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ORIGINAL RESEARCH

A Flexible and Sustainable Analysis of Waste Efficiency at the European Level

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Abstract *This paper analyses the waste management efficiency of European Union countries using a flexible non-parametric methodology known as directional data envelopment analysis (DEA). The study evaluates performance at the macro (country) level, considering waste generated as input, landfilled and incinerated waste as bad output and recycled waste as output. The analysis incorporates the heterogeneity and specificities of each country, with respect to social and economic sustainability, establishing specific and realistic targets for each country to achieve efficiency. The research introduces a flexible and innovative method for assessing waste management efficiency and provides new empirical evidence on European waste management, considering economic and social sustainability. The results reveal a significant disparity among European countries in both waste generation and waste recycling. Countries are categorised into five groups according to their level of efficiency, and Central European nations are observed to exhibit generally better performance. A pragmatic approach, based on clear collaboration among countries, could optimise the unique waste management characteristics of individual nations to enhance the overall efficiency of the European waste management system, contributing to a circular economy and sustainable development.*

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Introduction and Aim

The managerial approach of flexibility depends on the strategic use of resources and skills. While this approach may present significant opportunities (Singh et al., 2021; Sushil & Dinesh, 2022), its effective implementation requires appropriate methodologies tailored to the specific field of application (Sushil, 2018), also serving to mitigate risk (Kamsu-Foguem et al., 2023). One of the most pressing and complex challenges for which a flexible approach is needed is sustainability—understood broadly to include environmental, social and economic aspects. Sustainable communities, oriented towards the needs of future generations, require an optimal balance between economic opportunity, social welfare and ecosystem preservation (Biancardi et al., 2023). To remain competitive in a changing global landscape, organisations must redirect resources when outcomes fall short of profit goals (Garg & Sushil, 2024). Production processes must also incorporate sustainable practices with digital tools, enabling flexibility and maximal responsivity to market demands (Srivastava & Bag, 2023). The development of flexible industrial ecosystems further requires the

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incorporation of green and circular practices, renewable energy production and reuse/recycle/recovery methodologies (D'Adamo et al., 2023). In addition, waste management must be integrated with clean energy production (Singh et al., 2023).

Previous studies have highlighted the potential overlap between indicators for circular processes and their impacts (Garcia-Saravia Ortiz-de-Montellano & van der Meer, 2022), emphasising the need to address circular economy issues appropriately to prevent rebound effects (Ferrante et al., 2024). Additionally, research has identified that, in the transition to a zero-waste economy, supply chains must incorporate both closed- and open-loop operations (Le et al., 2023). The terms 'reuse' and 'recycling' are closely associated with the circular economy (Kirchherr, 2023), aimed at achieving sustainable development goal (SDG) 12 (sustainable consumption and production). In this context, the 'end of waste' concept is crucial, particularly within Europe. However, local authorities often struggle to precisely define when waste ceases to be waste (Mazzanti & Montini, 2014). To address this, the relationship between waste and products must be thoroughly analysed (Johansson & Forsgren, 2020) and clear and indisputable criteria must be established (Ragossnig & Schneider, 2019). Moreover, effective control measures must be installed to prevent a rise in illegal waste activities (D'Amato et al., 2018). Finally, technological support is needed to ensure efficient waste management (Hondroyiannis et al., 2024) and thereby improved quality of life (Romano et al., 2022). Notably, the literature is characterised by some concerning gaps, including an insufficient consideration of social implications (Mies & Gold, 2021), lower quality and limited availability of secondary materials (Hsu et al., 2022) and barriers related to consumers and corporate culture (Kirchherr et al., 2018).

In the European literature, significant attention has been given to recycling as a widely used circular economy practice (De Pascale et al., 2023), emphasising the necessity of increasing secondary raw materials in the production cycle among European Union (EU) countries (Chioatto & Sospiro, 2023). Studies have also highlighted the benefits of integrating municipal solid waste management with sustainable practices (Caglar et al., 2024; Sondh et al., 2024). Various indicators have been utilised to compare the performance of European countries in terms of the circular economy (D'Adamo et al., 2024) and specific impacts at the municipal solid waste level (Castillo-Giménez et al., 2019b), often using data envelopment analysis (DEA; Charnes et al., 1978; Chioatto et al., 2024; Molinos-Senante et al., 2024)). DEA is a performance measurement technique that is used to evaluate the efficiency of entities (e.g. organisations, regions, countries) in transforming resources or inputs into outputs, products and services.

Given the increasing emphasis on environmental sustainability, institutions have begun to implement rules and targets to mitigate the environmental impact of various activities, including municipal waste management. Numerous countries have enacted regulations and set targets for this purpose, such as landfill taxes and recycling mandates (for more detail, see Andretta et al., 2018). The EU has been particularly active in this area, setting ambitious waste management targets through the Waste Framework Directive.[1] Specifically, the EU has mandated that, by 2025, 55% of waste should be recycled and prepared for reuse. This target increases to 60% by 2030 and 65% by 2035. Additionally, the amount of waste sent to landfill should be reduced to a maximum of 10% by 2035. However, these stringent targets have been criticised for their uniformity, which do not consider the varying resources and capabilities of individual EU countries (see, for example, Castillo-Giménez et al., 2019a; Nicolli et al., 2012). Moreover, the EU directive focuses exclusively on environmental sustainability, without considering the social and economic impacts of municipal waste management activities.

In the present study, we analysed the efficiency of waste management activities across European countries, using the nonparametric methodology of directional DEA (Daraio & Simar, 2016). The flexibility of this methodology allowed us to consider not only the inputs that produced outputs but also the specific contexts and characteristics of each country. Our analysis, which referred to data from 2021 (the last data available), considered waste generated as input, landfilled and incinerated waste as bad output to be minimised and waste to be recycled as output. The directional DEA methodology enabled us to chart each country's path to the efficient frontier, taking into account 2021 levels of social and economic sustainability. Specifically, the approach defined 'directions' (or paths) to efficiency conditioned by external or contextual variables—specifically social sustainability (measured by the number of individuals involved in waste-related activities) and economic sustainability (measured by national government expenditure on waste management). This innovative methodology allowed us to propose more realistic and achievable targets for each EU country (relative to the uniform percentage targets currently in place) that also considered each country's unique social and economic contexts. Thus, the work contributed two novel outputs:

[1] European Union, 2008. Directive 2008/98/EC of the European Parliament and the Council of 19 November 2008 on Waste and Repealing Certain Directives. Official Journal of the European Union, 22/11/2008.

first, a flexible approach for estimating waste management efficiency at the macro (country) level using directional DEA (Daraio & Simar, 2016), and second, new empirical evidence on European waste management, incorporating economic and social sustainability into the evaluation of best practices.

The remainder of the paper presents the methodology, the data analysed, the main results and a concluding discussion.

Method

In the present study, we employed the directional DEA approach introduced by Daraio and Simar (2016). Traditional DEA (Charnes et al., 1978) evaluates the relative efficiency of multiple decision-making units by comparing the inputs used and the outputs produced. This method identifies the most efficient (i.e. best-performing) units and provides insight into how less efficient units can improve. DEA employs linear programming to construct a frontier of the most efficient units, with each unit's efficiency measured relative to this frontier. Units on the frontier are considered efficient, while those below it are deemed inefficient.

