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Measuring environmental performance in the treatment of municipal solid waste: The case of the European Union-28

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ABSTRACT

This paper proposes a measure of environmental performance in the treatment of municipal solid waste, which is defined as a ratio between a composite indicator of waste treated through environmentally desirable operations –recycling and recovery in our case study– and a composite indicator of waste treated through undesirable operations –landfill and incineration. Moreover, it contributes both *overall* and *treatment-specific* indicators of performance. Data Envelopment Analysis (DEA) techniques are used to compute the environmental performance indicators and they are illustrated with an empirical assessment of the environmental performance of the European Union-28 (EU-28) members in their treatment of municipal waste, with data for the year 2017. Our results point to a worryingly low average level of performance, with the best performers being mainly Nordic and Central European countries such as Sweden, Germany, Belgium, Finland and Denmark; at the opposite end of the spectrum, environmental performance in the treatment of waste is particularly low in most of the Eastern European countries that joined the EU-28 from the 2000s, and some Southern member states. The determinants of performance are also investigated, the main finding being a positive and statistically significant association between environmental performance in municipal waste treatment and the level of economic development.

1. Introduction, motivation and background

Achieving sustainable development is one of the more challenging targets in today's society. In the 1980s, the document known as the *Brundtland Report* introduced this concept as '*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*' (WCED, 1987). Since then, citizens' concern about how to reconcile their own needs with those of future generations has only grown, and nowadays tends to be particularly keenly felt among younger generations. Sustainability is, however, a broad concept that includes economic, social and environmental issues, among others. That said, the environment is perhaps the dimension of sustainability that is currently attracting the most attention from policymakers and society as a whole, especially in developed regions of the world. Accordingly, accomplishing environmentally sustainable development is one of the headline targets on the current agenda of policymakers in the European Union (EU). In this respect, the *Europe 2020 Strategy* (EC, 2010) already accounted for '*climate action, environment, resource efficiency and raw materials*' as one of the strategic pillars aimed at achieving smart, sustainable and inclusive growth. Currently, the European Commission (EC) is working on the *European 2030 Strategy,* which further emphasizes the role of the environment in reaching sustainable development goals (EC, 2019).

Amongst the numerous environmental problems of concern to policymakers in the EU, municipal solid waste stands out. The growing amount of waste is the result of increasing urbanization, economic and population growth, and European citizens' consumption patterns and lifestyles (Zaman, 2014; Chifari et al., 2018; Halkos and Petrou, 2019). Municipal waste produces environmental damage, such as CO_2 emissions arising from some waste treatments; plastic-filled rivers, seas and oceans; and pressure on both renewable and non-renewable natural resources. The accumulation of solid waste also has damaging effects on terrestrial and aquatic ecosystems; e.g., small plastic particles interact with terrestrial organisms that facilitate essential ecosystem functions, such as soil dwelling invertebrates and plant-pollinators. In addition, municipal waste can cause human health problems and, ultimately, lead to a deterioration in citizens' quality of life. Thus, sustainability in the management of municipal waste is essential to the accomplishment of sustainable development.

The members of the European Union-28 (EU-28) generated nearly

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0.25 billion tonnes of municipal waste in 2017, according to the most recent data from Eurostat –the Statistical Office of the EU– yielding an average of 486 kg per capita. The EU has already passed legislation for the sustainable management of municipal waste (Sarra et al., 2017). The *Waste Framework Directive* 2008/98/EC (EC, 2008) provided detailed guidelines for municipal waste management, including waste prevention and waste treatment; the latter comprising landfill, recycling, incineration, and composting and digestion (EC, 2017). Furthermore, the European Environmental Agency (EEA) compiled the EU's targets for municipal solid waste generation and treatment for 2010–50 and provided some projections on the progress towards meeting these targets (EEA, 2013). It is estimated that the EU will just miss its 2020 target for waste generation per inhabitant, while projections regarding the 'near-zero landfill' objective are even more pessimistic. In this respect, the latest goals of the EU include a target of recycling 65% of municipal waste and reducing landfill to maximum of 10% by 2030. The implementation of the EC's *2018 Circular Economy Package* (EC, 2018) plays an essential role in achieving these goals; the ultimate objective of the *Circular Economy Action Plan* contained in this document is turning production into a circular flow in which recycling, reuse and repair assume a crucial role in municipal waste management.

