforming a set of inputs into another set of outputs (Cooper et al., 2007). To calculate eco-efficiency, the first step is to transform undesirable outputs into desirable ones according to the approach suggested by Seiford and Zhu (2002), Lin and Xu (2017) and Ding et al. (2019). The production frontier is estimated by assuming constant returns to scale (CRS) or variable returns to scale (VRS) technologies. The former approach assumes that all units operate at an optimum level (Charnes et al., 1978). The latter approach compares units with similar scales (Banker et al., 1984). In the framework of the provision of MSW services in Chile, Llanquileo-Melgarejo and Molinos-Senante (2021) demonstrated that most municipalities presented CRS.

Assuming that there are n units (municipalities), and each unit uses m inputs to produce s outputs, it would be denoted as $x_{ij}(i=1,2,\ldots,m)$ and $y_{rj}(r=1,2,\ldots,s)$, respectively. To evaluate the eco-efficiency of municipality$_d$, the basic DEA-CCR model proposed by Charnes et al. (1978) is used:

$$Max\, E_d = \sum_{r=1}^{s} u_{rd} y_{rd} \tag{1}$$

s.t.

$$\sum_{r=1}^{s} u_{rd} y_{rj} - \sum_{i=1}^{m} \omega_{id} x_{ij} \le 0$$

$$\sum_{i=1}^{m} \omega_{id} x_{id} = 1$$

$$u_{rd} \ge 0 \qquad r=1,2,\ldots,s$$

$$\omega_{id} \ge 0 \qquad i=1,2,\ldots,m$$

where E_d is the eco-efficiency scores of the municipality$_d$, u_{rd} is the weight of output r, and ω_{id} is the weight of input i, for the evaluated municipality (municipality$_d$). Eco-efficiency scores (E_d) are bounded between 0 and 1. A municipality is considered eco-efficient if the eco-efficiency score equals unity, whereas it is considered inefficient if $0 \le E_d < 1$. The difference between the eco-efficiency score and value of 1 is considered as the potential improvement needed for a municipality to be eco-efficient. Model (1) selects the set of input and output weights that maximize the eco-efficiency of municipality$_d$. Consequently, inputs and outputs are allocated different weights for each evaluated municipality.

The basic premise of the CSW approach is to allocate the same weights to inputs and outputs for all evaluated units. To accomplish this, several approaches have been proposed, such as central values for all weights, maximizing the number of efficient units or maximizing the average of all units (Contreras, 2020). Here, we applied the DEA-CSW approach proposed by Wu et al. (2016), because it considers the degree of satisfaction of the units evaluated to allocate weights to variables. This approach is required for the proposed ranking by the evaluated municipalities to be accepted. This approach also incorporates Pareto-optimal solutions ensuring that the final generated CSW is a unique solution. Consequently, municipalities are ranked in a unique order (Karagiannis, 2024; López-Penabad et al., 2022).

The DEA-CSW model proposed by Wu et al. (2016) assumes that each municipality has its own upper and lower eco-efficiency target. In the DEA-CCR model, weights are allocated to maximize eco-efficiency scores. In comparison, under the CSW approach, the upper eco-efficiency target for a unit is its DEA-CCR eco-efficiency score, which is computed by solving Model (1), that is, $E_j^{max} = E_j$. The minimum eco-efficiency score (E_j^{min}) of each municipality is 0. However, it would not be accepted for any municipality. Therefore, Wu et al. (2016) proposed the following approach to calculate the lower eco-efficiency score:

$$E_j^{min} = min_{d \ne j} \left\{ min_{(\mu_{rd}^*, \varpi_{id}^*)} \frac{\sum_{r=1}^{s} \mu_{rd}^* y_{jr}}{\sum_{i=1}^{m} \varpi_{rd}^* x_{ij}} \right\} \forall j \tag{2}$$

where $(\mu_{rd}^*, \varpi_{id}^*, \nabla i, r)$ is (are) the most favorable set(s) of unit$_d$ weights generated from Model (1). According to Equation (2), the lower eco-efficiency target of a municipality is obtained when it is forced to use a set of weights that is most favorable for another municipality (Wu et al., 2016).

Considering the upper and lower eco-efficiency goals of municipalities, the CSW (W^R) is defined as:

$$W^R = \left\{ (\mu_{rd}, \varpi_{id}) / \sum_{r=1}^{s} \mu_r y_{jr} - E_j^{max} \sum_{i=1}^{m} \varpi_i x_{ij} + s_j^1 = 0 \right. \tag{3}$$

$$\forall j$$

$$\sum_{r=1}^{s} \mu_{rd} y_{jr} - E_j^{min} \sum_{i=1}^{m} \varpi_{rd} x_{ij} - s_j^2 = 0$$

$$\forall j$$

$$\sum_{i=1}^{m} \varpi_i \sum_{j=1}^{n} x_{ij} = n$$

$$\varpi_i \ge 0, \qquad \forall i$$

$$\mu_r \ge 0, \qquad \forall r$$

$$s_j^1 \ge 0, \qquad \forall j$$

$$s_j^2 \ge 0, \qquad \forall j \}$$

In Equation (3), s_j^1 is the bound for inputs for the unit j and s_j^2 is the bound for outputs for the unit j. According to Model (3), all eco-efficiency scores are between their upper and lower eco-efficiency goals. Yet, different sets of common weights could be selected for the eco-efficiency assessment of municipalities. To overcome this potential issue, Wu et al. (2016) proposed the concept of "satisfaction degree" of unit$_d$ for a weighting profile. This parameter is measured as the distance from the proposed eco-efficiency ratio to the eco-efficiency ratio determined using CSW. Each municipality is allowed to select common weights that achieve the upper eco-efficiency goal, E_d^{max}. However, in parallel, it is not possible to select a CSW that results in an eco-efficiency score less or less equal to its lowest efficiency goal, E_d^{min}. Thus, Wu et al. (2016) defined the satisfaction degree of unit$_d$ (ψ_d) as:

$$\psi_d = \frac{\frac{\sum_{r=1}^{s} \mu_{rd} y_{jr}}{\sum_{i=1}^{m} \varpi_{rd} x_{ij}} - E_d^{min}}{E_d^{max} - E_d^{min}} \forall j \tag{4}$$