Traditional DEA has been widely applied in waste management studies across various geographical scales, including comparisons of countries (Chioatto & Sospiro, 2023; Giannakitsidou et al., 2020; Halkos & Petrou, 2019) and municipalities (Lavigne et al., 2019; Lo Storto, 2024; Marques & Simões, 2009). Unlike parametric methods, such as stochastic frontier analysis (SFA; Aigner et al., 1977; Meeusen & van Den Broeck, 1977), DEA can accommodate multiple inputs and outputs without requiring a pre-specified functional form for the production process, thus offering flexibility for various applications. However, DEA is sensitive to outliers and assumes the free disposability of assets, convexity and either constant returns to scale (CRS) or variable returns to scale (VRS). It also presumes that all units operate in similar environments/contexts, which may not always be the case (for further detail, see Daraio & Simar, 2007). The relatively lower assumptions compared to parametric models render DEA highly versatile, making it applicable to sectors beyond waste management, such as banking (Konovalov et al., 2020), construction (Kundi & Sharma, 2015; Nguyen, 2020) and supply chain management (Kiani Mavi et al., 2023).

To estimate the efficiency of a unit (in the present case, a country), the methodology considers a vector of inputs $x \in R_+^p$ producing a vector of outputs $y \in R_+^q$. The production set Ψ may be defined as:

$$\Psi = \left\{ (x, y) \in R_+^{p+q} | x \, \text{can produce} \, y \right\}$$

where (x,y) represents a unit (i.e. country) using x inputs to produce y outputs, and Ψ represents the true but unknown production set, estimated through DEA and denoted by $\hat{\Psi}_{\text{DEA}}$.

The inefficiency of each unit (i.e. country) is determined by its distance to the frontier. The selection of a direction is crucial for this measurement. The traditional approach in DEA involves proportional distance, implying radial contraction of inputs or radial expansion of outputs. However, instead of assuming equi-proportional reductions or expansions, directional distance functions (DDFs) offer a more flexible alternative for evaluating each unit's distance from the frontier (see Färe & Grosskopf, 2000 for more detail). A directional distance measure (Chambers et al., 1998) is given by:

$$\delta(x, y) = \sup\left\{ \delta | \left(x - \delta d_x, y + \delta d_y \right) \in \Psi \right\}$$

where $d_x \in R_+^p$ and $d_y \in R_+^p$. Distance is measured along a path determined by a direction vector $\mathrm{d}' = (-\mathrm{d}'x, \mathrm{d}'y)$ in an additive way, where if (x, y) lies on the efficient frontier, then $\delta(x, y) = 0$.

The flexibility of directional distances allows for the inclusion of negative values for inputs and outputs (see Färe et al., 2008 for more detail). In the present study, we estimated the production set using the DEA VRS approach $\hat{\Psi}_{\text{DEA}-\text{VRS}}$ (Banker et al., 1984).

When employing flexible directional measures, the choice of the direction vector is critical, as it influences the estimations of efficiency scores. Many studies have proposed specific DDFs tailored to different contexts (see Färe et al., 2008; Fukuyama & Weber, 2017; Nepomuceno et al., 2020). However, the selection of a direction implies the definition of efficiency targets (e.g. the input and output values necessary for a country to become efficient), which is imposed on all analysed units. In the present study, to account for the heterogeneity of the countries analysed, we employed the directional DEA method proposed by Daraio and Simar (2016). This flexible method determines the direction to reach the efficient frontier based on external/contextual factors. It is a completely data-driven approach that follows three main steps (for more detail, see Daraio & Simar, 2016):

1. Transformation of each observed $p + q$-dimensional input/output matrix $X_i Y_i$ into polar coordinates (r_i, θ_i) for $i = 1, \ldots, n$, where $r_i > 0$ and $\theta_i = (\theta_i^1, \ldots, \theta_i^{p+q-1})$ (in the present study, $p + q = 3$).
2. Polar nonparametric regression for each component θ^j on W (the matrix of external factors $W \in R^d$) to estimate $E\left(\theta^j | W\right)$, considering $\theta^j, j = 1, \ldots, p + q - 1$. In the present study, for each regression j, j = 1, …,

$p+q-1$, we used the data set $\left(\theta_i^j|W_i\right)$, $i = 1, \ldots, n$, employing a cross-validation method for bandwidth selection.

3. Conversion of the polar coordinates $(r_i; \widehat{\theta}_i)$ to Cartesian coordinates, to derive the directional vector d, resulting in $\hat{d} = \left(r_i; \widehat{\theta}_i\right)$.

Following these steps, we used the estimated vector of directions $\widehat{\mathrm{d}}$ to estimate efficiency and efficiency targets using the DEA VRS method. The subsequent sections demonstrate the practical application of this approach.

Data

Our analysis of all 27 EU member states drew on data from EUROSTAT (https://ec.europa.eu/eurostat/data/database, last accessed 14/04/2024) pertaining to the year 2021. For Ireland, data from 2020 were utilised due to data unavail ability for 2021. EUROSTAT data are extensively employed in waste management studies, despite presenting certain limitations (Colasante et al., 2022; Di Foggia & Beccarello, 2023). We collected data on waste generation (measured in tonnes per inhabitant, denoted as X), waste disposed of in landfills, energy recovery and incineration (all measured in tonnes per inhabitant, denoted as BY) and waste recycled or sent for reuse (denoted as Y). This data collection approach aligned with EU waste directives, which aim at reducing reliance on waste disposal methods (e.g. landfilling, incineration) and promoting sustainable and responsible waste management practices to mitigate waste accumulation.

The study was grounded in the principle objectives of Directive 2008/98/EC of the European Parliament and Council, dated 19 November 2008, concerning waste and repealing certain directives. These objectives include the reduction of waste generation and disposal, alongside the promotion of waste recycling and recovery. We developed a model that considered waste generation (X) as input, waste recycling or reuse (Y) as output and waste disposal (BY) as bad output (to be minimised). Given the relatively small sample size (27 EU countries), the model was intentionally streamlined in terms of the number of variables.

Additionally, we collected data from EUROSTAT on the number of individuals involved in waste-related activities (denoted as 'Social Sus') and government expenditure on waste management (measured in millions of euros, denoted as 'Eco Sus') for all 27 EU countries.[2] In our model, the number of individuals engaged in waste-related activities (Social Sus) served as a proxy for social sustainability, acting as an external factor to determine the direction (or path) towards the efficient frontier. Government expenditure on waste management (Eco Sus) was used to represent economic sustainability, functioning as an additional external factor influencing the direction (or path) towards the efficient frontier. By incorporating these elements, we aimed at integrating economic and social sustainability considerations into the environmental sustainability aspects already defined by the input/output variables. Consequently, we were able to estimate sustainable targets encompassing all dimensions of sustainability (i.e. environmental, social, economic).

Table 1 presents a descriptive analysis of the collected variables, while Table 2 displays the correlations between these variables.

As presented in Table 2, there were no high correlations between variables, except between the two external factors considered (with a correlation equal to 0.86).

Figure 1 presents the distributions of the collected variables.

Results

This section summarises the results of the analysis, focused on the calculation of efficiency scores and the identification of flexible waste management targets for each European country. Efficiency scores and targets were derived from a model incorporating one input (X, waste generation), one bad output (waste disposal), one output (waste recycling or reuse) and two external factors (Soc Sus, Eco Sus) to determine the direction towards the efficient frontier.