While policymakers face the challenge of promoting sustainable waste management, researchers are charged with the task of providing them with sound information on which to base the design of improved environmental policies. In fact, the EEA has recently pointed out that '… *Environmental indicators are essential tools for assessing environmental trends, tracking progress against objectives and targets, evaluating the effectiveness of policies and communicating complex phenomena to non-technical audiences'* (EEA, 2014; p.5). In response to this demand, a large body of literature has emerged aimed at developing indicators capable of assessing performance in the management of municipal waste, as recently highlighted by Halkos and Petrou (2019). In doing so, several researchers have adopted approaches that jointly deal with waste prevention and treatment, including the waste hierarchy (Gharfalkar et al., 2015) and the life cycle assessment (Clearly, 2009), while others have focused exclusively on studying either waste prevention (Minelgaitė and Liobikienė, 2019) or waste management and treatment, as we do in this paper.

Within the line of research devoted to assessing performance in the treatment of municipal solid waste, the vast majority of papers have focused on the economic (cost) dimension of performance. However, the rapid deterioration in the sustainability of urban systems and the need to find ecological solutions to waste disposal have spurred research efforts devoted to assessing the environmental side of waste management and treatment. Accordingly, the development of environmental performance indicators has attracted growing attention in recent years. Rigamonti et al. (2016) review the literature on performance indicators for waste management systems from an environmental perspective. Moreover, these authors propose a comprehensive indicator to evaluate the environmental and economic sustainability of an integrated municipal solid waste management system; however, this indicator does not jointly include all possible waste treatments, so the authors themselves advocate the development of further indicators that incorporate more desirable and undesirable treatments.

In the same vein, other studies have focused on the evaluation of environmental performance of particular municipal solid waste treatments, such as incineration (Chen et al., 2010, 2012) or recycling (Lozano et al., 2004; Marques et al., 2012; Chang et al., 2013; Yeh et al., 2016; Expósito and Velasco, 2018). Moreover, Callao et al. (2019) separately analyse the environmental performance of several waste management treatments –including incineration, disposal and recovery– in a number of European countries. Conversely, Castillo-Giménez et al. (2019a) and Castillo-Giménez et al. (2019b) build a composite indicator of performance in municipal waste treatment, which jointly includes landfill, recycling, incineration, and composting and digestion as treatment options; however, environmental performance is not addressed in these papers, i.e., no distinction is made between desirable and undesirable treatment operations.

Against this background, the contribution of this paper is twofold. On the one hand, it proposes a composite indicator of environmental performance in the treatment of municipal solid waste. This indicator, which is computed with Data Envelopment Analysis (DEA), is defined as a ratio between an aggregate measure of waste treated through desirable operations and an aggregate measure of waste treated through undesirable operations. On the other hand, the composite indicator is empirically illustrated with an assessment of the environmental performance of the EU-28 members in their treatment of municipal solid waste. In this empirical application, as explained in more detail later, recycling and recovery are considered as desirable treatments since they reduce the impact of municipal solid waste on the environment, and make resources available for other productive activities. Conversely, landfill and incineration are seen as undesirable treatments because of their higher impact on the environment. Furthermore, this characterization of waste treatments reflects the European Union's current environmental policy priorities.

Several previous papers have employed DEA to study different facets of environmental performance in municipal solid waste treatment, including Halkos and Papageorgiou (2016), Díaz-Villavicencio et al. (2017), Sarra et al. (2017), Expósito and Velasco (2018) and Halkos and Petrou (2018, 2019). Our indicator is distinctive in that it jointly incorporates all available waste treatments, after first categorizing them as either desirable or undesirable. This allows us to calculate a composite indicator of overall environmental performance in municipal waste treatment. In addition, we propose a series of indicators of performance at the level of particular treatments. A further feature of our indicators is that they are easily understandable for policymakers and the general public, with scores ranging between 0 (worst performance) and 1 (best performance). In a second stage of our research, we study the distribution of environmental performance in municipal waste treatment across EU-28 countries, as well as its determinants, using truncated regression and bootstrapping, as suggested by Simar and Wilson (2007).