$\psi_d \in [0,1]$, $\forall d$. A ψ_d equal to 1 means that the selected CSW meets the upper efficiency target of unit$_d$, E_d^{max}. By contrast, a value of 0 for ψ_d means that the selected CSW gives unit$_d$ its lowest efficiency, E_d^{min}.

To define the CSW for the eco-efficiency assessment, the satisfaction degree (Equation 4) for all evaluated units is maximized. To improve the willingness to accept the set of common weights defined, the selected CSW should not result in units with noticeably different satisfaction degrees. The multi-objective programming Equation (5) is thus used to define the CSW of the evaluated municipalities:

$$\max_{\mu,\varpi} \min_{j=1,\dots,n} \frac{s_j^2}{s_j^1 + s_j^2} \tag{5}$$

s.t.

$$\sum_{r=1}^{s} \mu_r y_{rj} - E_j^{max} * \sum_{i=1}^{m} \varpi_i x_{ij} + s_j^1 = 0$$

$$\sum_{r=1}^{s} \mu_r y_{rj} - E_j^{min} * \sum_{i=1}^{m} \varpi_i x_{ij} - s_j^2 = 0$$

$$\sum_{i=1}^{m} \varpi_i \sum_{j=1}^{n} x_{ij} = n$$

$$\varpi_i \geq 0 \quad \forall i$$

$$\mu_r \geq 0 \quad \forall r$$

$$s_j^1 \geq 0 \quad \forall j$$

$$s_j^2 \geq 0 \quad \forall j$$

Model (5) maximizes the satisfaction degrees of all municipalities as follows:

$$\max_{\mu,\varpi} \Phi \tag{6}$$

s.t.

$$\sum_{r=1}^{s} \mu_r y_{rj} - E_j^{max} * \sum_{i=1}^{m} \varpi_i x_{ij} + s_j^1 = 0$$

$$\sum_{r=1}^{s} \mu_r y_{rj} - E_j^{min} * \sum_{i=1}^{m} \varpi_i x_{ij} - s_j^2 = 0$$

$$\sum_{i=1}^{m} \varpi_i \sum_{j=1}^{n} x_{ij} = n$$

$$\frac{s_j^2}{s_j^1 + s_j^2} \geq \Phi$$

$$\varpi_i \geq 0 \quad \forall i$$

$$\mu_r \geq 0 \quad \forall r$$

$$s_j^1 \geq 0 \quad \forall j$$

$$s_j^2 \geq 0 \quad \forall j$$

The definition of CSW to estimate eco-efficiency scores is based on solving Model (6).[2]

3.2 | Municipal solid waste management in Chile

Chile is a Latin-American country with a gross domestic product (GDP) per capita in 2020 of US$ 13,231 in 2020 (INE, 2022a). Therefore, it is considered a middle-income country. According to Chilean national statistics (INE, 2022b), the country has a population of 19.8 million people, of which 42% live in the Metropolitan Region of Santiago, one of the 16 regions in the country. Aysen is a less populated region, which is in the south part of the country, with just 0.5% of the total population. Aysen covers 108,494 km^2 area, whereas the Metropolitan Region of Santiago covers 15,403 km^2 area (INE, 2022b). These figures demonstrate the marked differences in terms of population density in the country. Since 2010 Chile has been part of the Organization for Economic Co-operation and Development (OECD). It was the first South American country to join this organization.

Municipalities are responsible for collecting and treating MSW in Chile. However, in most cases, these services are outsourced to private companies. Informal recyclers also play a relevant role in managing MSW, mainly in the poorest municipalities (Valenzuela-Levi, 2021). MSW is mainly collected door-to-door and landfills are a very common disposal option. According to SINIA (2021), approximately 80% of solid waste in Chile is disposed in landfills. Local and national policies to enhance MSW recycling are emerging and are considered out-of-date compared to those in European Union (EU) countries. The most relevant law to improve the management of solid waste, which follows the waste management hierarchy, is the Law for Promoting Recycling and Extended Producer Responsibility. This law was approved by the Chilean government in 2016 but was not actually launched until mid-2020 (Llanquileo-Melgarejo & Molinos-Senante, 2021).

According to OECD data (OECD, 2022), the generation of MSW per capita in Chile (last available year) was 424 kg/year in 2018, whereas it was 294 kg/year in 2000. Moreover, Chile is one of a few OECD countries where per capita MSW generation increased in the last five years. Thus, policy makers and authorities in Chile must develop and implement more effective policies to prevent MSW generation. MSW recycling in Chile is also emerging as it is not compulsory for local authorities and municipalities to implement independent initiatives based on available municipal budget (Araya-Córdova et al., 2021). According to the SINIM database (SINIM, 2022), the operational expense (OPEX) for MSW management (collection and treatment) at the country level was 448,967 Chilean Pesos per year (CLP/year) (US$528 million per year), whereas it was 208,128 CLP/year (US$ 245 million per year) in 2012. The marked increase in OPEX for MSW management demonstrates the need for municipalities to improve the eco-efficiency in the provision of MSW services.