Figure 2 presents the results of the efficiency analysis. All EU countries were categorised into five groups based on their efficiency quartiles:

- *Efficient group* Countries on the efficient frontier, with an efficiency score of 0 (in green).
- *Low inefficiency group* Countries with an efficiency score greater than 0 but less than 0.036 (in light green).
- *Medium–low inefficiency group* Countries with an efficiency score between 0.036 and 0.088 (in light yellow).
- *Medium–high inefficiency group* Countries with an efficiency score between 0.088 and 0.145 (in yellow).
- *High inefficiency group* Countries with an efficiency score greater than 0.145 (in red).

[2] Due to a lack of available data for Cyprus in 2021, we estimated the number of employees in the waste sector based on the percentage of employees in similar sectors in similarly sized countries (e.g. Malta, Luxembourg; approximately 2%). This equated to roughly 1700 people.

Table 1 Descriptive statistics of the collected variables

	Min	First quartile	Mean	Median	Third quartile	Max	Standard deviation
X	302	454	545	511	637	835	136
BY	87	243	291	270	345	544	95
Y	34	143	233	213	34	521	128
Social Sus	626	7287	38,607	14,465	626	207,825	58,121
Eco Sus	25	108	1931	439	25	12,882	3477

Table 2 Correlation matrix

	X	*BY*	*Y*	Social Sus	Eco Sus
X	1.00				
BY	0.44	1.00			
Y	0.78	− 0.13	1.00		
Social Sus	− 0.09	− 0.30	0.17	1.00	
Eco Sus	− 0.04	− 0.21	0.14	0.86	1.00

Fig. 1 Distributions of inputs, outputs and sustainability indicators. From top left: distribution of waste generated (*X*), distribution of waste sent to landfill and incinerated (*BY*), distribution of waste to be recycled (*Y*), distribution of social sustainability (Social Sus) and distribution of economic sustainability (Eco Sus)

The map in Fig. 2 reveals that Central European countries (i.e. Germany, Austria, Slovenia, Poland, Romania) excelled in waste management. Countries with slight inefficiency, including Bulgaria and the Netherlands, bordered the most efficient nations. In contrast, the majority of medium–low-efficiency countries were dispersed across both Northern Europe (i.e. Denmark, Sweden, Lithuania, Latvia) and Southern Europe (i.e. Italy, Spain).

Medium–high inefficiency countries included Central European countries such as France, Belgium, Luxembourg and Czechia, as well as Balkan countries such as Hungary and Croatia. Finally, Ireland, Malta, Greece, Cyprus, Portugal and Finland exhibited high inefficiency. These findings are somewhat surprising, as they indicate a predominance of Central European countries with high efficiency in waste management, with no clear East–West or North–South European divide. Notably, Romania's efficiency could be attributed to its low waste generation (34 tonnes/inhabitant), representing the lowest rate in Europe.

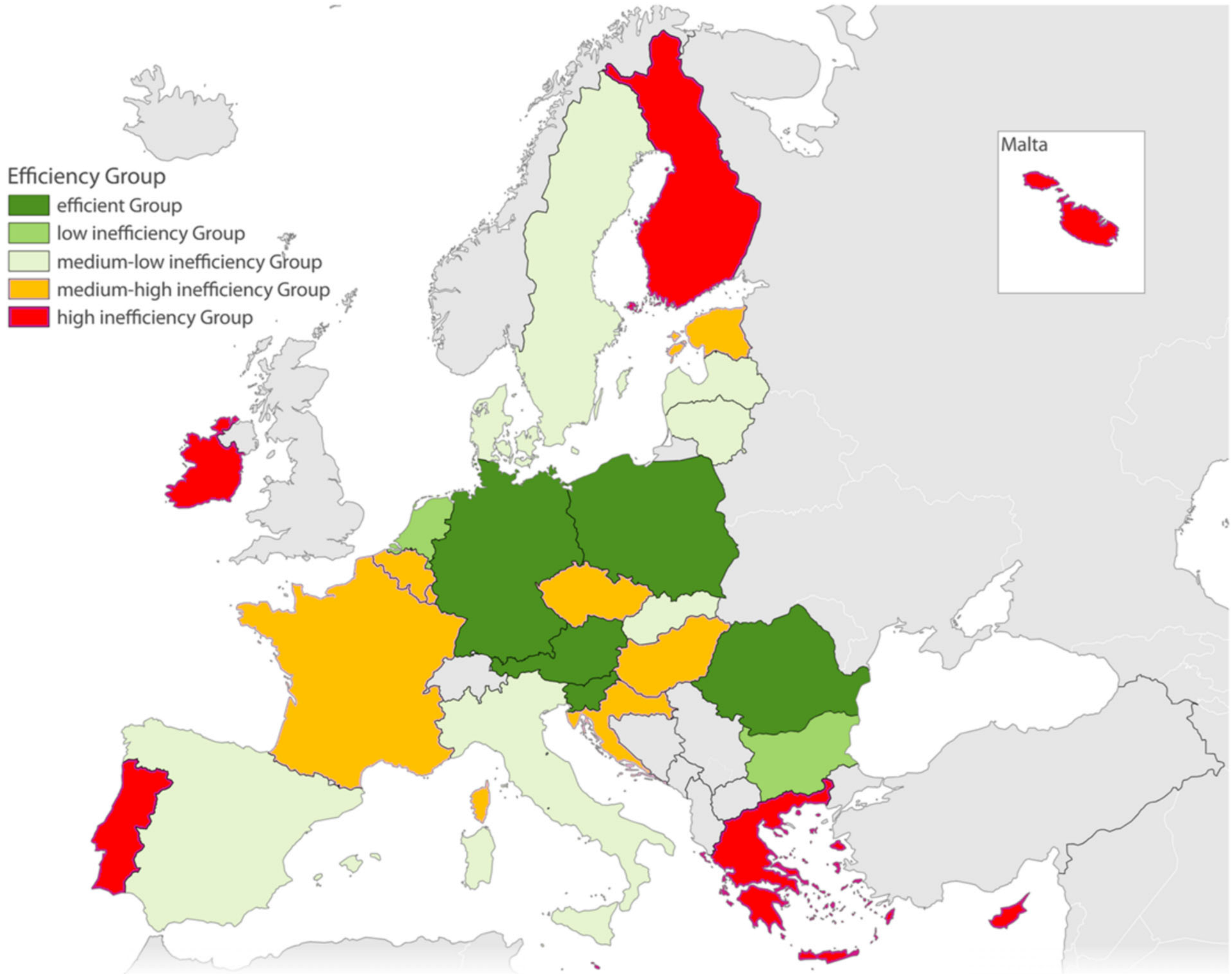

Fig. 2 Map of EU countries by waste efficiency cluster (Color figure online)

As outlined in the 'Method' section, our approach enabled us to easily calculate the sustainable targets that each country should reach to become efficient (see Table 3). These targets identified that countries in the efficient group (in green in Table 3) should aim at maintaining their original values of X, Y and BY, as they are already operating at optimal efficiency. To provide deeper insight into the results, Table 4 presents the efficiency scores in the second column and the percentage reduction in waste generation ($RX\%$) in the third column. This reduction is calculated as $\frac{\text{Target}X-X}{X}$. The results indicate that several EU countries need to significantly reduce their waste generation, by up to 40% (as observed for Malta).