Following this Introduction, Section 2 presents the data and their sources, as well as the methodology; Section 3 discusses the results for the environmental performance of the EU-28 members in their treatment of municipal solid waste, and its determinants; finally, Section 4 concludes and comments on some policy issues.

2. Data, sources and methodological issues

2.1. Municipal solid waste in the European Union: Data and sources

As noted in the Introduction, one of the purposes of this research is to assess the performance of the European Union members in their treatment of municipal solid waste. In this regard, although the European Union was back to 27 members in January 2020, after the exit of the United Kingdom, our analysis focuses on the EU-28 since the statistics used are previous to that year.[1] In particular, the data have been collected at the country level from Eurostat and belong to year 2017.[2] As stated by the EC (EC, 2017), municipal solid waste consists of waste generated by households and other sources (such as commerce, small businesses, office buildings and public institutions), which is collected by (or on behalf of) local governments and disposed of through waste

[1] The European Unión-28 includes the following countries: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, and the United Kingdom.

[2] The data were accessed through https://ec.europa.eu/eurostat/web/main/data/database on 15 May 2019.

Table 1
Sample description: Desirable and undesirable treatments of municipal solid waste, 2017 (*Tonnes of waste per € billion of GDP in PPP*).

	Desirable treatments		Undesirable treatments	
	Recycling	Recovery	Landfill	Incineration
Austria	8.66	5.81	0.31	0.00
Belgium	6.31	4.95	0.10	0.10
Bulgaria	10.18	0.98	18.18	0.00
Croatia	5.29	0.01	16.23	0.00
Cyprus	4.01	0.09	18.87	0.00
Czechia	4.37	2.22	6.21	0.02
Denmark	9.42	10.76	0.17	0.00
Estonia	4.69	6.97	3.15	0.00
Finland	6.32	9.13	0.14	0.00
France	7.07	5.80	3.56	0.06
Germany	11.52	4.67	0.15	0.72
Greece	4.71	0.27	19.97	0.00
Hungary	6.63	3.05	9.17	0.00
Ireland	4.32	3.11	2.73	0.00
Italy	8.06	3.07	3.95	0.15
Latvia	5.09	0.54	5.94	0.00
Lithuania	9.32	3.55	6.34	0.00
Luxembourg	3.86	3.55	0.55	0.00
Malta	1.31	0.00	17.77	0.00
Netherlands	7.23	5.78	0.19	0.14
Poland	5.04	3.39	6.23	0.25
Portugal	6.00	4.17	10.01	0.00
Romania	2.01	0.62	10.25	0.00
Slovakia	4.94	1.58	10.02	0.00
Slovenia	10.67	1.40	1.88	0.70
Spain	5.62	2.16	8.98	0.00
Sweden	5.83	6.57	0.05	0.00
United Kingdom	6.46	5.38	2.50	0.42
European Union-28				
Mean	6.25	3.56	6.56	0.09
Standard deviation	2.47	2.80	6.50	0.20
Maximum	11.52	10.76	19.97	0.72
Minimum	1.31	0.00	0.05	0.00

management systems. In this respect, Eurostat provides country-level data on the amount of waste generated and treated through four main treatment operations: landfill, incineration (with or without energy recovery), recycling, and composting and digestion. According to the EC (EC, 2017), landfill consists of depositing municipal waste into or onto land. Incineration involves the thermal treatment of waste in an incineration plant; this treatment may include energy recovery, defined as the type of incineration that fulfils the energy efficient criteria established by the *Waste Framework Directive* of 2008 (EC, 2008). Recycling includes any treatment operation by which waste is reprocessed into materials or substances for either their original use or other usages. Finally, composting and digestion are biological decomposition processes of biodegradable waste under controlled conditions.

