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Eco-efficiency approach in sustainable waste management: An uncertainty analysis for Chile

Ramon Sala-Garrido [a], Manuel Mocholi-Arce [a], Alexandros Maziotis [b], Maria Molinos-Senante [c,d,*]

[a] Departamento de Matemáticas para la Economía y la Empresa, Universidad de Valencia, Avd. Tarongers S/N, Valencia, Spain
[b] School of Business, New York College, 38 Amalias Avenue, Syntagma, Greece
[c] Institute of Sustainable Processes, Universidad de Valladolid, C/ Mergelina S/N, Valladolid 47011, Spain
[d] Department of Chemical Engineering and Environmental Technology, Universidad de Valladolid, C/ Mergelina S/N, Valladolid 47011, Spain

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ABSTRACT

Municipalities require eco-efficiency in managing solid waste to enhance sustainability and achieve a circular economy. Despite the relevance of waste statistics, there is high data uncertainty, which limits attempts to benchmark eco-efficiency in this sector. To overcome this limitation, the data envelopment analysis tolerance method was used to evaluate the eco-efficiency of solid waste management for a sample of municipalities in Chile. For each municipality, a composite indicator embracing operational cost, recycled waste rates, and non-valorized waste rate was estimated. Data uncertainty was integrated in the assessment by simulating 729 scenarios for each municipality. Average eco-efficiency of the sample was 0.180, demonstrating the extremely poor performance of the municipalities in sustainable waste management. However, the eco-efficiency scores varied across municipalities, indicating differences in local capacity to develop and implement strategies for promoting circular economy. Large potential to improve eco-efficiency estimated in this study clearly shows that current solid waste management policies are not suitable for achieving circular economy objectives in Chile, thus alternative approaches should be adopted to enhance sustainable waste management.

1. Introduction

The circular economy is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing, and recycling existing materials and products for as long as possible (European Commission, 2023). This economy has undergone a paradigm shift from the depletive "produce-consume-dispose" model of the linear economy to the "reduce-reuse-recovery-recycle-redesign-remake" model (Sharma et al., 2021). Sustainable Waste Management (SWM) is an integral part of both the circular economy and sustainability (Halkos and Aslanidis, 2023a). Global waste is expected to grow from 2.01 billion tons at present to 3.4 billion tons by 2050 (Kaza et al., 2018). The generation of waste incurs costs in its collection, treatment, and disposal. It also contributes to various environmental issues, such as greenhouse gas emissions and air, ground, and water pollution (Fan et al., 2020). Effective and sustainable municipal solid waste (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 (Guerrero et al., 2013; Deus et al., 2022).

Recent studies have highlighted the relevance of efficiency assessments of MSW management in the transition towards a circular economy, and in fulfilling its objectives (Cerciello et al., 2019; Lombardi et al., 2021). Eco-efficiency is defined as the production of more goods (products) and services with fewer resources (inputs) and lower environmental impact (Beltrán-Esteve et al., 2017). The prefix "eco" represents environmental and economic issues, with eco-efficiency assessments providing relevant information from both economic and environmental perspectives (Lo Storto, 2021) towards implementing a circular economy for SWM. Previous studies evaluated the eco-efficiency of municipalities in managing MSW in different countries such as Italy (Guerrini et al., 2017; Sarra et al., 2017, 2019; Romano et al., 2020, 2021; Romano and Molinos-Senante, 2020); Spain (Delgado-Antequera et al., 2021); Chile (Llanquileo-Melgarejo and Molinos-Senante, 2021; Llanquileo-Melgarejo et al., 2021;

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[*] Corresponding author at: Institute of Sustainable Processes, Universidad de Valladolid, C/ Mergelina S/N, Valladolid 47011, Spain.
E-mail address: maria.molinos@uva.es (M. Molinos-Senante).

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Molinos-Senante et al., 2022a, 2022b; Sala-Garrido et al., 2022) or Portugal (Amaral et al., 2022).

The eco-efficiency of managing MSWs has previously been evaluated using data envelopment analysis (DEA). This approach uses the input and output data of municipalities to construct the eco-efficient frontier (Simoes et al., 2012). The distance of municipalities from the frontier shows their relative eco-inefficiency (Ye et al., 2022). However, DEA is deterministic, whereby it is limited when dealing with imprecise data (Struk and Boda, 2022). It might be a relevant limitation in the framework of MSW where having precise data is challenging (UNECE, 2017). To address this data uncertainty, some studies have used partial frontier techniques, such as order-m and order-α, to assess the economic efficiency of the solid waste sector (Simoes et al., 2012; Pérez-López et al., 2016; Struk and Boda, 2022). Romano et al. (2021) and Amaral et al. (2022) employed this approach to assess the eco-efficiency of municipalities in managing MSW in Italy and Portugal, respectively. Partial frontier techniques are less sensitive to outliers and allow the inclusion of environmental variables in efficiency assessments. However, selecting an appropriate "m" value is challenging because it affects efficiency scores (Da Cruz and Marques, 2014; Molinos-Senante and Sala-Garrido, 2019). As an alternative to this approach, Simoes et al. (2010, 2012), Benito et al. (2011, 2014), Salazar-Adams (2021), and Molinos-Senante et al. (2022b) used the double bootstrap DEA method, developed by Simar and Wilson (2007), to assess the performance of municipal waste management systems.

Traditional DEA models have been extended in various ways to integrate data uncertainty in efficiency assessment, with the DEA-tolerance model by Bonilla et al. (2004) being of particular interest. This DEA-tolerance model captures uncertainty by constructing intervals of data (Dyson and Shale, 2010), and incorporating statistical data tolerance (Yadav et a., 2022). Selected feasible input-output combinations of each unit are evaluated to relative selected combinations for other units based on the defined tolerance (Dong et al., 2017). Hence, multiple scenarios are simulated for each unit by integrating potential data variability in the efficiency assessment (Sala-Garrido and Molinos-Senante, 2020). DEA-tolerance has some relevant positive features. First, it is simpler to be implemented and faster when compared to the double bootstrap method, which provides similar results (Bonilla et al., 2004). Second, it is less subjective than fuzzy method because the definition of fuzzy sets is not required (Dong et al., 2017). Third, combining it with the indicators proposed by Boscá et al. (2011) allows ranking units integrating uncertainty. The DEA-tolerance approach has been successfully applied to assess the eco-efficiency of wastewater treatment plants (Dong et al., 2017; Gómez et al., 2018; Ramírez-Melgarejo et al., 2021).