Due to the flexibility of the directional measure, we were able to estimate the required increase in municipal waste recycling relative to the waste generated (see Table 4, column three). We also compared the ratio of Y to target X (Table 4, column four) with the original Y to X ration. The efficiency targets generally show a need to increase the recycling rate, with some targets exceeding the 55% regulatory target set by the European waste regulatory framework (highlighted in green in the table). Specifically, while seven EU countries met the regulatory target in 2021, our estimates suggest that thirteen countries will need to achieve at least 55% recycling to become efficient. Notably, not all EU countries must meet this regulatory target to become efficient, highlighting the potential drawbacks of inflexible regulatory targets on waste efficiency.

As a final analysis, we compared the ratio of BY and Y to X (i.e. the ratio of waste treated to waste generated) in 2021 with the same ratio for the calculated targets (Fig. 3). To clarify, the values in orange in Fig. 3 represent $\frac{BY+Y}{X}$, while those in green represent $\frac{\text{Target}BY+\text{Target}Y}{\text{Target}X}$.

It is important to emphasise, as indicated in Table 4, that nearly all countries require a reduction in waste generation to achieve their target X. Consequently, a 'green' result in Fig. 3 exceeding 100% implies this reduction in X (i.e. the denominator of the calculated value). The comparison demonstrates that, in general, for most EU countries to become efficient, they must manage more waste per capita

Table 3 Sustainable efficiency targets for input *X*, output *Y* and bad output *BY* for each EU country

Country	Target *X*	Target *BY*	Target *Y*
Austria	**835**	**314**	**521**
Belgium	670.52	288.89	458.43
Bulgaria	441.33	140.00	126.67
Croatia	383.06	226.76	169.32
Cyprus	402.15	268.05	190.46
Czechia	486.03	285.35	283.35
Denmark	706.17	291.89	471.99
Estonia	356.82	248.71	136.34
Finland	504.64	317.01	303.96
France	487.75	272.36	285.25
Germany	**651.00**	**193.00**	**451.00**
Greece	368.99	343.06	153.74
Hungary	376.82	241.43	162.41
Ireland	520.24	307.88	320.24
Italy	472.28	177.99	268.12
Latvia	427.33	239.63	218.35
Lithuania	439.44	221.01	231.76
Luxembourg	703.14	302.71	470.83
Malta	368.26	397.31	152.94
Netherlands	503.13	210.47	302.29
Poland	**362.00**	**217.00**	**146.00**
Portugal	411.79	335.34	201.13
Romania	**302.00**	**246.00**	**34.00**
Slovakia	463.52	223.81	258.42
Slovenia	**511.00**	**87.00**	**311.00**
Spain	425.48	247.53	216.30
Sweden	390.39	235.88	177.44

Efficient countries highlighted in bold

than they generate (indicated by the red dashed line in Fig. 3). While this result may appear counterintuitive, it could indicate two key points. First, smaller EU countries (e.g. Malta) could benefit from importing waste for disposal from larger EU countries with lower disposal capacity (e.g. Italy), thereby offsetting investment costs or even generating revenue. Second, the estimated targets consider reductions in both *X* and *BY*, implying improvements in *Y*. As shown in Tables 3 and 4, for EU countries to achieve efficiency, they must significantly focus on reducing *X*. Consequently, the relationship illustrated in Fig. 3 indicates that when countries strive for efficiency, their reduction in waste generation may result in overcapacity in waste disposal (both beneficial and harmful). This overcapacity can be utilised to manage waste generated in previous years and stored in landfills, reintroducing 'stationary' raw materials into the economy. Alternatively, it can be leveraged on a global scale through the importation of waste from other countries for reintroduction into the market as raw material. In particular, this latter approach could position the EU as a significant geopolitical player in waste management and resource recovery.

However, to support the transformation of the EU along these lines, further research should consider the costs associated with waste transportation and disposal, which were not accounted for in this study due to data limitations. The physical movement of waste incurs transportation costs, and there are cost differences in disposal between countries. While this may lead to internal competition within the EU, it may also serve as a strategic advantage: if each country specialises in a certain type of waste (e.g. paper), thereby reducing production costs, this could result in lower expenditures for the country(ies) utilising this asset for recycling. Of course, policymakers must consider whether, after accounting for transportation costs, the export of waste remains advantageous compared to internal handling (in alignment with the classic 'make-or-buy' framework). Additionally, domestic acceptance of waste

Table 4 Efficiency scores (second column), percentage reduction of *X* (i.e. target efficiency compared to the original value; third column), percentage of *Y* on *X* for the original data (fourth column) and Target *Y* on Target *X* (fifth column)

Country	Efficiency score	*RX%**	Original recycle rate (%)	Target recycle rate (%)
Austria	0	0	**62**	**62**
Belgium	0.115	− 11	**56**	**68**
Bulgaria	0.001	− 1	28	29
Croatia	0.144	− 14	32	44
Cyprus	0.382	− 38	14	47
Czechia	0.145	− 15	43	**58**
Denmark	0.084	− 8	**58**	**67**
Estonia	0.091	− 10	30	38
Finland	0.194	− 20	39	**60**
France	0.137	− 14	44	**58**
Germany	0	0	**69**	**69**
Greece	0.240	− 28	17	42
Hungary	0.091	− 9	35	43
Ireland	0.190	− 19	41	**62**
Italy	0.049	− 5	52	**57**
Latvia	0.073	− 7	44	51
Lithuania	0.087	− 8	44	53
Luxembourg	0.116	− 11	**55**	**67**
Malta	0.332	− 40	13	42
Netherlands	0.024	− 2	**58**	**60**
Poland	0	0	40	40
Portugal	0.177	− 20	30	49
Romania	0	0	11	11
Slovakia	0.069	− 7	49	**56**
Slovenia	0	0	**61**	**61**
Spain	0.088	− 9	42	51
Sweden	0.065	− 7	39	45

*Reduction of *X* from original value to Target *X* value (in percentage). Countries with recycle rates above or equal to 55% are shown in bold

disposal infrastructure (falling outside the scope of the present study) is a critical aspect that is challenging but necessary to evaluate.

Discussion

Before discussing the results and comparing them with those of previous studies, we must first address a primary limitation of the present research. Foremost, our analysis was constrained by the limited number of variables due to the small sample size. However, this structure was necessary to mitigate the 'curse of dimensionality' (see Daraio & Simar, 2007) affecting nonparametric analyses, which favour large datasets and parsimonious models.

Comparing our results with findings reported in the literature, there are notable similarities in the efficient countries identified (i.e. the efficient group in Fig. 2). Slovenia, included in our efficient group, is also recognised in the literature as one of the most efficient countries in municipal waste treatment (Marques & Teixeira, 2022; Ye et al., 2022). However, there are some discrepancies between our work and previous studies, as Ye et al. (2022) identified Germany and Austria as low-efficiency countries, yet we included them in our efficient group. However, our findings regarding Austria and Germany as countries on or near the efficient frontier align with most previous works (Castillo-Giménez et al., 2019b; Ríos & Picazo-Tadeo, 2021). Moreover, our results corroborate the analyses of Minelgaitė and Liobikienė (2019) with regard to Austria and Germany's intention to recycle.