Regarding the management of municipal waste, article 4 of the *Waste Framework Directive* of 2008 established the following priorities for legislation and policy in the EU: '… *The following waste hierarchy shall apply as a priority order in waste prevention and management legislation and policy: (a) prevention; (b) preparing for re-use; (c) recycling; (d) other recovery* (e.g., *energy recovery); and (e) disposal*'. Accordingly, beyond waste prevention, the most environmentally desirable operations to treat municipal solid waste are recycling and other recovery operations, including energy recovery. Recycling and recovery increase the availability of resources for other productive activities, reduce the environmental impact associated with waste management and promote job creation and investment (Expósito and Velasco, 2018; Castillo-Giménez et al., 2019a, 2019b). Conversely, waste disposal operations such as landfilling and incineration, are considered to be the least desirable options for the environment, due to their high costs in terms of landscape degradation and pollution (Halkos and Petrou, 2019).

Based on the abovementioned EU's environmental policy priorities, and given the data for municipal solid waste treatment available from Eurostat, two environmentally desirable treatment operations for municipal waste have been considered, namely, *recycling* –which also includes composting and digestion as recommended by the EC (EC, 2017)– and *recovery*, which includes energy recovery (Callao et al., 2019). On the other hand, the undesirable treatment operations are *landfill* and *incineration* excluding energy recovery. For practical purposes, the quantities of waste treated through these operations at the level of EU-28 member states have been calculated relative to countries' GDP, measured in € in *Purchasing Power Parity* (PPP).[3] In this way, we aim to account for the fact that municipal waste is closely related to economic activity and household consumption, as emphasized by Halkos and Papageorgiou (2016). Table 1 presents some descriptive statistics.

On average, the most commonly-used operation for waste treatment across the members of the EU-28 is landfill (6.56 tonnes of waste per € billion of GDP in PPP), closely followed by recycling (6.25 tonnes); on the other hand, the average value for recovery is 3.56 tonnes and only 0.09 tonnes for incineration, which is by far the least widespread waste treatment operation. Looking beyond these average figures, there are major differences across the EU-28. Municipal waste disposed of in landfill ranges from 19.97 tonnes per € billion of GDP in Greece to 0.05 tonnes in Sweden; moreover, 11.52 tonnes are recycled in Germany and only 1.31 in Malta. There are also substantial differences in the cases of recovery and incineration. Generally speaking, this initial exploratory analysis points to a pattern of behaviour wherein Nordic and Central European countries make greater use of environmentally-sensitive waste treatment operations, while most Southern and Eastern European countries still rely more heavily on treatment operations such as landfill rather than other, more environmentally desirable operations.

2.2. Methodological issues

The indicators proposed in this research to assess environmental performance in the treatment of municipal solid waste in the EU-28 are described in detail below. Furthermore, instead of constraining their presentation to the particular case of the data described in Section 2.1, these performance indicators are developed in a general framework. In our opinion, this should greatly facilitate their use in other contexts.[4]

Accordingly, let us assume that the waste generated can be treated through t = 1,…,T operations. Furthermore, d = 1,…,D of these treatment operations are considered as environmentally friendly or *desirable*, while u = 1,…,U are considered *undesirable* operations due to their damaging impact on the environment; moreover, T = D + U. Environmental performance in the treatment of municipal waste can then be defined as a ratio between an aggregate or composite indicator of desirable treatments and an aggregate indicator of undesirable treatments. Formally:

[3] The data on EU-28 members' GDP in PPPs come from Eurostat and were accessed on 15 May 2019 through https://ec.europa.eu/eurostat/web/main/data/database.