3.3 | Sample data

Data from 36 municipalities in Chile were used in this study, which represent around 65% of the population of the country. Because MSW recycling in Chile is emerging, only municipalities with formal MSW recycling initiatives were considered. Inputs and outputs were selected based on past practices evaluating the eco-efficiency of municipalities regarding the provision of MSW services (e.g., Romano et al., 2021; Sala-Garrido et al., 2022; Sarra et al., 2017) and on the available data for municipalities in Chile. The OPEX spent by municipalities per year to manage MSW was selected as the input. The SINIM database includes the municipal cost for the collection, transport, recycling, and disposal of MSW. Unsorted waste was considered as an undesirable output, expressed in tonnes per year. Four desirable outputs were selected: (i) recycled paper and cardboard; (ii) recycled glass; (iii) recycled plastic and (iv) recycled organic waste. These four variables were also measured in annual tonnes. Data on cost was collected from the "Sistema National de Información Municipal," and data on MSW generation and treatment was collected from the "Sistema Nacional de Declaración de Residuos". Data from 2018 was used, with Table 1 presenting summary statistics.

4 | RESULTS

Eco-efficiency scores for municipalities in Chile were computed using DEA-CCR and DEA-CSW methods. Based on DEA-CCR, four municipalities had an eco-efficiency score of one, meaning they were eco-efficient (Table 2). However, because they had the same eco-efficiency, it was not possible to rank them. In other words, the DEA-CCR method does not allow effective discrimination of municipalities when ranking them. This is because under this methodological approach, inputs, and outputs weights (Equation 1) are allocated endogenously to boost the eco-efficiency scores of each individual municipality. In contrast, when eco-efficiency scores were estimated using DEA-CSW, only one municipality (Municipality 19) was identified as eco-efficient. This arises from the fact that the weights assigned to inputs and outputs are determined by the concept of the satisfaction degree (Equation 4) and are consistent across all the evaluated municipalities. Therefore, it was ranked as the best municipality (out of the 36 evaluated municipalities) regarding the provision of MSW services. Compared to DEA-CCR, one of the main advantages of DEA-CSW was better discriminatory power (Figure 2, Table 2). For example, the ranking of 22 out of 36 municipalities (61.1%) changed when eco-efficiency scores were computed using DEA-CSW compared to DEA-CCR (Figure 1). This result demonstrates the strength of the performance assessment method used when benchmarking the eco-efficiency of municipalities in the provision of MSW services. This issue is highly relevant when benchmarked results are used for regulatory purposes and/or defining investment priorities.

The average eco-efficiency for the 36 municipalities in Chile was 0.413 and 0.377 when scores were computed using the DEA-CCR and DEA-CSW, respectively. Thus, on average, municipalities could increase their recycling rates by 58.7% (DEA-CCR) and 62.3% (DEA-CSW) under

TABLE 1 Summary statistics of variables.

Variables	Unit of measurement	Mean	Std. dev.	Minimum	Maximum
Total, costs	CLP/year	3,295,618	3,252,562	24,857	14,574,943
Paper & cardboard recycled	Tons/year	367	1068	0	6023
Glass recycled	Tons/year	413	642	10	2759
Plastic recycled	Tons/year	91	307	0	1842
Organic waste recycled	Tons/year	1949	5568	0	29,369
Unsorted waste	Tons/year	70,771	78,474	400	360,451

Note: Number of observations: 36.

TABLE 2 Eco-efficiency scores of Chilean municipalities based on the DEA-CCR and DEA-CSW methods.

Chilean municipality	Eco-efficiency score DEA-CCR	Eco-efficiency score DEA-CSW
Municipality 8	1.000	0.952
Municipality 14	1.000	0.880
Municipality 19	1.000	1.000
Municipality 21	1.000	0.829
Municipality 25	0.616	0.512
Municipality 26	0.565	0.468
Municipality 27	0.523	0.502
Municipality 2	0.508	0.477
Municipality 36	0.504	0.447
Municipality 6	0.474	0.406
Municipality 33	0.443	0.397
Municipality 32	0.438	0.426
Municipality 20	0.434	0.402
Municipality 11	0.415	0.390
Municipality 22	0.414	0.363
Municipality 13	0.405	0.384
Municipality 1	0.387	0.360
Municipality 18	0.378	0.361
Municipality 31	0.351	0.316
Municipality 10	0.339	0.321
Municipality 24	0.321	0.306
Municipality 4	0.305	0.277
Municipality 29	0.288	0.262
Municipality 35	0.285	0.263
Municipality 5	0.277	0.250
Municipality 28	0.270	0.258
Municipality 7	0.258	0.214
Municipality 15	0.241	0.224
Municipality 30	0.227	0.224
Municipality 12	0.213	0.203
Municipality 3	0.194	0.180
Municipality 23	0.192	0.177
Municipality 9	0.176	0.166
Municipality 34	0.156	0.145
Municipality 17	0.145	0.137
Municipality 16	0.127	0.124

the same operational costs if they were eco-efficient. The minimum eco-efficiency score was very similar for both approaches (0.127 for DEA-CCR and 0.124 for DEA-CSW) and corresponded to the same municipality (Municipality 16), which was identified as the least eco-efficient in the provision of MSW services.