Because a circular economy based on SWM is integral towards promoting the three cornerstones of sustainable development (Sharma et al., 2021), establishing the eco-efficiency of municipalities in MSW management has become a major focus. Data on waste and associated statistics are of high policy interest in meeting Sustainable Development Goals (SDGs). However, the concepts, definitions, and methodologies used lack standardization (UNECE, 2017), hindering rigorous performance assessments.

This study first aimed to assess the sustainability of MSW management by computing the eco-efficiency of a sample of municipalities and integrating data uncertainty. Using the DEA-tolerance method, 729 scenarios were simulated for 44 municipalities in Chile. We then used 729 simulated eco-efficiency scores to generate a robust benchmark for the sampled municipalities. Chile is a relevant case study because in 2016, the Law for Promoting Recycling and Extended Producer Responsibility was adopted. The main objective of this law was: "to incorporate the valorization of byproducts as a fundamental element in the management of solid waste and to introduce economic instruments as a tool to increase the levels of waste recycling." The adoption of this law generated a paradigm shift in the management of solid waste from a linear approach to a circular economy. However, the positive effects of its implementation are still limited because the Law was launched mid-2020 (Llanquileo-Melgarejo and Molinos-Senante, 2021).

This study makes a significant contribution to the field of SWM by integrating the DEA method with uncertainty evaluation to estimate the eco-efficiency of MSW service providers. This innovative methodological approach stands out for several reasons: i) The eco-efficiency of each municipality is evaluated under 729 different scenarios. This extensive range of scenarios provides a more thorough and nuanced assessment of eco-efficiency, considering a wide array of possible conditions and outcomes. This approach acknowledges and addresses the inherent uncertainties and variabilities in waste management operations: ii) The study is pioneering in its approach to categorically rank municipalities based on both economic and environmental performance. This dual focus is crucial as it balances the economics of waste management with environmental sustainability and; iii) The insights gained from this unique ranking system are invaluable for policy formulation. By understanding how municipalities perform in terms of eco-efficiency, policymakers can develop targeted strategies to improve waste management practices. This is particularly relevant in the context of achieving targets related to waste management under the SDGs.

The structure of the paper is organized as follows: Section 2 offers a concise review of literature about the role of managing MSW in achieving SDGs targets. Section 3 delves into the methodology utilized in this study. This is followed by an examination of the sample data in Section 4. Section 5 highlights the principal findings of the research. The paper concludes with a final section that encapsulates the study's key conclusions and implications.

2. The relevance of SWM in the framework of SDGs: a literature review

The United Nations' SDGs highlight the significance of waste management at both municipal and national levels, as reflected in various SDG targets and indicators. These targets encompass a range of objectives, such as ensuring access to basic services (Target 1.4), improving water quality by eliminating dumping (Target 6.3.), managing municipal solid waste effectively (Target 11.6), reducing food waste (Target 12.3), addressing issues related to chemicals and hazardous waste including e-waste (Target 12.4), promoting recycling (Target 12.5), and tackling marine litter (Target 14.1) (Maalouf and Agamuthu, 2023). The process of MSW management begins with the collection of solid waste. The optimization of solid waste collection (SWC) is intricately linked to 10 out of the 17 SDGs (Hannan et al., 2020). Previous studies have investigated the connection between SWC and various SDG targets finding that effective SWC can contribute to water protection (SDG 6.3) (Chandra Manna et al., 2018), reduce greenhouse gas emissions (SDG 13) (Rajaeifar et al., 2017), prevent waste from entering oceans (SDG 14.1) (Luttenberger, 2020), and improve air quality (SDG 11.6) (Azevedo et al., 2019).

A significant portion of MSW (approximately 40 %) is organic, making it suitable for anaerobic digestion (AD) and composting (Soni et al., 2022). Some studies have underscored the role of AD in advancing various SDGs. Piadeh et al. (2014) conducted a comprehensive literature review and concluded that AD technology contributes to all 17 SDGs. Research has also focused on biogas production, emphasizing its role in reducing reliance on natural energy resources (SDG 7) and addressing climate change (SDG 13) (Obaideen et al., 2022; Welfle, Roder, 2022). Additionally, Mancini and Raggi (2021) discussed how waste-to-energy technologies can support SDG 11 by fostering sustainable cities and communities, reducing landfill waste, and recovering valuable resources from waste.

In exploring the connection between performance assessment and SDGs, Halkos and Aslanidis (2023b) evaluated the productivity change in MSW management in various countries including Italy, Cyprus, Spain, Greece, France, Croatia, Slovenia, and Malta. This assessment aimed to analyze the contribution of these countries to SDGs 12.1.1, 12.2.2, 12.7.1, and 12.8.1.

3. Methodology

3.1. Eco-efficiency estimation

Design Science Research Methodology (DSRM) creates and evaluates artefacts intended to solve identified organizational problems (Gregorio et al., 2021). These artefacts should exhibit two essential characteristics: relevance and novelty (Tsolas et al., 2020). Relevance is ensured through the methodology proposed, which integrates uncertainty in assessing eco-efficiency in the provision of MSW services. This represents a novel approach as previous studies on eco-efficiency in MSW services have primarily focused on the deterministic nature of the DEA method and did not incorporate uncertainty. Furthermore, DEA combined with DSRM (DEA + DSRM) follows a structured sequence of activities essential in the artefact creation process (Charles et al., 2019). DSRM involves six main steps, which are adapted for this study as follows (Peffers et al., 2007; Chou et al., 2013):

i) problem identification and motivation: deterministic nature of DEA and the need of integrating data uncertainty in assessing the eco-efficiency of MSW service providers.
ii) definition of the objectives for a solution: development of an eco-efficiency indicator that integrates data uncertainty and allows ranking municipalities under different scenarios.
iii) design and development: integration of tolerance values in DEA models according to the description provided below.
iv) demonstration: case study for a sample of 44 Chilean municipalities.
v) evaluation: comparison of the eco-efficiency scores estimated under the 729 scenarios assessed with the "original" scenario which does not integrate data uncertainty.
vi) communication: presentation of the results to waste managers.

A DEA tolerance model was used to compute eco-efficiency by integrating data uncertainty. DEA is a non-parametric technique that is based on linear programming, which uses the inputs and outputs of evaluated units (municipalities in this case study) to construct an efficient production frontier (Cooper et al., 2011). The units located on the frontier are efficient because they use a minimum of inputs to produce given outputs (input orientation), or they use given inputs to generate maximum outputs (output orientation) (Sala-Garrido and Molinos-Senante, 2020).