[4] The application of our indicators of environmental performance in the treatment of municipal solid waste to any other geographical context must be preceded by a detailed analysis of data availability, environmental policy preferences, and the variables with which to characterize the aggregate indicators of desirable and undesirable waste treatments; as we have done in Section 2.1 regarding the European Union.

$$\text{Environmental performance} = \frac{\text{Aggregate indicator of desirable waste treatments}}{\text{Aggregate indicator of undesirable waste treatments}}$$

$$= \frac{(w_1\text{desirable treatment}_1 + \cdots + w_D\text{desirable treatment}_D)}{(v_1\text{undesirable treatment}_1 + \cdots + v_U\text{undesirable treatment}_U)} = \frac{\sum_{d=1}^{D} w_d\text{desirable treatment}_d}{\sum_{u=1}^{U} v_u\text{undesirable treatment}_u} \quad (1)$$

where desirable treatment$_d$ (d = 1,…,D) denotes the amount of waste treated through operation d, and w_d the weight of this treatment operation in building the aggregate indicator of desirable waste treatments. Similarly, undesirable treatment$_u$ and v_u (u = 1,…,U) represent the quantity of waste treated by operation u and the weight of this operation in the aggregate indicator of undesirable waste treatments, respectively.

According to expression (1), environmental performance in the treatment of municipal waste will improve when the numerator increases with respect to the denominator. The issue of aggregation, i.e., the selection of the weights that represent the relative importance of the different operation treatments involved in our indicator of environmental performance, is however one of the main concerns when computing composite indicators[5]. In keeping with the recommendations of the Organization for Economic Co-operation and Development (OECD, 2008), researchers in this field have applied a wide range of weighting approaches to build composite indicators, all of which have pros and cons (see Greco et al., 2019).

In this respect, a popular approach has been the use of equal weightings, which, in practice, means assigning the same importance to all the variables included in the aggregate indicator. Conversely, some researchers have resorted to exogenous weightings that can differ across variables, and are based on expert opinion and techniques such as the Analytic Hierarchy Process (AHP) (Saaty, 1980), the budget allocation process (Jesinghaus, 1997) or conjoint analysis (Green and Rao, 1971). Furthermore, several approaches to building composite indicators are grounded in multivariate techniques for data reduction that group variables according to their degree of correlation; these include factor analysis and principal component analysis (see Rencher and Christensen, 2012). In line with recent trends as well as recommendations from the OECD (2008), our composite indicator of environmental performance in the treatment of municipal waste is built using DEA. These techniques have been widely used to assess performance in the waste sector (Simões and Marques, 2012), and have been revealed as a valuable tool for researchers and policymakers (Halkos and Petrou, 2019).

DEA is a technique based on mathematical programming proposed in the 1970s by Charnes et al. (1978) to assess the performance of production processes. This approach, which has been extensively used in empirical applications (see Emrouznejad and Yang, 2018 for a recent survey), was later adapted to the computation of composite indicators by Lovell et al. (1995). As acknowledged by the OECD (2008), DEA avoids subjectivity in the choice of weights, which are data-driven; in addition, the indicators built using this approach are easily understandable for the general public, as they can be normalized to one. That said, let us assume that we observe the amount of waste treated by a sample of i = 1,…,N municipalities, regions or countries –referred to as decision-making units (DMUs) in DEA jargon– through different treatment operations, including both desirable and undesirable ones. Moreover, we assume that each DMU makes use of at least one desirable treatment operation and one undesirable treatment. Environmental performance in the management of municipal waste of DMU i' can then be straightforwardly computed by adapting the basic output-oriented CCR model (Charnes et al., 1978) as:

$$\text{Environmental performance}^{i'} = \text{Minimize}_{w^{i'},v^{i'}} \frac{\sum_{u=1}^{U} v_u^{i'}\text{undesirable treatment}_u^{i'}}{\sum_{d=1}^{D} w_d^{i'}\text{desirable treatment}_d^{i'}} \quad (2)$$

Subject to:

$$\frac{\sum_{u=1}^{U} v_u^{i'}\text{undesirable treatment}_u^{i}}{\sum_{d=1}^{D} w_d^{i'}\text{desirable treatment}_d^{i}} \geq 1 \quad i = 1, \cdots, N \quad (2i)$$

$$w_d^{i'} \geq 0 \quad d = 1, \cdots, D \quad (2ii)$$

$$v_u^{i'} \geq 0 \quad u = 1, \cdots, U \quad (2iii)$$

Grounded in the so-called *benefit-of-the-doubt* principle (Cherchye et al., 2007), program (2) –which is an adaptation of the *multiplier* form of the CCR model[6]– seeks the set of weights for desirable and undesirable treatments that minimizes the inverse of our composite indicator of environmental performance for DMU i' when it is compared to all other DMUs in the sample using the same set of weights; i.e., when its performance is maximized. Hence, the score obtained as the solution to this program measures the environmental performance in the treatment of municipal solid waste by DMU i', and is lower bounded to one, a score that represents the best performance; furthermore, the higher the score, the lower the environmental performance.