The municipality with the best performance (Municipality 19) is a medium sized city (68,401 people) (SINIM, 2022), located at the centre of the country (Valparaiso Region). Within the last 5 years, this municipality received funds from the Chilean Government (SUBDERE, Secretary of Regional and Administrative Development) to develop and implement plans to promote the separative collection of solid waste. MSW generation per capita in this municipality was 385.9 kg/year for 2018, which was 13% lower than the average in Chile (436.6 kg/year). However, while this variable is not used to estimate eco-efficiency scores, it shows that people from Municipality 19 exhibited relatively good behavior regarding MSW issues. The percentage of recycled MSW for this municipality was 13.1% for 2018. Compared to recycling rates in European countries, this value was very low, and in the context of Chile, was considered exceptional. Of note, Valenzuela-Levi (2021) showed that during 2013–2017, the average

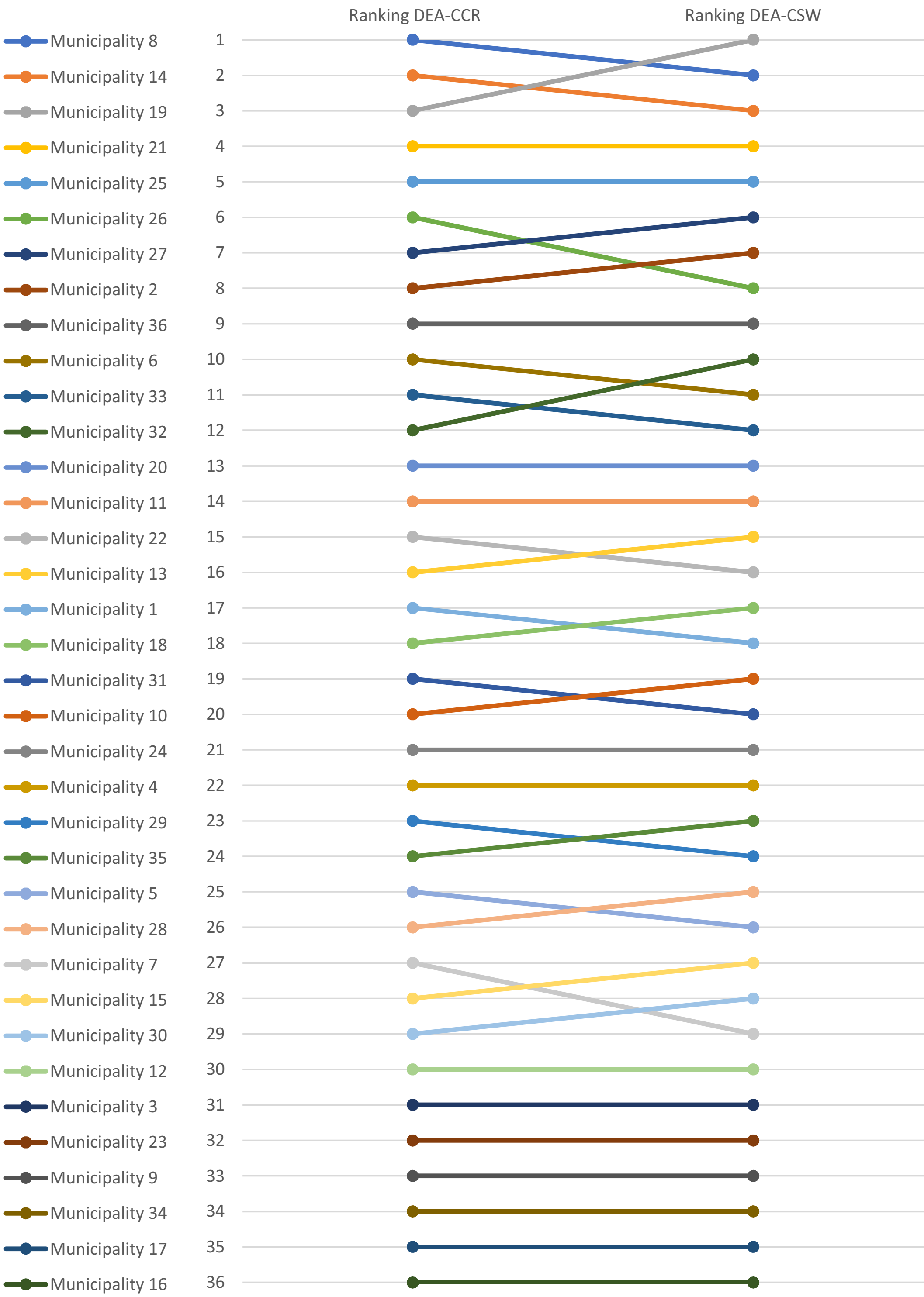

FIGURE 2 Ranking of Chilean municipalities based on eco-efficiency scores estimated using DEA-CCR and DEA-CSW methods.

recycling rate in Chile was 1.7%. The operational costs of the provision of MSW services are a relevant variable for estimating eco-efficiency scores. The annual average costs for providing MSW services for Municipality 19 was 12,912 CLP/ton in 2018. This value was notably lower compared to the average operational cost for the sample of evaluated municipalities in Chile (48,335 CLP/ton).

In addition to the larger discriminatory power, a relevant positive feature of DEA-CSW is that the weights allocated to inputs and outputs are common for all evaluated units (Hammami et al., 2022). The weights allocated to all variables considered to estimate eco-efficiency scores under DEA-CCR and DEA-CSW are presented in Table 3.