The DEA approach has also been used to evaluate eco-efficiency by integrating environmental impacts as undesirable outputs of the production process (Kuosmanen and Kortelainen, 2005). In this context, the eco-efficiency synthetic index is estimated using DEA to integrate the three dimensions of eco-efficiency. These three dimensions are: (1) recycled waste as a desirable output (service value); (2) operational costs as an input (resource consumption); and (3) non-valorized waste as an undesirable output (environmental impact) (Chiang and Lee, 2022). Eco-efficiency scores that are estimated using the DEA method range between 0 and 1 (Deus et al., 2022). A municipality is eco-efficient when its score is equal to 1. If the eco-efficiency score is below 1, the municipality is eco-inefficient, with the capacity to improve performance in relation to the best performers, such as those municipalities located on the efficient production frontier (Wang and Feng, 2020).

The DEA-tolerance approach is based on constructing intervals for data that are then used to model eco-efficiency scenarios (Dong et al., 2017). This procedure allows data uncertainty to be reduced because it provides information on possible variation in the eco-efficiency of municipalities related to changes in data (inputs and outputs) (Gómez et al., 2018). In other words, the DEA-tolerance model assumes that all input and output values are ranges, not fixed values (Sala-Garrido et al., 2012). Hence, the first step in estimating eco-efficiency scores integrating data uncertainty is to define the tolerance values for each variable in the DEA model. Tolerance represents variation in the data in the original input and output values. The methodological approach suggested by Medal and Sala (2009) was used to define tolerance values for municipalities in Chile. Tolerance values were defined based on the annual averages of each variable in the municipalities evaluated during 2015–2019.

Given that $k = 1, 2\ldots, n$, municipalities with each using a vector of M inputs $x_k = (x_{1k}, x_{2k}, \ldots, x_{Mk})$ (operational costs) to produce a vector of S desirable outputs $y_k = (y_{1k}, y_{2k}, \ldots, y_{Sk})$ (recycled waste) and a vector of L undesirable outputs $b_k = (b_{1k}, b_{2k}, \ldots., b_{Lk},)$ (unsorted waste) tolerance values were defined as follows:

Tolerance for inputs: $\alpha_{ik} = x_{ik} r_{ik}$

$$\text{Tolerance for desirable outputs}: \quad \beta_{rk} = y_{rk} s_{rk} \tag{1}$$

Tolerance for undesirable outputs: $\gamma_{lk} = b_{lk} t_{lk}$

where: r_{ik}, s_{rk}, and t_{lk} are percentages of deviation from the original values for inputs, desirable outputs, and undesirable outputs, respectively, with a range of $[0 - 100]$. r_{ik}, s_{rk}, and t_{lk} are non-negative scalar values. They were estimated based on historical data (see Tables 1 and 2).

Based on the defined tolerance values (Eq. (1)), the range in the variation of inputs is $[x_{ik}(1 - r_{ik}), x_{ik}, (1 + r_{ik})]$, in desirable outputs is $\left[y_{rk}(1 - s_{rk}), y_{rk,}(1 + s_{rk})\right]$ and in undesirable outputs is $\left[b_{lk}(1 - y_{lk}), b_{lk}, (1 + t_{lk})\right]$. In other words, eco-efficiency is estimated using multiple inputs, desirable outputs and undesirable outputs rather a single value as in the conventional DEA method.

Based on past research (e.g., Molinos-Senante et al., 2016; Dong et al., 2017; Ramírez-Melgarejo et al., 2021; Yadav et al., 2022), three scenarios and six feasible input-output combinations were modelled (i. e., 3^6). This process involved 729 eco-efficiency simulations for each municipality. In other words, for each municipality, 729 eco-efficiency scores were computed, which allowed us to evaluate the impact of data variability in the economic and environmental performance of municipalities for MSW management. The three simulated scenarios were: (i) original data; (ii) most favorable data; and (iii) least favorable data. The feasible input-output combinations that were modelled included: (i) inputs for the evaluated municipality; (ii) inputs for the other municipalities; (iii) desirable outputs for the evaluated municipality; (iv) desirable outputs for the other municipalities; (v) undesirable outputs for the evaluated municipality; and (vi) undesirable outputs for the other municipalities. Accordingly, two out of the 729 modeled scenarios were the most extreme for each municipality, namely, the best- and worst-case scenarios. The best-case scenario considers the minimum values for inputs and undesirable outputs and the maximum values for desirable outputs for the evaluated municipality. The opposite settings were defined for the other municipalities in the sample, with the largest values for inputs and undesirable outputs and the smallest values for desirable outputs. The worst-case scenario had the opposite set up to the best-case scenario. Specifically, for the analyzed municipality, the maximum values for inputs and undesirable outputs were used, along with minimum values for desirable outputs. In parallel, for the other municipalities, the minimum values for inputs and undesirable outputs, and the maximum values for desirable outputs, were used to estimate the eco-efficiency score. The values for inputs, desirable outputs, and undesirable outputs for both extreme scenarios were set as follows (Gómez et al., 2018):

$$\text{Best-case scenario:}\mathit{Input} = \begin{cases} x_{ik_0} * (1 - r_{ik}) \\ x_{ik} * (1 + r_{ik}) \end{cases}$$

$$\mathit{Desirable\ output} = \begin{cases} y_{rk_0} * (1 + s_{rk}) \\ y_{rk} * (1 - s_{rk}) \end{cases} \tag{2}$$

$$\mathit{Undesirable\ output} = \begin{cases} b_{lk_0} * (1 - t_{lk}) \\ b_{lk} * (1 + t_{lk}) \end{cases}$$

Worst-case scenario:

Table 1
Summary of the variables used to estimate eco-efficiency scores of Chilean municipalities.[a]

Type of variable	Variables	Unit	2015		2019	
			Average	Std. Dev	Average	Std. Dev
Input	OPEX	10^3 CLP per capita	87.95	152.24	121.40	200.37
Desirable outputs: Recycled waste	Paper & cardboard	Kg per capita	9.71	96.76	44.08	374.29
	Glass	Kg per capita	3.53	17.65	10.37	30.04
	Organic waste	Kg per capita	53.53	460.59	27.42	147.76
	Plastic	Kg per capita	0.88	8.14	5.14	65.59
	Other waste	Kg per capita	33.82	237.94	107.45	763.01
Undesirable output	Non-valorized waste	Kg per capita	2163.82	3848.33	4868.52	45,909.41

[a] On 13 January, the conversion rate was 1 US$ ≅ 800.78 CLP.