For computational ease, fractional program (2) is transformed into a linear program (see Cooper et al., 2007; p.59) expressed as:

$$\text{Environmental performance}^{i'} = \text{Minimize}_{w^{i'},v^{i'}} \sum_{u=1}^{U} v_u^{i'}\text{undesirable treatment}_u^{i'} \quad (3)$$

Subject to:

$$\sum_{d=1}^{D} w_d^{i'}\text{desirable treatment}_d^{i'} = 1 \quad (3i)$$

$$\sum_{u=1}^{U} v_u^{i'}\text{undesirable treatment}_u^{i} \geq \sum_{d=1}^{D} w_d^{i'}\text{desirable treatment}_d^{i} \quad i = 1, \cdots, N \quad (3ii)$$

$$w_d^{i'} \geq 0 \quad d = 1, \cdots, D \quad (3iii)$$

$$v_u^{i'} \geq 0 \quad u = 1, \cdots, U \quad (3iv)$$

Alternatively, program (2) can be linearized from its *dual* formulation –known as the *envelopment* form of the CCR model– which enables the identification of the peers or best performers shaping the environmental *frontier* DMU i' is compared to. Formally, this dual program is (see Cooper et al., 2007; p.58):

$$\text{Environmental performance}^{i'} = \text{Maximize}_{z^i,\eta^{i'}} \eta^{i'} \quad (4)$$

Subject to:

$$\eta^{i'}\text{desirable treatment}_d^{i'} \leq \sum_{i=1}^{N} z^i\text{desirable treatment}_d^{i} \quad d = 1, \cdots, D \quad (4i)$$

[5] Becker et al. (2017) discuss the importance of weights in building composite indicators, with empirical illustrations relating to environmental issues.

[6] In program (2), undesirable waste treatments are formally considered as inputs in the conventional CCR model. In this respect, treating *undesirables* as inputs is a common practice in the literature devoted to assessing production performance with environmental effects (see Dakpo et al., 2016).

Table 2
Environmental performance in the treatment of municipal solid waste (*0 worst – 1 best*).

	Overall indicator	Treatment-specific indicators	
		Recycling	Recovery
Austria	0.2641	0.2641	0.1573
Belgium	0.5735	0.5735	0.3992
Bulgaria	0.0053	0.0053	0.0005
Croatia	0.0031	0.0031	0.0000
Cyprus	0.0020	0.0020	0.0000
Czechia	0.0066	0.0066	0.0030
Denmark	0.5219	0.5152	0.5219
Estonia	0.0185	0.0140	0.0185
Finland	0.5276	0.4117	0.5276
France	0.0187	0.0187	0.0136
Germany	0.7250	0.7250	0.2605
Greece	0.0022	0.0022	0.0001
Hungary	0.0068	0.0068	0.0028
Ireland	0.0149	0.0149	0.0095
Italy	0.0191	0.0191	0.0065
Latvia	0.0081	0.0081	0.0008
Lithuania	0.0138	0.0138	0.0047
Luxembourg	0.0657	0.0657	0.0537
Malta	0.0007	0.0007	–
Netherlands	0.3605	0.3605	0.2559
Poland	0.0076	0.0076	0.0045
Portugal	0.0056	0.0056	0.0035
Romania	0.0018	0.0018	0.0005
Slovakia	0.0046	0.0046	0.0013
Slovenia	0.0534	0.0534	0.0062
Spain	0.0059	0.0059	0.0020
Sweden	1.0000	1.0000	1.0000
United Kingdom	0.0243	0.0243	0.0180
European Union-28			
Mean	0.1522	0.1476	0.1212
Standard deviation	0.2698	0.2644	0.2382
Maximum	1.0000	1.0000	1.0000
Minimum	0.0007	0.0007	0.0000