TABLE 3 Weights allocated to inputs and outputs in DEA-CCR and DEA-CSW models.

Weights allocated	Total, costs (%)	Paper & cardboard recycled (%)	Glass recycled (%)	Plastic recycled (%)	Organic waste recycled (%)	Unsorted waste (%)
DEA-CSW	0.18	62.63	15.01	15.93	4.10	2.15
DEA-CCR						
Municipality 1	21.00	0.00	1.93	1.40	0.00	75.67
Municipality 2	28.65	0.00	4.19	0.21	10.46	56.49
Municipality 3	48.65	0.00	2.95	0.00	0.00	48.40
Municipality 4	17.63	0.00	0.60	0.00	0.14	81.63
Municipality 5	48.70	0.00	0.30	0.03	0.00	50.97
Municipality 6	28.51	19.17	0.00	0.00	0.00	52.32
Municipality 7	43.60	0.00	10.15	0.00	0.00	46.25
Municipality 8	36.17	47.28	0.00	0.00	8.82	7.73
Municipality 9	18.97	0.00	3.33	0.15	0.00	77.55
Municipality 10	22.72	0.00	2.54	0.12	0.00	74.62
Municipality 11	58.99	1.32	0.00	0.10	0.00	39.59
Municipality 12	47.66	0.00	3.04	0.32	0.72	48.26
Municipality 13	24.75	4.95	0.00	0.00	0.00	70.30
Municipality 14	85.95	0.00	12.54	0.00	0.51	1.00
Municipality 15	35.66	0.00	2.29	0.00	0.00	62.05
Municipality 16	48.72	0.00	6.42	0.00	1.90	42.96
Municipality 17	13.73	7.00	0.00	0.35	0.00	78.92
Municipality 18	43.65	0.00	2.47	0.22	0.00	53.66
Municipality 19	54.68	0.00	3.95	0.25	0.00	41.12
Municipality 20	15.72	0.00	2.40	0.21	0.00	81.67
Municipality 21	0.00	0.00	0.00	50.00	0.00	50.00
Municipality 22	42.14	0.00	6.42	0.00	0.00	51.44
Municipality 23	36.66	9.00	0.00	0.00	0.00	54.34
Municipality 24	45.29	1.87	0.00	0.18	0.00	52.66
Municipality 25	23.01	44.02	0.00	0.00	0.00	33.02
Municipality 26	15.20	0.00	2.49	0.00	35.52	46.79
Municipality 27	27.76	1.34	0.00	0.23	2.13	68.54
Municipality 28	28.96	0.00	2.03	0.00	0.00	69.01
Municipality 29	29.99	0.00	0.88	0.00	0.00	69.13
Municipality 30	43.06	0.00	3.94	0.32	0.00	52.68
Municipality 31	27.40	0.00	0.21	0.02	0.26	72.11
Municipality 32	22.32	0.00	8.07	0.00	0.00	69.61
Municipality 33	21.65	1.90	0.00	0.26	37.52	38.68
Municipality 34	15.76	0.00	2.50	0.00	1.20	80.54
Municipality 35	37.68	0.00	2.21	0.24	0.00	59.87
Municipality 36	57.73	0.00	0.06	0.01	0.00	42.20

When using DEA-CSW, recycled paper & cardboard is the most relevant variable for estimating eco-efficiency scores because this variable was given a 62.6% weighting. By contrast, the weight allocated to operational costs was just 0.18%. Nevertheless, all variables included in the DEA model had a weighting larger than 0.0%. Consequently, they were considered to estimate eco-efficiency scores effectively. A different situation was observed when eco-efficiency scores were estimated using DEA-CCR. In this case, none of the 36 evaluated municipalities had positive weights for any of the inputs and outputs. In other words, when eco-efficiency scores were computed, not all variables defined in the model contributed to performance assessment because some of the weights allocated to them were 0.0%. This issue was particularly relevant for recycled paper & cardboard and recycled organic waste because 0.0% weight was allocated to these

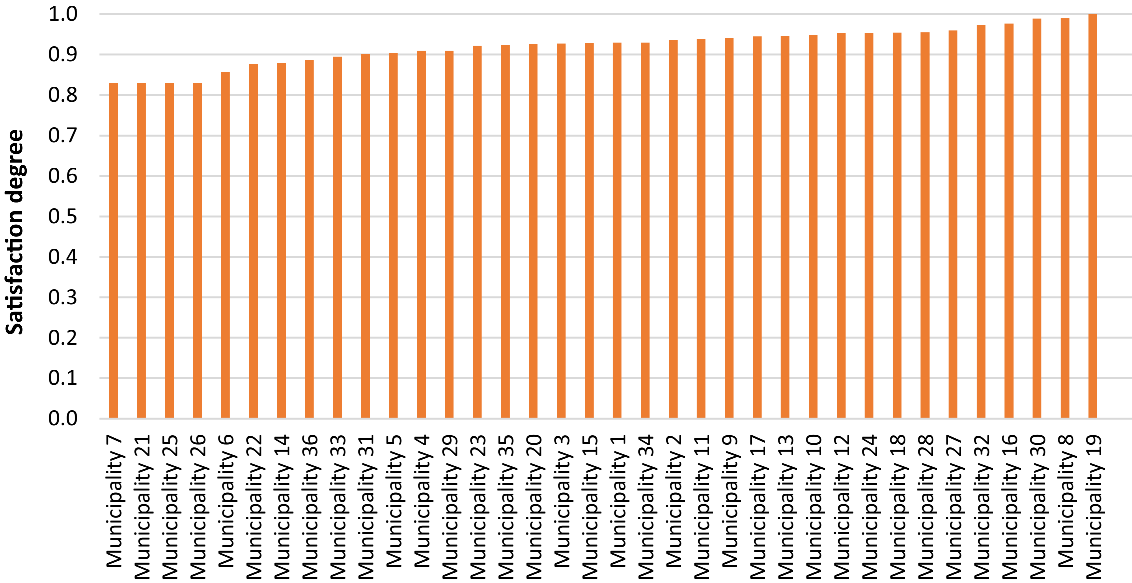

FIGURE 3 Satisfaction degrees of the Chilean municipalities evaluated.