Table 2
Estimated tolerances for input, desirable outputs and undesirable output (%).

OPEX	Recycled paper & cardboard	Recycled glass	Recycled organic waste	Recycled plastic	Other waste recycled	Non-valorized waste
2.10	14.17	9.57	5.63	14.22	10.34	2.05

$$Input = \begin{cases} x_{ik_0} * (1 + r_{ik}) \\ x_{ik} * (1 - r_{ik}) \end{cases}$$

$$Desirable\ output = \begin{cases} y_{rk_0} * (1 - s_{rk}) \\ y_{rk} * (1 + s_{rk}) \end{cases} \tag{3}$$

$$Undesirable\ output = \begin{cases} b_{lk_0} * (1 + t_{lk}) \\ b_{lk} * (1 - t_{lk}) \end{cases}$$

where x_{ik_0}, y_{rk_0} and b_{lk_0} are the inputs, desirable outputs and undesirable outputs of the municipality evaluated (k_0) whereas x_{ik}, y_{rk}, b_{lk} are the inputs, desirable outputs and undesirable outputs of the other municipalities.

Once the data variability and scenarios for the models had been defined, the last step to estimate the eco-efficiency scores using DEA involved solving the following linear programming problem for each municipality k_0 and scenario:

$$\begin{aligned} & Min\ \theta \\ & s.t. \\ & \sum_{k=1}^{n} \lambda_k x_{ik} \leq \theta x_{ik_0} \quad 1 \leq i \leq M \\ & \sum_{k=1}^{n} \lambda_k y_{rk} \geq y_{rk_0} \quad 1 \leq r \leq S \\ & \sum_{k=1}^{n} \lambda_k b_{lk} = b_{lk_0} \quad 1 \leq l \leq L \\ & \sum_{k=1}^{n} \lambda_k = 1 \\ & \lambda_k \geq 0 1 \leq k \leq n \end{aligned} \tag{4}$$

where λ_k is a vector of intensity and θ is the eco-efficiency score; M is the total number of inputs; S is the total number of desirable outputs; L is the total number of undesirable outputs and; n is the total number of municipalities evaluated. Note, Eq. (4) assumed that the variable returns to scale, with the operational costs of managing MSWs being affected by economies of scale (Caldas et al., 2019; Llanquileo-Melgarejo and Molinos-Senante, 2021; Amaral et al., 2022).

The discriminatory power of traditional DEA models is limited. Thus, several municipalities could be identified as eco-efficient, hindering the ranking process (See et al., 2022). Computing the eco-efficiency scores under 729 scenarios overcomes this limitation. In particular, Boscá et al. (2011) proposed two indicators to rank units (municipalities) based on eco-efficiency scores previously computed using the DEA-tolerance approach. These two indicators are as follows:

$$R_{729}^{Eco-eff} = \frac{e_{k_0}}{729} \tag{5}$$

$$R_{729}^{Eco-ineff} = \begin{cases} \dfrac{S_{k_0} - e_{k_0}}{729 - e_{k_0}} if 729 \neq e_{k_0} \\ 0 if R_{729}^{Eco-eff} = 1 \end{cases} \tag{6}$$

where e_{k_0} is the number of times that municipality k_0 is eco-efficient (i.e., $\theta = 1$); and S_{k_0} is the sum of the eco-efficiency scores of municipality k_0.

$R_{729}^{Eco-eff}$ is bounded between 0 and 1, and represents the proportion of times that municipality k_0 is eco-efficient. $R_{729}^{Eco-eff} = 0$ means that municipality k_0 is not eco-efficient in any of the 729 simulated scenarios. In contrast, $R_{729}^{Eco-eff} = 1$ shows that municipality k_0 is efficient in all scenarios, including the worst-case scenario. $R_{729}^{Eco-ineff}$ was used to rank municipalities that have the same $R_{729}^{Eco-eff}$ values, and ranges between 0 and 1.

3.2. Municipal solid waste management in Chile

Chile is a middle-income country that had a gross domestic product of 16,265 US$ per capita in 2020 (World Bank, 2023). Chile has a population of 19.8 million people (INE, 2022), of which 42 % live in the Metropolitan Region of Santiago, one of the 16 regions of the country. The collection, transport, valorization, and final disposal of MSW in Chile is the responsibility of local authorities. However, in several municipalities, these activities are outsourced to private companies. MSW is mainly collected door-to-door (Valenzuela-Levi, 2021). The recycling programs emerged as local independent initiatives based on the available municipal budget (Valenzuela-Levi, 2019). Twenty-five percent of local authorities use informal recyclers in their recycling policies. Informal recyclers that serve poorer communities perceive recycling as a potential source of income (Valenzuela-Levi, 2021).

One incipient policy adopted in Chile for managing MSW is the Policy for the Integrated Management of Solid Waste adopted in 2005. Since then there has been a significant advancement in the development of waste management policies. In 2009 the Municipal Environmental Certification created a voluntary system that promotes improvement in management and empowerment of municipal environmental units. In 2010, the Ministry of the Environment was created, which has a leading role in proposing policies and formulating norms, plans, and programs in waste matters.

An important advancement occurred in 2016 with the enactment of the Extended Producer Responsibility (REP) and Recycling Promotion Law. This law promotes the reduction in waste generation and the promotion of recycling. For this purpose, it holds producers and importers responsible for financing the proper management of the waste generated by the products they market. The law establishes collection targets for six priority products that will start to apply in 2023 (Law N° 20.920, 2016). This law is still in its initial stages, as its Regulations have not been published yet.

During 2021, two relevant instruments for the future of waste management in Chile were published. These are the Roadmap for a Circular Chile by 2040 and the National Strategy for Organic Waste Chile 2040, developed by the Ministry of the Environment. Although these documents do not constitute a norm, they are public policy instruments that operate because they set clear goals for the sectors involved with an ambitious vision of sustainable development in the medium and long term.

In Chile, the generation of MSW per capita has increased from 294 kg/year in 2000 to 437 kg/year in 2018, representing a 49 % increase (OECD, 2023). Landfill remains the most commonly used option (80 %) for solid waste disposal (SINIA, 2021). In contrast, the use of recycling and other recovery alternatives rates remains limited (< 5 %) (Araya-Córdova et al., 2021). The operational expense (OPEX) devoted to MSW management has also increased from around US$ 245 million per year in 2012 to US$ 528 million per year in 2021 (116 % increase). The evolution of these basic performance indicators associated to the sustainable management of MSWs demonstrate the need for municipalities in Chile to design and implement effective policies to improve eco-efficiency in solid waste management.