Although we identified Romania as efficient in municipal waste management, other studies (Castillo-Giménez et al., 2019a; Marques & Teixeira, 2022; Ríos & Picazo-Tadeo, 2021) have positioned Romania among the lowest performing countries. A potential explanation for this is

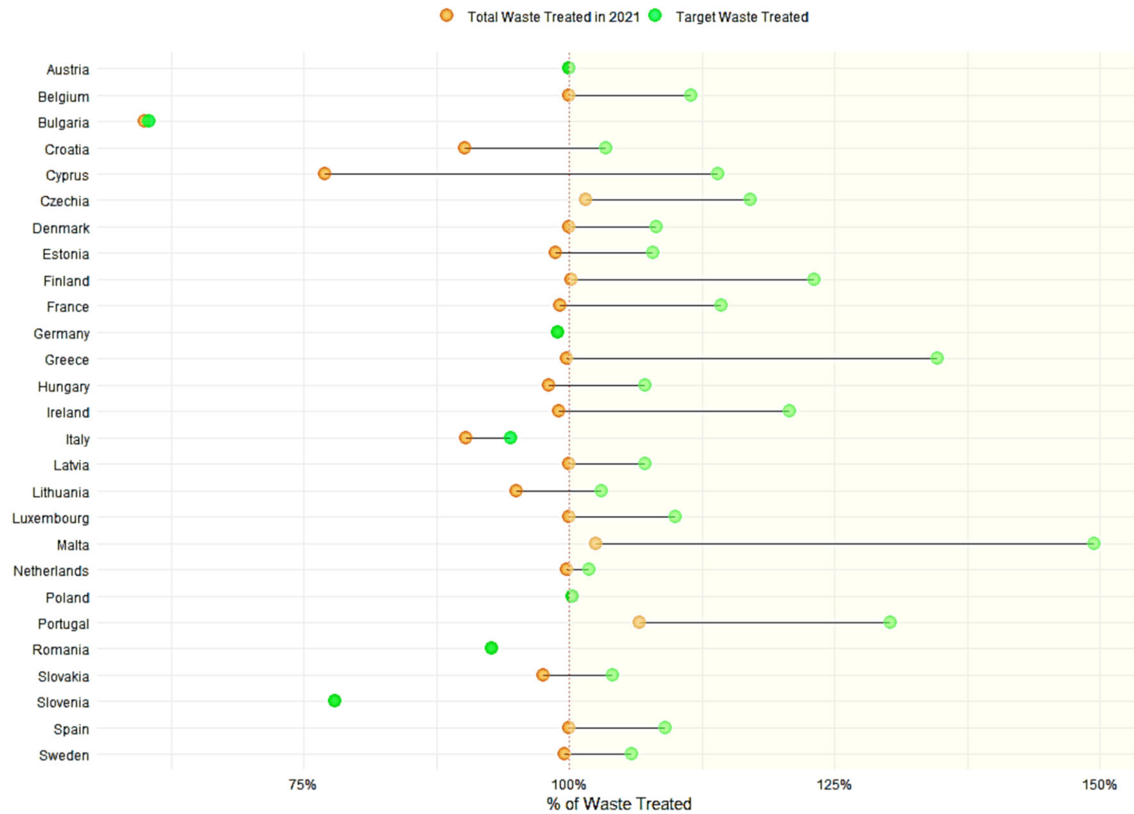

Fig. 3 Comparison between $\frac{BY+Y}{X}$ (in orange) and $\frac{\text{Target}_{BY}+\text{Target}_{Y}}{\text{Target}_{X}}$ (in green). The dotted red line represents the 100% ratio (Color figure online)

that, relative to previous works, our analysis placed greater emphasis on the resources expended. Minelgaitė and Liobikienė (2019) observed the highest levels of waste generation in the most economically developed EU countries, as measured by gross domestic product (GDP), highlighting the unsustainability of EU targets for all countries. Indeed, while GDP reflects economic development, it does not necessarily indicate investment in municipal waste management (the indicator adopted in the present analysis). In the case of Romania, Minelgaitė and Liobikienė (2019) found a low propensity for reuse and waste reduction, partly due to low waste generation per capita, as corroborated by our analysis (i.e. 302 tonnes/ inhabitant in Romania versus an average of 545 tonnes/inhabitant for all countries considered). These findings suggest that Romania may be an outlier—a factor that more robust order-m estimators (for an introduction, see Daraio & Simar, 2007) could mitigate more effectively than the DEA VRS method (see, for example, Di Leo et al., 2024).

A significant finding of our research is a general need for reduced waste generation (RX% in Table 4), which will require concerted effort from both producers and consumers. At the producer level, alternative business strategies are being implemented in high-impact industries (e.g. fashion) by redefining traditional sales models (Ritch & Siddiqui, 2023), also to better align with consumer needs (Papamichael et al., 2024). In other sectors (e.g. food), consumer involvement in waste reduction has been identified as crucial (Stancu et al., 2016). While effective methods to combat food waste and prevent food loss must be identified (Economou et al., 2024), the purchase of food items nearing expiry (Principato et al., 2021) may contribute significantly. Additionally, end-of-life approaches such as energy generation from waste (Amato et al., 2023) present viable options, though they require rigorous sustainability analyses. Attention must also be given to the added value that resides in specific wastes (Ippolito et al., 2023) and appropriate waste management strategies in emerging economies (Fosso Wamba et al., 2023; Kuhn et al., 2024).

Institutional efforts must be intensified to implement best practices from various sectors (including those highlighted above) to reduce municipal waste. In addition, decision-making must consider the costs of inaction, emphasising forward-looking policy choices (Cucchiella et al., 2014) and the creation of waste collection communities (Daraio et al., 2024). Furthermore, although European regulations govern waste management, each country has specific goals and targets. The EU should therefore consider national regulatory outcomes and evaluate their effects. Fixed EU-wide targets do not adequately reflect the diversity among countries and could exacerbate existing disparities.

Cross-country comparisons, identifying benchmarks and addressing challenges, are crucial for achieving sustainability goals (Chioatto et al., 2024; Molinos-Senante et al., 2024). Different waste categories may require unique technologies and solutions (Colasante et al., 2022), and performance towards circular models may vary across Europe. In this context, efforts to reduce illegal waste, invest in circular technologies and ensure the equitable distribution of value among stakeholders are imperative (D'Adamo et al., 2024). Flexible management may represent a pragmatic and non-ideological approach recognising waste management as a complex system with multiple inputs. Countries should aim at enhancing their specific competencies and collaborating on strategies of industrial symbiosis, to create sustainable communities with other countries. Only in this way can Europe achieve ambitious goals with effective and just results.

Limitations and Future Research Directions

While the flexibility of our proposed method and analysis may allow for a paradigm shift in regulation, certain limitations must be acknowledged. The foremost limitation pertains to the dataset, which extended only to the year 2021. Consequently, it was not possible to consider technological advancements or efficiency changes over time. This limitation can only be mitigated in the future, when more data become available (particularly on the individuals involved in waste disposal activities). Policymakers should therefore intensify their efforts to maintain and disseminate data in this area to facilitate accurate and up-to-date scientific analyses.

Another limitation concerns the model employed. In our analysis, we considered the bad output as input. Future research could explore the application of variants of the DEA model, such as the by-production model (Murty et al., 2012). In particular, this model may be useful for incorporating other negative externalities, such as CO_2 emissions (as demonstrated by Aparicio et al., 2020).

A further issue, again concerning data, is the limited number of observations. As the EU comprises only 27 member states, only 27 observations were collected. Future analyses could be extended to include a larger sample of non-European countries, addressing the challenge of data comparability across different sources.