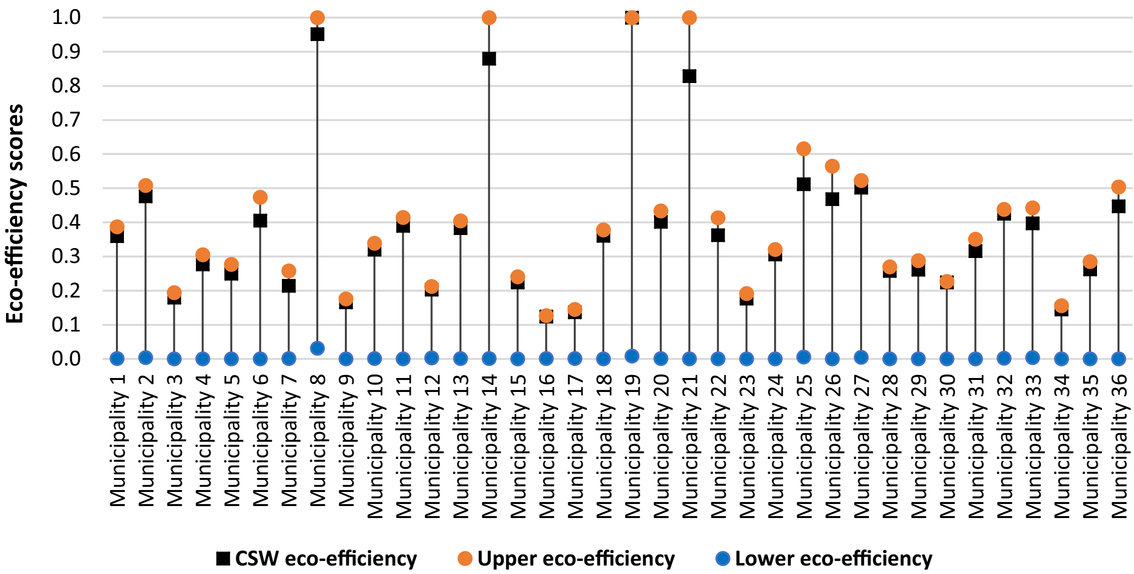

FIGURE 4 Upper, lower, and common set weights (CSW) eco-efficiency scores for the Chilean municipalities evaluated.

variables in municipalities 25 and 26. By contrast, the unsorted waste variable had a positive weight for all analyzed municipalities. In the DEA-CCR model the weights allocated to some variables are zero because as it is shown in Equation (1) weights are endogenously assigned to maximize eco-efficiency scores. Consequently, if a municipality displays subpar performance in certain variables, the model inherently assigns a zero weight to that specific variable, ensuring it does not negatively impact its eco-efficiency score. As a result, large variability among municipalities arises in the weights allocated to the same variable. Large variability in the weights allocated to inputs and outputs hinders the use of eco-efficiency scores for benchmarking the performance of units (Contreras, 2020), which were municipalities in this case study.

For DEA-CSW, weights are allocated based on the degree of satisfaction (termed satisfaction degree) (Equation 4) of each unit (municipality) (Soltanifar et al., 2022) and therefore, none of the variables present zero weight. In our empirical application, the satisfaction degree ranged between 0.829 and 1.000 (Figure 3). From a theoretical perspective, the satisfaction degree ranges between 0 and 1. All 36 evaluated municipalities had high satisfaction with common weights allocated to inputs and outputs. From a policy perspective, this result indicates that when eco-efficiency scores are used for regulatory purposes, eco-efficiency estimations would be accepted by most municipalities, as the satisfaction degrees is high. As expected, the satisfaction degree of the best performing municipality (Municipality 19) was 1.000 indicating full satisfaction with the weights allocated to variables considered to estimate eco-efficiency scores. In contrast, the lowest satisfaction degree (0.829) was obtained for Municipalities 7, 21, 25 and 26, which had medium to low eco-efficiency scores.

Based on a previously presented method, DEA-CSW allows the computation of eco-efficiency, lower eco-efficiency, and common weight eco-efficiency scores as it is shown in Figure 4. The minimum estimated eco-efficiency scores were lower than 0.05 for the 36 evaluated municipalities (Figure 4). In contrast, based on the maximum eco-efficiency estimation, four municipalities were eco-efficient. Thus, three additional municipalities were eco-efficient (Municipality 8, 14, 21) compared to DEA-CSW eco-efficiency estimates (Table 2). These municipalities were the most negatively affected for allocating common weights because they were not considered within the group of best performers under DEA-CSW. For most of the evaluated municipalities, the eco-efficiency gap between the upper and CSW scores was small (Figure 3). For instance, the maximum value was 0.171 for 33 out of 36 municipalities (91.7%), with a gap lower than 0.1, which was correlated with the high satisfaction degree of municipalities (Figure 3). In other words, our case study showed that the allocation of common weights to inputs and outputs did not noticeably "penalize" the eco-efficiency scores computed for municipalities in Chile, but allowed them to be benchmarked according to a common basis.