4. Case study

To have a general knowledge on the sustainability of MSW management, the eco-efficiency of a sample of 44 municipalities in Chile was assessed.[1] Its size varied from 6905 inhabitants (Perquenco) to 625,551 inhabitants (Puente Alto). This noticeable variation in size led to a relative divergence among the municipalities assessed. Consequently, the optimization model applied to each municipality (Eq. (4)) incorporates variable returns to scale. Hence, the model that is used to assess eco-efficiency scores integrates potential economies of scale of municipalities in the provision of MSW services.

From an initial sample of 106 municipalities, our study's framework necessitated a focus on the availability of data for the chosen inputs and outputs. Initially, 42 municipalities were excluded because they reported zero values for at least one of the variables used to estimate eco-efficiency scores, reducing the sample to 64 municipalities. To ensure the robustness of our data, we further evaluated for outliers using the average and standard deviation values, following the methodology outlined by Tukey (1977). This analysis identified 20 out of the 64 municipalities as outliers based on at least one of the seven variables considered for assessing eco-efficiency. Consequently, after considering data availability and outlier impacts, the final sample size was narrowed down to 44 municipalities.

Inputs and outputs (desirable and undesirable) were selected using the following criteria: (i) main objective of the study; (ii) statistical data available and; (iii) previous studies evaluating the eco-efficiency of municipalities for MSW management (e.g., Guerrini et al., 2017; Sarra et al., 2020; Romano et al., 2021; Sala-Garrido et al., 2022; Ferraro et al., 2023). Based on the broad concept of eco-efficiency,[2] MSW recycling rates, economic costs, and non-valorized MSW rates were correspondingly chosen as three groups of variables in the model. The annual OPEX spent by municipalities to manage MSW was selected as input (CLP/year). Statistical information was collected from SINIM database (National System of Municipal Information). It involves the total operational cost for the collection, transport, valorization, and final disposal of MSW. Taking into account that MSW management in Chile does not include the reuse and preparation for reuse step, once MSW is generated, according to the waste management hierarchy, waste recycling is the preferred option for waste valorization (European Commission, 2018). Thus, desirable outputs included the quantity of items recycled annually (expressed as tons per year) for: (i) paper and cardboard; (ii) glass; (iii) plastic; (iv) organic waste; and (v) other waste. Based on the waste management hierarchy, the least preferred option was final disposal in landfill or other finalist solutions (European Commission, 2018). Hence, the annual quantity (tons/year) of non-valorized MSW (usually disposed in landfill) was selected as undesirable outputs. Data on the generation of MSW and management alternatives were collected from the SINADER (National System for Waste Declaration). It is a web platform that facilitates compliance with legal obligations related to the declaration of non-hazardous wastes. SINADER enables the selective collection and recording of MSW data while providing separate data for waste generated by industry and commerce. This comprehensive data collection approach ensures that data used for estimating the eco-efficiency scores focused on MSW.

Eco-efficiency was assessed for 2019, whereas data were collected from 2015 to 2019 to estimate the tolerance values for each input and output. The inputs and outputs of the 44 municipalities assessed are summarized in Table 1. Except for organic waste, the annual quantity of recycled waste increased from 2015 to 2019. However, the average quantity of non-valorized waste and OPEX for the assessed municipalities also increased. Notable differences among municipalities may be attributed to variations in budget allocations for developing MSW recycling programs, as well as differing levels of environmental concern among residents.

5. Results and discussion

5.1. Estimates of data uncertainty

The first stage for evaluating the eco-efficiency of municipalities for the 729 scenarios was to estimate the tolerance values for each variable in the DEA model. These tolerance values reflect the potential uncertainty based on historical data. Hence, a greater amplitude of the tolerance intervals represented higher sensitivity to possible changes in inputs and outputs (Sala-Garrido et al., 2012). In this case study, the determination of tolerance values for each variable was informed by data changes observed from 2015 to 2019. A unique tolerance value was calculated for each municipality and for each specific variable, reflecting the variability and specific circumstances of each municipality in the dataset. However, it was observed that the tolerance divergences among the municipalities were relatively small, with variations less than 5 %. Due to this minimal divergence, an average tolerance value derived from all 44 municipalities was adopted as a common tolerance level for all municipalities in the study. This approach simplifies the analysis while still maintaining a reasonable level of accuracy and relevance to the overall dataset. It is important to note that in scenarios where municipalities exhibit significant differences in their tolerance values, individualized tolerance values can be applied for each analyzed unit.

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[1] The municipalities assessed are: Vicuña, Ovalle, Temuco, Perquenco, Villarrica, Concepción, Curanilahue, Yumbel, Palmilla, San Javier, Yerbas Buenas, Futaleufú, Lanco, Los Lagos, Panguipulli, Santiago, Independencia, La Florida, La Granja, La Reina, Lo Barnechea, Lo Prado, Maipú, Peñalolén, Providencia, Recoleta, San Joaquín, San Miguel, Vitacura, Puente Alto, Colina, Lampa, Calera de Tango, Melipilla, María Pinto, El Monte, Peñaflor, Quirihue, Valparaiso, Casablanca, Quintero, Viña del Mar, Santo Domingo and San Felipe.

[2] Eco-efficiency is defined as the ratio of the value of products or services with environmental impacts and resource consumption (Ji, 2013).

Table 2 shows the values of the symmetric tolerance values estimated for the inputs, desirable outputs, and undesirable output.

Tolerance values for OPEX (input) and non-valorized waste (undesirable output) were quite similar, and were lower than those estimated for desirable outputs (recycled waste). This result was attributed to municipal managers having greater control over costs and waste disposed without valorization. In contrast, the quantity of recycled waste only depends on managerial actions carried out by municipalities but also from selective waste separation by citizens. However, the emerging effects of implementing the Law for Promoting Recycling and Extended Producer Responsibility might also affect the larger tolerances estimated for recycled wastes. Of note, among other wastes, “containers and packaging” are defined as priority products by the Law.

5.2. Eco-efficiency scores

By applying the DEA model with the uncertainty assessment (Eq. (5)), this study obtained 729 eco-efficiency scores for each municipality under 729 possible scenarios. Eco-efficiency scores of four specific groups were selected for in depth evaluation: (i) original eco-efficiency scores without considering uncertainty (“original”); (ii) mean eco-efficiency score of the 729 scenarios (“mean”); (iii) minimum eco-efficiency score (“min”), which represents the worst-case scenario and; (iv) maximum eco-efficiency score (“max”), which represents the best-case scenario (Dong et al., 2017; Gómez et al., 2018).