As previously mentioned, the study did not account for the costs associated with waste transportation and disposal, primarily due to limited data availability. This aspect warrants further exploration in future research. Similarly, the social acceptance of waste recycling and disposal facilities among citizens was not investigated, again due to data unavailability. Policymakers must engage more effectively with citizens on this issue, communicating the advantages and disadvantages of such facilities and providing, where possible, data for future research regarding public acceptance indices.

A final criticism that may be levelled against this research concerns its 'cumulative' view of municipal waste, without distinguishing between different waste types (e.g. paper, metals). This limitation is predominantly attributable to the lack of disaggregated data. Future research could address this by focusing on specific waste types to establish more targeted goals. Additionally, the method employed was susceptible to the influence of outliers, as evidenced in the case of Romania. Future robust analyses could resolve this issue by incorporating additional observations.

Conclusions

The present study analysed the municipal waste management of all 27 EU member states, estimating efficiency using a flexible directional DEA method. This method considered the specific characteristics of each country and determined pathways to reach the efficient frontier through external factors encompassing social and economic sustainability. This approach further enabled the calculation of flexible and sustainable targets for each country.

The proposed targets provide valid alternatives to the rigid regulatory benchmarks proposed by the EU in the Waste Framework Directive, prioritising efficiency in environmental, social and economic spheres. The results indicate that, to become efficient, EU countries must make substantial efforts to reduce the amount of waste generated, in alignment with the primary goal of the waste hierarchy framework. Notably, achieving 55% recycling or reuse of waste by 2025, as stipulated by current regulations, may not be necessary for all countries to reach efficiency.

The findings reveal that as countries increase their efficiency, they will likely acquire greater disposal capacity (both good and bad) than their volume of waste generated. This surplus capacity may be reinvested locally or positioned for international trade by a unified European entity. Additionally, the results show that, within Europe, Romania demonstrates greater efficiency due to its lower waste generation per capita. Central European countries (e.g. Germany, Austria, Slovenia, Poland) also perform well, showing satisfactory waste management. However, significant disparities exist within Europe, suggesting that enhanced collaboration could result in positive impacts (e.g. reductions in illegal waste, transportation and dependence on raw materials from non-European countries).

Flexible waste management appears crucial for achieving sustainability goals. Ideological approaches that minimise waste generation at the expense of economic growth and/or jobs do not represent sustainable development. Thus, the circular economy model underpinning waste management advocates for dynamic targets for different countries, balancing the three dimensions of sustainability with efficient resource use.

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Declarations

Conflict of interest The authors declare that they have no known conflict of financial interests or personal relationships that have, or could be perceived to have, influenced the work reported in this article. Author Idiano D'Adamo is a member of the board of the Global Journal of Flexible Systems Management as Associate Editor.

Ethical Approval This study utilised secondary data and did not involve any human or animal subjects.

References

Aigner, D., Lovell, C. A. K., & Schmidt, P. (1977). Formulation and estimation of stochastic frontier production function models. *Journal of Econometrics, 6*(1), 21–37. https://doi.org/10.1016/0304-4076(77)90052-5

Amato, A., Tsigkou, K., Becci, A., Beolchini, F., Ippolito, N. M., & Ferella, F. (2023). Life cycle assessment of biomethane vs. fossil methane production and supply. *Energies, 16*(12), 4555. https://doi.org/10.3390/en16124555

Andretta, A., D'Addato, F., Serrano-Bernardo, F., Zamorano, M., & Bonoli, A. (2018). Environmental taxes to promote the eu circular economy's strategy: Spain vs. Italy. *Environmental Engineering and Management Journal, 17*(10), 2307–2311. https://doi.org/10.30638/eemj.2018.229

Aparicio, J., Kapelko, M., & Zofío, J. L. (2020). The measurement of environmental economic inefficiency with pollution-generating technologies. *Resource and Energy Economics, 62*, 101185. https://doi.org/10.1016/j.reseneeco.2020.101185

Banker, R. D., Charnes, A., & Cooper, W. W. (1984). Some models for estimating technical and scale inefficiencies in data envelopment analysis. *Management Science, 30*(9), 1078–1092. https://doi.org/10.1287/mnsc.30.9.1078

Biancardi, A., Colasante, A., D'Adamo, I., Daraio, C., Gastaldi, M., & Uricchio, A. F. (2023). Strategies for developing sustainable communities in higher education institutions. *Scientific Reports, 13*(1), 20596. https://doi.org/10.1038/s41598-023-48021-8

Caglar, A. E., Gökçe, N., & Şahin, F. (2024). Sustaining environment through municipal solid waste: Evidence from European Union economies. *Environmental Science and Pollution Research, 31*(4), 6040–6053. https://doi.org/10.1007/s11356-023-31494-5

Castillo-Giménez, J., Montañés, A., & Picazo-Tadeo, A. J. (2019a). Performance in the treatment of municipal waste: Are European Union member states so different? *Science of the Total Environment, 687*, 1305–1314. https://doi.org/10.1016/j.scitotenv.2019.06.016

Castillo-Giménez, J., Montañés, A., & Picazo-Tadeo, A. J. (2019b). Performance and convergence in municipal waste treatment in the European Union. *Waste Management, 85*, 222–231. https://doi.org/10.1016/J.WASMAN.2018.12.025

Chambers, R. G., Chung, Y., & Färe, R. (1998). Profit, directional distance functions, and Nerlovian efficiency. *Journal of Optimization Theory and Applications, 98*(2), 351–364. https://doi.org/10.1023/A:1022637501082

Charnes, A., Cooper, W. W., & Rhodes, E. (1978). Measuring the efficiency of decision making units. *European Journal of Operational Research, 2*(6), 429–444. https://doi.org/10.1016/0377-2217(78)90138-8

Chioatto, E., Fedele, A., Ciro Liscio, M., & Sospiro, P. (2024). Testing data envelopment analysis models on the performance of European Union regions in sustainable waste management. *Waste Management, 175*, 170–182. https://doi.org/10.1016/j.wasman.2024.01.008

Chioatto, E., & Sospiro, P. (2023). Transition from waste management to circular economy: The European Union roadmap. *Environment, Development and Sustainability, 25*(1), 249–276. https://doi.org/10.1007/s10668-021-02050-3

Colasante, A., D'Adamo, I., Morone, P., & Rosa, P. (2022). Assessing the circularity performance in a European cross-country comparison. *Environmental Impact Assessment Review, 93*, 106730. https://doi.org/10.1016/j.eiar.2021.106730

Cucchiella, F., D'Adamo, I., & Gastaldi, M. (2014). Strategic municipal solid waste management: A quantitative model for Italian regions. *Energy Conversion and Management, 77*, 709–720. https://doi.org/10.1016/j.enconman.2013.10.024

D'Adamo, I., Favari, D., Gastaldi, M., & Kirchherr, J. (2024). Towards circular economy indicators: Evidence from the European Union (EU). *Waste Management & Research*. https://doi.org/10.1177/0734242X241237171

D'Adamo, I., Gastaldi, M., Piccioni, J., & Rosa, P. (2023). The role of automotive flexibility in supporting the diffusion of sustainable mobility initiatives: A stakeholder attitudes assessment. *Global Journal of Flexible Systems Management, 24*(3), 459–481.