5 | DISCUSSION

The use of the DEA-CSW methodology in estimating eco-efficiency has provided a clear and objective ranking of the municipalities based on their economic and environmental performance. This approach ensures that the weights assigned to the variables for calculating eco-efficiency are uniform across all evaluated units, that is, the municipalities. Such a standardized approach enhances the comparability and fairness of the assessment, making the results more palatable for regulatory purposes and likely to be more readily accepted by the municipalities involved. This uniformity in weighting can allows for the development of equitable and transparent regulatory frameworks, potentially facilitating the implementation of targeted improvements and policy interventions aimed at enhancing eco-efficiency across municipalities.

The eco-efficiency scores, as estimated using both the DEA-CCR and DEA-CSW models (0.413 and 0.377, respectively), reveal that Chilean municipalities exhibit poor economic and environmental performance in their management of MSW. This finding aligns with previous research, as demonstrated by Llanquileo-Melgarejo et al. (2021), who calculated an average eco-efficiency score of 0.540 for a sample of 298 Chilean municipalities providing MSW services. In a smaller sample comprising 142 Chilean municipalities, Llanquileo-Melgarejo and Molinos-Senante (2021) reported an average eco-efficiency score of 0.580. Both prior studies (Llanquileo-Melgarejo et al., 2021; Llanquileo-Melgarejo & Molinos-Senante, 2021) employed DEA models that allocate flexible weights to inputs and outputs, specifically the DEA-CCR model. Consequently, their eco-efficiency score estimations also support the primary finding of this study, which is that the DEA-CCR approach tends to overestimate eco-efficiency scores in comparison to the DEA-CSW approach.

Assessing eco-efficiency for sustainable waste management is crucial in today's era of rapid urbanization, population growth, and relevant environmental challenges (Amaral et al., 2022). Eco-efficiency focuses on diminishing the environmental repercussions of MSW while amplifying the economic worth of resources. Hence, this evaluation is paramount for sustainable waste management. It aids in lessening environmental damages, enhancing economic productivity, adhering to regulatory norms, and bolstering the circular economy (Llanquileo-Melgarejo & Molinos-Senante, 2021). Previous eco-efficiency estimations in past research encountered relevant limitations related to their discriminatory power. From a policy perspective, this issue arises because more than one municipality could be classified as eco-efficient, making it difficult to unequivocally rank the assessed municipalities. Furthermore, municipalities had the flexibility to assign different weights to the variables encompassing the eco-efficiency synthetic indicator. Consequently, municipalities were evaluated under varying criteria, raising questions about the validity of performance comparisons. Our study addresses both limitations by employing a DEA-CSW method to evaluate the eco-efficiency of municipalities in their MSW management. This approach enables the identification of a single municipality as the top performer and facilitates the comparison of eco-efficiency scores among municipalities using a standardized set of criteria, thus enhancing the robustness of performance assessments.

The findings of this research have relevant implications for MSW regulators and policymakers, offering insights to elevate the management of MSW. The DEA-CCR method demonstrates restricted differentiating ability, complicating the task of ranking municipalities based on their eco-efficiency in MSW service provision. Using this methodology, four municipalities emerged as eco-efficient, suggesting that these municipalities' practices could be adopted elsewhere due to their similar performance metrics in MSW services. However, it is critical to note that these municipalities were deemed eco-efficient primarily because certain variables were assigned zero weights. In practical terms, this means that these variables were sidelined in eco-efficiency evaluations. This observation is especially crucial from a policymaking viewpoint, as the eco-efficiency assessment was skewed towards variables where the municipality performed well, instead of incorporating all variables deemed pertinent by the regulator. By employing the DEA-CSW approach for gauging eco-efficiency scores, this limitation is rectified. According to this methodology, only one municipality (Municipality 19) was classified as eco-efficient, as shown in Table 2. Consequently, the MSW regulator can now clearly identify the front-runner, offering a performance standard for the rest of the municipalities to follow.

Another relevant finding from a policy perspective is that when using the DEA-CSW approach, all variables (both inputs and outputs) that encompass the concept of eco-efficiency receive positive weights. This ensures that they are genuinely factored in when determining eco-efficiency scores. A distinct advantage of DEA-CSW, particularly significant when these scores are utilized for regulatory objectives, is the consistent weighting for inputs and outputs across all municipalities. With this standardized method, municipalities are more likely to accept and trust the benchmarking outcomes. This anticipated acceptance is further reinforced in our specific case study where every assessed municipality reported high degrees of satisfaction.

Previous studies evaluating the eco-efficiency of MSW providers employed DEA models, allocating weights to inputs and outputs that maximize the eco-efficiency score for each municipality (DEA-CCR). While this approach provides large flexibility, it lacks discriminatory power, with the weights allocated to variables potentially differing across units, hindering comparison. These issues are relevant when eco-efficiency scores are used for regulating MSW service providers. Thus, in our study the DEA-CSW method was proposed and applied, for the first time, to assess the eco-efficiency of a sample of municipalities regarding the management of MSW. This methodological approach allocates weights to variables based on the satisfaction degree, which gauges the gap between the minimum and maximum eco-efficiency scores determined at the unit level. As a result, all the assessed municipalities maintain uniform weights for inputs and outputs, which streamlines the benchmarking process between them.