The results without accounting for uncertainty (i.e., “original” eco-efficiency scores) produced an average value of 0.180 for the 44 evaluated municipalities (Table 3). It corresponds to eco-efficiency estimation based on a conventional DEA model assuming variable returns to scale. This performance was considered to be very poor when taking into account that eco-efficiency scores range from 0 to 1. An eco-efficiency score of 0.180 means that, on average the assessed municipalities could reduce their costs and non-valorized waste by 82 % (1–0.180). This result was lower than the eco-efficiency scores estimated by past research on this topic. When using traditional DEA models (i.e., without uncertainty), Llanquileo-Melgarejo et al. (2021) estimated an average eco-efficiency score of 0.54 for 298 municipalities in Chile in 2018. A similar value (0.58) was reported by Llanquileo-Melgarejo and Molinos-Senante (2021) for a same sample of municipalities. Potential input (cost savings) was estimated by Molinos-Senante et al. (2022a) as 37.8 %, also for a sample of 298 municipalities in Chile. When applying the stochastic semi-parametric envelopment of data method, Molinos-Senante et al. (2022a) reported an average eco-efficiency score of 0.332 for a sample of Chilean municipalities in the management of MSW. The poor performance of municipalities in Chile regarding MSW management from a circular economy perspective was also highlighted by Valenzuela-Levi (2021).

It is important to highlight that the estimated eco-efficiency scores in our study are based on inputs, desirable outputs and undesirable outputs, i.e., OPEX, quantity of MSW recycled, and non-valorized waste. This means that exogenous factors, such as population density, waste collection methods, or tourist flows, which may influence the eco-efficiency of municipalities, have not been included in the assessment (Guerrini et al., 2017). Therefore, the observed differences in eco-efficiency among municipalities could also be attributed to variations in these exogenous or environmental variables, which were not accounted for in our evaluation.

The large divergence in eco-efficiency scores among municipalities in Chile regarding MSW management is still growing. Twenty-nine out of 44 municipalities (65.9 %) had an eco-efficiency score below 0.1, demonstrating extremely poor performance. This score was attributed to the very low quantity of MSW recycled by these municipalities. This result demonstrates the importance of integrating environmental indicators when assessing the performance of municipalities in MSW management in a circular economy. Based on the original eco-efficiency scores, only 12 out of 44 municipalities (27.3 %) exhibited eco-efficiency of 0.1–0.4, indicating poor performance. Then, a single municipality (M4) had an eco-efficiency score is 0.771. Finally, four out of 44 municipalities (9.1 %) were identified as eco-efficient with scores of 1.0. These four municipalities are: Yumbel, Palmilla, San Javier and Yerbas Buenas. These four municipalities had a noticeably larger recycling rate compared to inefficient municipalities. The average recycling rate for the 44 evaluated municipalities was 12.9 %, whereas it was 51.4 % for the eco-efficient municipalities (peaking at 77.7 % for M8). Moreover, they are characterized for being small municipalities as their population ranges between 12,482 (Palmilla) and 45,547 (San Javier).

Table 3
Eco-efficiency of Chilean municipalities in the management of MSW considering data uncertainty.

Municipality	Original	Mean	Min	Max
M1	0.174	0.176	0.099	0.273
M2	0.229	0.231	0.180	0.292
M3	0.060	0.060	0.046	0.079
M4	0.771	0.775	0.607	0.980
M5	0.020	0.020	0.015	0.026
M6	0.020	0.020	0.015	0.026
M7	0.009	0.009	0.007	0.011
M8	1.000	1.000	1.000	1.000
M9	1.000	0.826	0.337	1.000
M10	0.035	0.036	0.028	0.046
M11	1.000	1.000	1.000	1.000
M12	1.000	1.000	1.000	1.000
M13	0.012	0.012	0.009	0.015
M14	0.014	0.014	0.010	0.018
M15	0.074	0.074	0.058	0.095
M16	0.095	0.095	0.074	0.122
M17	0.014	0.014	0.011	0.018
M18	0.024	0.024	0.019	0.031
M19	0.004	0.005	0.003	0.006
M20	0.149	0.150	0.117	0.191
M21	0.251	0.253	0.197	0.320
M22	0.120	0.121	0.094	0.153
M23	0.300	0.301	0.235	0.381
M24	0.113	0.113	0.089	0.144
M25	0.082	0.082	0.063	0.106
M26	0.036	0.037	0.028	0.047
M27	0.006	0.006	0.005	0.008
M28	0.011	0.012	0.009	0.015
M29	0.041	0.041	0.031	0.054
M30	0.400	0.403	0.315	0.509
M31	0.021	0.021	0.016	0.028
M32	0.297	0.299	0.234	0.377
M33	0.307	0.308	0.241	0.391
M34	0.009	0.009	0.007	0.012
M35	0.025	0.025	0.019	0.033
M36	0.030	0.031	0.015	0.064
M37	0.005	0.005	0.004	0.007
M38	0.005	0.005	0.004	0.006
M39	0.008	0.008	0.006	0.010
M40	0.039	0.039	0.029	0.051
M41	0.014	0.014	0.010	0.018
M42	0.020	0.020	0.015	0.026
M43	0.052	0.053	0.040	0.069
M44	0.032	0.032	0.025	0.041
Average	0.180	0.177	0.145	0.207
Std. Dev.	0.299	0.289	0.263	0.312

For eco-efficiency scores integrating data uncertainty, the average eco-efficiency scores ranged from 0.145 (for the worst-case scenario; min) to 0.207 (for the best-case scenario; max), with a 30 % amplitude. The amplitude could be interpreted as the variability in eco-efficiency among the 729 scenarios evaluated. Fig. 1 and Table 3 show that in absolute terms most municipalities had low amplitude values (i.e., eco-efficiency disparities between the best-case and worst-case scenarios were less than 0.1). This result was attributed to the eco-efficiency scores being very low, even in the best-case scenario. However, when amplitude was expressed as a percentage, disparities between the minimum and maximum eco-efficiency scores exceeded 30 % except for eco-efficient municipalities. Thus, the estimated eco-efficiency scores were