D'Amato, A., Mazzanti, M., Nicolli, F., & Zoli, M. (2018). Illegal waste disposal: Enforcement actions and decentralized environmental policy. *Socio-Economic Planning Sciences, 64*, 56–65. https://doi.org/10.1016/j.seps.2017.12.006

Daraio, C., Di Leo, S., & Simar, L. (2024). Viable eco-efficiency targets for waste collection communities. *Scientific Reports, 14*(1), 15038. https://doi.org/10.1038/s41598-024-66077-y

Daraio, C., & Simar, L. (2007). *Advanced robust and nonparametric methods in efficiency analysis: Methodology and applications* (Vol. 4). Springer. https://doi.org/10.1007/978-0-387-35231-2

Daraio, C., & Simar, L. (2016). Efficiency and benchmarking with directional distances: A data-driven approach. *Journal of the Operational Research Society, 67*(7), 928–944. https://doi.org/10.1057/jors.2015.111

De Pascale, A., Di Vita, G., Giannetto, C., Ioppolo, G., Lanfranchi, M., Limosani, M., & Szopik-Depczyńska, K. (2023). The circular economy implementation at the European Union level. Past, present and future. *Journal of Cleaner Production, 423*, 138658. https://doi.org/10.1016/j.jclepro.2023.138658

Di Foggia, G., & Beccarello, M. (2023). Sustainability pathways in European waste management for meeting circular economy goals. *Environmental Research Letters, 18*(12), 124001. https://doi.org/10.1088/1748-9326/ad067f

Di Leo, S., Chicca, M., Daraio, C., Guerrini, A., & Scarcella, S. (2024). A robust benchmarking of direct margin in Italy's energy retail markets. *Utilities Policy, 86*, 101701. https://doi.org/10.1016/j.jup.2023.101701

Economou, F., Chatziparaskeva, G., Papamichael, I., Loizia, P., Voukkali, I., Navarro-Pedreño, J., et al. (2024). The concept of food waste and food loss prevention and measuring tools. *Waste Management & Research*. https://doi.org/10.1177/0734242X241237187

Färe, R., & Grosskopf, S. (2000). Theory and application of directional distance functions. *Journal of Productivity Analysis, 13*(2), 93–103. https://doi.org/10.1023/A:1007844628920

Färe, R., Grosskopf, S., & Margaritis, D. (2008). Efficiency and productivity: Malmquist and more. In H. O. Fried, C. A. K. Lovell, & S. S. Schmidt (Eds.), *The measurement of productive efficiency and productivity growth* (Vol. 5, pp. 522–622). Oxford University Press.

Ferrante, M., Vitti, M., Facchini, F., & Sassanelli, C. (2024). Mapping the relations between the circular economy rebound effects dimensions: A systematic literature review. *Journal of Cleaner Production, 456*, 142399. https://doi.org/10.1016/j.jclepro.2024.142399

Fosso Wamba, S., Fotso, M., Mosconi, E., & Chai, J. (2023). Assessing the potential of plastic waste management in the circular economy: A longitudinal case study in an emerging economy. *Annals of Operations Research*. https://doi.org/10.1007/s10479-023-05386-3

Fukuyama, H., & Weber, W. L. (2017). Advances in DEA theory and applications. In K. Tone (Ed.), *Chap 3." In advances in DEA theory and applications: With extensions to forecasting models* (1st ed., pp. 20–27). Wiley Online Library.

Garcia-Saravia Ortiz-de-Montellano, C., & van der Meer, Y. (2022). A theoretical framework for circular processes and circular impacts through a comprehensive review of indicators. *Global Journal of Flexible Systems Management, 23*(2), 291–314. https://doi.org/10.1007/s40171-022-00300-5

GargSushil, S. (2024). Reflecting theoretical perspective on de-internationalization strategies: A cross-case analysis using flowing stream strategy framework. *Global Journal of Flexible Systems Management, 25*(1), 43–61. https://doi.org/10.1007/s40171-023-00361-0

Giannakitsidou, O., Giannikos, I., & Chondrou, A. (2020). Ranking European countries on the basis of their environmental and circular economy performance: A DEA application in MSW. *Waste Management, 109*, 181–191. https://doi.org/10.1016/j.wasman.2020.04.055

Halkos, G., & Petrou, K. N. (2019). Assessing 28 EU member states' environmental efficiency in national waste generation with DEA. *Journal of Cleaner Production, 208*, 509–521. https://doi.org/10.1016/j.jclepro.2018.10.145

Hondroyiannis, G., Sardianou, E., Nikou, V., Evangelinos, K., & Nikolaou, I. (2024). Waste generation and macroeconomic drivers: A panel study for European countries and regions. *Management of Environmental Quality: an International Journal*. https://doi.org/10.1108/MEQ-08-2023-0297

Hsu, W.-T., Domenech, T., & McDowall, W. (2022). Closing the loop on plastics in Europe: The role of data, information and knowledge. *Sustainable Production and Consumption, 33*, 942–951. https://doi.org/10.1016/j.spc.2022.08.019

Ippolito, N. M., Passadoro, M., Ferella, F., Pellei, G., & Vegliò, F. (2023). Recovery of metals from printed circuit boards by gold-REC 1 hydrometallurgical process. *Sustainability, 15*(9), 7348. https://doi.org/10.3390/su15097348

Johansson, N., & Forsgren, C. (2020). Is this the end of end-of-waste? Uncovering the space between waste and products. *Resources, Conservation and Recycling, 155*, 104656. https://doi.org/10.1016/j.resconrec.2019.104656

Kamsu-Foguem, B., Clermont, P., Tchuente, D., Tiako, P., & Fosso Wamba, S. (2023). Service provider risk mitigation in aeronautics supply chains. *Global Journal of Flexible Systems Management, 24*(4), 615–631. https://doi.org/10.1007/s40171-023-00354-z

Kiani Mavi, R., Kiani Mavi, N., Hosseini Shekarabi, S. A., Pepper's, M., & Arisian, S. (2023). Supply chain resilience: A common weights efficiency analysis with non-discretionary and non-controllable inputs. *Global Journal of Flexible Systems Management, 24*(1), 77–99. https://doi.org/10.1007/s40171-024-00380-5

Kirchherr, J. (2023). Bullshit in the sustainability and transitions literature: A provocation. *Circular Economy and Sustainability, 3*(1), 167–172. https://doi.org/10.1007/s43615-022-00175-9

Kirchherr, J., Piscicelli, L., Bour, R., Kostense-Smit, E., Muller, J., Huibrechtse-Truijens, A., & Hekkert, M. (2018). Barriers to the circular economy: Evidence from the European Union (EU). *Ecological Economics, 150*, 264–272. https://doi.org/10.1016/j.ecolecon.2018.04.028

Konovalov, N., Gromoff, A., Vladimirova, A. V., & Gorchakov, Y. (2020). Can CRM flexibility raise bank efficiency? *Global Journal of Flexible Systems Management, 21*(2), 101–112. https://doi.org/10.1007/s40171-020-00232-y

Kuhn, S., Opoku, R., Diaba, D. D., Agyarko, K. A., & Never, B. (2024). The transition of Ghana's cooling appliance sector to a circular economy via a small wins governance framework. *Sustainable Production and Consumption, 46*, 119–131. https://doi.org/10.1016/j.spc.2024.02.016

Kundi, M., & Sharma, S. (2015). Efficiency analysis and flexibility: A case study of cement firms in India. *Global Journal of Flexible Systems Management, 16*(3), 221–234. https://doi.org/10.1007/s40171-015-0094-0