This study serves as a pioneering contribution to the application of DEA methods that assign common weights to variables when assessing the eco-efficiency of MSW service providers. However, several avenues for expanding this research beckon future exploration. Firstly, there is merit in examining the dynamic eco-efficiency of MSW service providers, that is, tracking shifts in eco-productivity over years through the lens of the DEA-CSW methodology. Such an examination would help determine the extent and direction of performance evolution among municipalities over time. This data proves invaluable for policy makers keen to institute measures for sustainable MSW management. Secondly, the eco-efficiency scores of municipalities could be explored using alternative multicriteria methodologies such as the analytic hierarchy process (AHP) (Saaty, 1990) or goal programming (Blancas et al., 2010). Engaging with these methods will facilitate a comparative review, highlighting potential methodological dependencies. Lastly, a subsequent phase of research, rooted in regression analysis, may be pursued. The goal here would be to uncover potential exogenous variables, external to the management practices of municipalities, which might bear an impact on eco-efficiency in providing MSW service.

6 | CONCLUSIONS

Improving municipal solid waste (MSW) management is one of the targets defined by the Sustainable Development Goals. Assessing eco-efficiency for sustainable solid waste management is an essential step in understanding and improving environmental performance, while also achieving economic benefits. Eco-efficiency encourages the efficient use of resources and minimizing environmental impact. Moreover, by improving eco-efficiency, municipalities can reduce costs associated with waste treatment and disposal. A focus on eco-efficiency promotes the idea of a circular economy, where products and materials are reused, refurbished, and recycled. From a policy perspective, policymakers and regulators can use eco-efficiency assessments as a foundation to develop new regulations or guidelines for sustainable waste management.

The comparison of eco-efficiency scores based on Charnes, Cooper and Rhodes Data Envelopment Analysis (DEA-CCR) and DEA common set of weights (DEA-CSW) approaches, which is the first objective of the study, illustrated that from the DEA-CCR method four municipalities were identified as eco-efficient, whereas the DEA-CSW approach singled out just one municipality as eco-efficient. Notably, this sole municipality ranked highest among all municipalities assessed. Delving into the second objective, it became evident that the municipality rankings based on eco-efficiency varied depending on the chosen DEA model. Addressing the third objective, discrepancies were observed in the weights assigned to inputs and outputs between the DEA-CCR and DEA-CSW methods, which have policy implications. Under DEA-CCR, some municipalities were allocated a weight equal to zero for certain variables used to estimate eco-efficiency scores. Consequently, these variables were excluded from the eco-efficiency assessment, resulting in the regulator failing to evaluate eco-efficiency appropriately.

From a policy formulation standpoint, the insights gleaned from this study underscore the critical importance of applying common weights across all municipalities in the context of eco-efficiency evaluations. In pursuit of a standardized assessment, the DEA-CSW methodology emerges as a commendable choice, not only for its inherent accuracy but also for the increased likelihood of its findings being embraced by the municipalities under evaluation. Eco-efficiency metrics derived from such a harmonized approach can serve as invaluable compass points for regulators and policy architects. These quantifiable measures can steer the development and refinement of regulations and initiatives centered around the sustainable management of MSW.

While the innovative methodology and the insights yielded by this study are noteworthy, it is important to acknowledge certain limitations. Firstly, owing to constraints in statistical data availability, the eco-efficiency scores were estimated from a singular input, specifically the total costs associated with managing MSW. Consequently, the research results did not pinpoint distinct cost elements where municipalities could potentially implement measures to enhance eco-efficiency. Secondly, from a methodological vantage point, both the DEA_CCR and DEA_CSW models sidestep the possibility of data errors. This is attributable to DEA's deterministic nature. Lastly, the eco-efficiency scores were derived using data from 2018. This means that the findings do not shed light on the evolving performance dynamics of municipalities over time. Incorporating data spanning multiple years would certainly augment the analysis, offering insights into eco-efficiency trends in the realm of MSW service provision.

While this study contributes significantly to the field, future research could expand on this foundation in several ways. Firstly, investigating the dynamic eco-efficiency of MSW service providers through DEA-CSW methodology could offer insights into how eco-productivity evolves over time. Such longitudinal analyses are crucial for understanding performance trends and assisting policymakers in developing sustainable MSW management strategies. Secondly, employing alternative multicriteria methodologies could provide a broader perspective on the eco-efficiency of municipalities. This comparative analysis could reveal the strengths and limitations of different methodologies and their impact on eco-efficiency assessments. Lastly, integrating regression analysis in future research could identify exogenous factors influencing MSW service eco-efficiency. By exploring these avenues, subsequent research can build on this study's findings, offering a more comprehensive and nuanced understanding of eco-efficiency in MSW services and informing more effective policy and management decisions.

AUTHOR CONTRIBUTIONS

María Molinos-Senante: Conceptualization, Writing—Review & Editing; **Alexandros Maziotis**: Methodology, Software, Writing—Original Draft; **Ramón Sala-Garrido**: Data Curation, Writing—Review & Editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data will be available upon a reasonable request.

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ENDNOTES

[1] FDH constructs a nonconvex frontier with a staircase shape, because it assumes that each unit has just one peer (Ferreira et al., 2018).

[2] Model (6) is nonlinear and, therefore, cannot be directly solved. To overcome this limitation, Wu et al. (2016) proposed two algorithms that allow CSW to be estimated. These algorithms are presented in the Data S1.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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