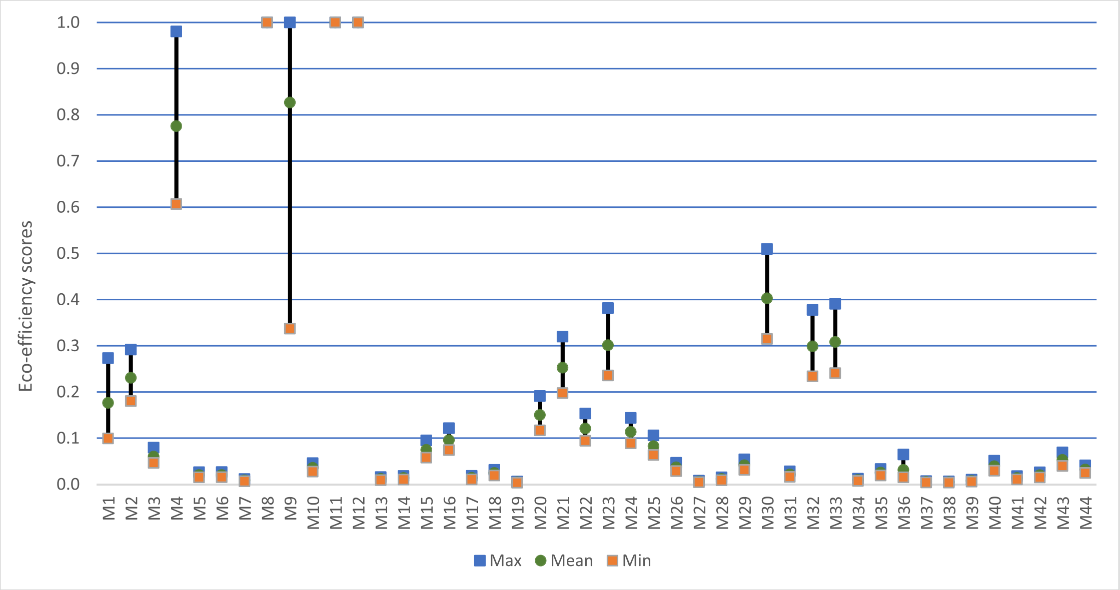

Fig. 1. Amplitude in eco-efficiency estimations for Chilean municipalities.

highly sensitive to variation in inputs and outputs. M9 presented a clear example of how uncertainty in inputs and outputs uncertainty affected eco-efficiency estimates. Based on the original data and under the best-case scenario, this municipality was considered eco-efficient (i.e., it was located on the efficient production frontier). In contrast, when eco-efficiency scores were estimated based on the worst-case scenario for this municipality, its performance dropped to 0.337, with a 66.3 % amplitude in eco-efficiency scores.

From a management perspective, large divergence in the eco-efficiency scores demonstrated that improvements to MSW recycling rates and/or reductions in operational costs could significantly increase the eco-efficiency of municipalities. Three municipalities (M8, M11, and M12) were eco-efficient in the 729 modeled scenarios. These municipalities were identified as the best municipalities for managing MSW out of the evaluated sample based on their of eco-efficiency performance. The eco-efficiency of these three municipalities was not affected by data uncertainty, unlike the other municipalities. The mean eco-efficiency score showed how a municipality performed under the 729 modeled scenarios (i.e., integrating data uncertainty). Thus, this score represented a more reliable measurement of eco-efficiency compared to the original score (Dong et al., 2017). The average mean eco-efficiency score for the 729 scenarios was 0.177, which was very close to the average score based on the original data (Table 3).

5.3. Ranking of municipalities based on eco-efficiency scores

To rank municipalities based on their eco-efficiency scores under the 729 simulated scenarios, $R_{729}^{Eco-eff}$ and $R_{729}^{Eco-ineff}$ were estimated (denoted in Fig. 2 as $R_{729\text{-eff}}$ and $R_{729\text{-ineff}}$). Both indicators were largely robust, because they were based on the 729 scenarios, not a single estimate (original eco-efficiency score), as in the case of traditional DEA assessments (Gómez et al., 2018). When a municipality was more frequently assigned as eco-efficient, the indicator $R_{729}^{Eco-eff}$ was closer to one, and the municipality occupied a superior position in the ranking (Yadav et al., 2022). Municipalities 8, 11, and 12 occupied first position in the ranking because they were eco-efficient under all the 729 simulated scenarios

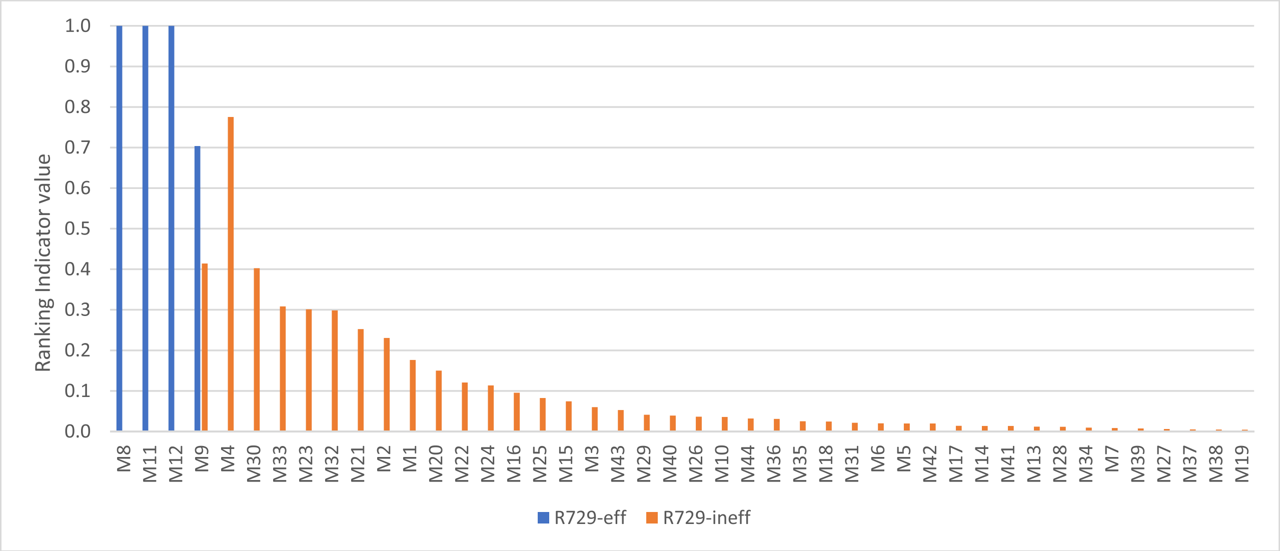

Fig. 2. Ranking of municipalities based on its eco-efficiency scores.