Lavigne, C., De Jaeger, S., & Rogge, N. (2019). Identifying the most relevant peers for benchmarking waste management performance: A conditional directional distance Benefit-of-the-Doubt approach. *Waste Management, 89*, 418–429. https://doi.org/10.1016/j.wasman.2019.04.006

Le, T. T., Behl, A., & Graham, G. (2023). The role of entrepreneurship in successfully achieving circular supply chain management. *Global Journal of Flexible Systems Management, 24*(4), 537–561. https://doi.org/10.1007/s40171-023-00353-0

Lo Storto, C. (2024). Measuring the eco-efficiency of municipal solid waste service: A fuzzy DEA model for handling missing data. *Utilities Policy, 86*, 101706. https://doi.org/10.1016/j.jup.2023.101706

Marques, A. C., & Teixeira, N. M. (2022). Assessment of municipal waste in a circular economy: Do European Union countries share identical performance? *Cleaner Waste Systems, 3*, 100034. https://doi.org/10.1016/j.clwas.2022.100034

Marques, R. C., & Simões, P. (2009). Incentive regulation and performance measurement of the Portuguese solid waste management services. *Waste Management & Research, 27*(2), 188–196. https://doi.org/10.1177/0734242X08095025

Mazzanti, M., & Montini, A. (2014). Waste management beyond the north-south divide: Spatial analyses of geographical, economic and institutional dimensions. *Handbook on waste management* (pp. 1–22). Edward Elgar Pub. Ltd.

Meeusen, W., & van Den Broeck, J. (1977). Efficiency estimation from Cobb-Douglas production functions with composed error. *International Economic Review, 18*(2), 435–444. https://doi.org/10.2307/2525757

Mies, A., & Gold, S. (2021). Mapping the social dimension of the circular economy. *Journal of Cleaner Production, 321*, 128960. https://doi.org/10.1016/j.jclepro.2021.128960

Minelgaitė, A., & Liobikienė, G. (2019). Waste problem in European Union and its influence on waste management behaviours. *Science of the Total Environment, 667*, 86–93. https://doi.org/10.1016/j.scitotenv.2019.02.313

Molinos-Senante, M., Maziotis, A., & Sala-Garrido, R. (2024). Estimating the eco-efficiency of urban waste services towards sustainable waste management. *Sustainable Development*. https://doi.org/10.1002/sd.2983

Murty, S., Robert Russell, R., & Levkoff, S. B. (2012). On modeling pollution-generating technologies. *Journal of Environmental Economics and Management, 64*(1), 117–135. https://doi.org/10.1016/j.jeem.2012.02.005

Nepomuceno, T. C. C., Daraio, C., & Costa, A. P. C. S. (2020). Combining multi-criteria and directional distances to decompose non-compensatory measures of sustainable banking efficiency. *Applied Economics Letters, 27*(4), 329–334. https://doi.org/10.1080/13504851.2019.1616051

Nguyen, N.-T. (2020). Performance evaluation in strategic alliances: A case of Vietnamese construction industry. *Global Journal of Flexible Systems Management, 21*(1), 85–99. https://doi.org/10.1007/s40171-019-00230-9

Nicolli, F., Mazzanti, M., & Iafolla, V. (2012). Waste dynamics, country heterogeneity and european environmental policy effectiveness. *Journal of Environmental Policy & Planning, 14*(4), 371–393. https://doi.org/10.1080/1523908X.2012.719694

Papamichael, I., Voukkali, I., Economou, F., Liscio, M. C., Sospiro, P., Naddeo, V., & Zorpas, A. A. (2024). Investigation of customer behavior regarding circular fashion. *Sustainable Chemistry and Pharmacy, 41*, 101675. https://doi.org/10.1016/j.scp.2024.101675

Principato, L., Mattia, G., Di Leo, A., & Pratesi, C. A. (2021). The household wasteful behaviour framework: A systematic review of consumer food waste. *Industrial Marketing Management, 93*, 641–649. https://doi.org/10.1016/j.indmarman.2020.07.010

Ragossnig, A. M., & Schneider, D. R. (2019). Circular economy, recycling and end-of-waste. *Waste Management & Research, 37*(2), 109–111. https://doi.org/10.1177/0734242X19826776

Ríos, A.-M., & Picazo-Tadeo, A. J. (2021). Measuring environmental performance in the treatment of municipal solid waste: The case of the European Union-28. *Ecological Indicators, 123*, 107328. https://doi.org/10.1016/j.ecolind.2020.107328

Ritch, E. L., & Siddiqui, N. (2023). Fashioning the circular economy with disruptive marketing tactics mimicking fast fashion's exploitation of social capital: A case study exploring the innovative fashion rental business model "wardrobe." *Sustainability, 15*(19), 14532. https://doi.org/10.3390/su151914532

Romano, G., Lombardi, G. V., Rapposelli, A., & Gastaldi, M. (2022). The factors affecting Italian provinces' separate waste-collection rates: An empirical investigation. *Waste Management, 139*, 217–226. https://doi.org/10.1016/j.wasman.2021.12.037

Singh, A., Sushil, & Sharma, H. K. (2023). Total Interpretive structural modeling-polarity (TISM-P) to analyze the impact of energy on the sustainability performance of hotels: A case study. *Environment, Development and Sustainability*. https://doi.org/10.1007/s10668-023-03485-6

Singh, S., Dhir, S., Evans, S., & Sushil. (2021). The trajectory of two decades of global journal of flexible systems management and flexibility research: A bibliometric analysis. *Global Journal of Flexible Systems Management, 22*(4), 377–401. https://doi.org/10.1007/s40171-021-00286-6

Sondh, S., Upadhyay, D. S., Patel, S., & Patel, R. N. (2024). Strategic approach towards sustainability by promoting circular economy-based municipal solid waste management system—A review. *Sustainable Chemistry and Pharmacy, 37*, 101337. https://doi.org/10.1016/j.scp.2023.101337

Srivastava, S. K., & Bag, S. (2023). Recent developments on flexible manufacturing in the digital era: A review and future research directions. *Global Journal of Flexible Systems Management, 24*(4), 483–516. https://doi.org/10.1007/s40171-023-00351-2

Stancu, V., Haugaard, P., & Lähteenmäki, L. (2016). Determinants of consumer food waste behaviour: Two routes to food waste. *Appetite, 96*, 7–17. https://doi.org/10.1016/j.appet.2015.08.025

Sushil. (2018). How to check correctness of total interpretive structural models? *Annals of Operations Research, 270*(1), 473–487. https://doi.org/10.1007/s10479-016-2312-3

Sushil, & Dinesh, K. K. (2022). Structured literature review with TISM leading to an argumentation based conceptual model. *Global Journal of Flexible Systems Management, 23*(3), 387–407. https://doi.org/10.1007/s40171-022-00309-w

Ye, M., Jin, Y., & Deng, F. (2022). Municipal waste treatment efficiency in 29 OECD countries using three-stage Bootstrap-DEA model. *Environment, Development and Sustainability, 24*(9), 11369–11391. https://doi.org/10.1007/s10668-022-02227-4

Key Questions

1. How can we decide flexible regulatory targets to be efficient in municipal waste management for European Union countries?
2. What are the potentials of using data envelopment analysis with conditional directions in the waste regulatory field?
3. How can policy makers alternatively use the pursuit of efficiency to make the European Union an international key player in municipal waste management?

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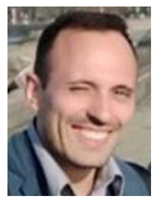

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