(Fig. 2). Municipality 9 had an $R_{729}^{Eco-eff}$ of 0.703, because it was eco-efficient in 513 out of the 729 scenarios (70.3 %). In contrast, the $R_{729}^{Eco-eff}$ of all other municipalities (40 out of 44) was 0.0, because they were not eco-efficient, even in the best-case scenario.

To facilitate the ranking of the municipalities that had the same value of $R_{729}^{Eco-eff} \neq 1$, $R_{729}^{Eco-\mathrm{ineff}}$ was computed. Because most municipalities (90.9 %) in our case study had an $R_{729}^{Eco-eff}$ of 0.0, it was necessary to estimate $R_{729}^{Eco-\mathrm{ineff}}$ to rank them. Out of the eco-efficient municipalities, M4 held the highest position (Fig. 2). This refers to "Perquenco," a small municipality with 6905 inhabitants located in the southern part of the country. Despite having a MSW recycling rate of 42 %, which is higher than the average in our study, Perquenco's eco-efficiency is not maximum due to its high operational costs. Specifically, the OPEX for MSW management in Perquenco are estimated at 117,000 Chilean Pesos (CLP) per ton, which is more than double the average of 56,000 CLP/ton observed across the 44 municipalities assessed. A notable factor contributing to these high costs is Perquenco's relative isolation, leading to significantly higher transportation expenses.

In contrast, M19 ($R_{729}^{Eco-\mathrm{ineff}}$ of 0.0045) was ranked lowest as it had the worst performance. This municipality refers to La Granja which has a population of 116,571. Despite its relatively large population, La Granja does not benefit from economies of scale in its waste management practices. In fact, its MSW recycling rate is just 0.55 %, reflecting a minimal production of desirable outputs. This low rate of recycling significantly contributes to the municipality's low eco-efficiency.

Waste management service is essential to the well-being of citizens, public health, and economic activities (Ferreira et al., 2020). In Chile, local authorities are legally responsible for managing MSWS, and sometimes outsource this service. Regardless of whether MSW service providers are public or private, they operate under a monopoly regime. As in other countries, "self-regulation" is considered sufficient (Barkenbus, 1983). In other words, there is not a regulatory authority devoted to promoting the quality of service provided by operators (municipalities) or implementing common policies to attain greater efficiency (ERSAR, 2023). Thus, the results of this study are very relevant. This study clearly showed that the evaluated municipalities are very eco-inefficient in the management of MSW, with a large opportunity to improve SWM. In contrast, marked differences in performance (eco-efficiency scores) were identified among municipalities. These differences were attributed to inequality in SWM among citizens in Chile. Results from our study suggest that the "self-regulation" of MSW services in Chile has failed. Nevertheless, our sample just embraces 44 Chilean municipalities and therefore, we should be cautious is to extrapolate the findings from this study to the entire country. The creation of a regulatory authority is recommended to promote eco-efficiency, innovation and sustainability in the waste sector, as implemented in other countries like Portugal, Italy, and Brazil (Marques et al., 2018). The waste regulator should also regulate investments to increase MSW recycling rates. The role of the waste regulator should not be limited to MSW management, but should also include solid waste from different economic activities. Of note, the provision of water and wastewater treatment services has been regulated since 1990 in Chile, before the water industry was privatized (SISS, 2023). Hence, there is experience in Chile in creating and operating regulatory authorities.

In the framework of the SDGs 11.6 and 12.5 which target: "By 2030, reduce the negative environmental impact per capita of cities, including paying particular attention to air quality and municipal waste management" and "By 2030, significantly reduce the generation of waste through prevention, reduction, recycling, and reuse activities", Chile adopted the Law for Promoting Recycling and Extended Producer Responsibility in 2016. However, the current study (data from 2019) clearly demonstrated that only a few municipalities (4 out of 44) are on the right track towards a paradigm shift from linear economy to circular economy. Therefore, in the upcoming years it is crucial for Chilean authorities to formulate and implement additional policies aimed at enhancing eco-efficiency in the management of MSW. These initiatives will be instrumental in achieving SDGs 11.6 and 12.5, among other related SDGs.

6. Conclusions

Eco-efficiency in managing MSW is essential for SWM and moving towards a circular economy. Despite data on waste being of high importance, sometimes data is imprecise, hindering robust evaluation of the performance of MSW providers. The current study demonstrated the potential of using the DEA-tolerance approach to estimate the eco-efficiency of MSW providers. This methodological approach allowed data uncertainty to be integrated through simulating 729 scenarios for each of 44 municipalities. Hence, this study provided information on the sensitivity of eco-efficiency in municipalities with respect to changes in OPEX, recycling rates, and non-valorized MSW rates.

The divergence in eco-efficiency across the 729 simulated scenarios underscores the importance of incorporating data uncertainty into performance assessments. Additionally, the use of a broad range of simulations, as opposed to relying on a single estimation, enables a more robust ranking of municipalities based on their eco-efficiency scores. This approach ensures that our assessments and rankings are grounded in reliable, well-rounded estimations, reflecting a more accurate picture of eco-efficiency across different scenarios.

While this study introduced a novel methodological approach to integrate data uncertainty in eco-efficiency assessment of MSW service providers, it is important to acknowledge its limitations. Two notable limitations are as follows. Firstly, the study primarily estimates the eco-efficiency of municipalities in MSW provision based on their costs and the quantity of recycled and non-valorized MSW. It does not account for the potential impact of exogenous variables and environmental conditions, such as population density, geographic conditions, and tourist flows. A more comprehensive analysis, including a second stage that utilizes hypothesis testing to evaluate the impact of these variables, could offer deeper insights into the reasons behind the low eco-efficiency in some of the assessed municipalities. Secondly, the study considers desirable outputs as those MSW components generated in larger quantities, but does not necessarily address those wastes whose mismanagement may have more significant environmental impacts. Including other types of MSW, such as electronic and electrical waste, used oils, batteries, etc., could be beneficial. Incorporating these additional waste types would aid in developing more effective strategies and policies for improving the environmental management of MSW. Addressing these limitations in future research could enhance understanding and management of eco-efficiency in MSW services.

CRediT authorship contribution statement

Alexandros Maziotis: Writing – review & editing, Software, Methodology, Investigation. **Maria Molinos-Senante:** Writing – original draft, Data curation, Conceptualization. **Manuel Mocholi-Arce:** Writing – review & editing, Methodology, Formal analysis. **Ramon Sala-Garrido:** Writing – review & editing, Data curation, Conceptualization.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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