Note: In the case of the treatment-specific indicator for recovery, descriptive statistics for the EU-28 have been computed excluding Malta; the reason is that this country does not apply this treatment for treating waste, and so we found no solution from program (5).

$$\text{undesirable treatment}_u^{i'} \geq \sum_{i=1}^{N} z^i \text{undesirable treatment}_d^i \qquad u = 1, \cdots, U \tag{4ii}$$

$$z^i \geq 0 \qquad i = 1, \cdots, N \tag{4iii}$$

where z^i measures the intensity with which DMU i enters into the composition of the *virtual* reference set to which DMU i' is compared.

The interpretation of the performance indicators obtained from program (4) –which we will refer to as the *overall* performance indicator– is straightforward. An optimal value of, for example, 1.5 for the parameter $\eta^{i'}$ in the objective function of this program would mean that, given the amount of municipal waste treated through undesirable operations, DMU i' would have to increase the waste treated by environmentally desirable operations by 50% in order to reach the level of environmental performance of the best performers in the sample. Alternatively, it could be interpreted that the amount of waste that DMU i' treats with desirable operations is only 66% of that treated by the DMUs with the best performance (0.66 is the inverse of 1.5). To keep things simple, we apply the second interpretation of our environmental performance indicators as we believe it is much easier for the general public to understand, since performance is bounded between zero (worst performance) and one (best performance).

In addition to the overall performance indicator described above, we also suggest a series of indicators of performance in individual waste treatment operations, which we denote *treatment-specific* indicators. Formally, the *treatment-specific* indicator for DMU i' and desirable municipal waste treatment d_j is obtained from the following program:

$$\text{Environmental performance}_{d_j}^{i'} = \text{Maximize}_{z^i} \eta_{d_j}^{i'} \tag{5}$$

Subject to:

$$\eta_{d_j}^{i'} \text{desirable treatment}_{d_j}^{i'} \leq \sum_{i=1}^{N} z^i \text{desirable treatment}_{d_j}^{i'} \qquad d_j \in d \text{ and } j \notin -j \tag{5i}$$

$$\text{desirable treatment}_d^{i'} \leq \sum_{i=1}^{N} z^i \text{desirable treatment}_d^{i'} \qquad d_{-j} \in d \tag{5ii}$$

$$\text{undesirable treatment}_u^{i'} \geq \sum_{i=1}^{N} z^i \text{undesirable treatment}_d^{i'} \qquad u = 1, \cdots, U \tag{5iii}$$

$$z^i \geq 0 \qquad i = 1, \cdots, N \tag{5iv}$$

The interpretation of the *treatment-specific* indicator of environmental performance obtained from program (5) is also very simple; e.g., a score of 2 for DMU i' and desirable treatment d_j would indicate that, given the amount of municipal waste treated through undesirable treatment operations and that treated by the remaining desirable treatment operations (other than d_j), DMU i' could double the waste treated by means of operation d_j. In other words, the amount of waste treated by this DMU through desirable treatment operation d_j is only half that treated by the best environmental performers (in this case, 0.5 is the inverse of 2).

3. Environmental performance in the treatment of municipal waste in the EU-28

3.1. Results and discussion

Making use of the dataset described in Section 2.1 and the indicators of environmental performance developed in Section 2.2, we have assessed the performance in the treatment of municipal waste of the EU-28 members using expressions (4) and (5). In doing so, as stated earlier, recycling and recovery are considered as desirable treatments, and landfill and incineration as undesirable ones. Table 2 displays the results.[7,8]

At first sight, a low level of environmental performance across countries can be observed, with an average overall indicator score of 0.1522; this score means that, given their respective amounts of waste treated through undesirable operations, countries are using environmentally friendly operations to treat, on average, only 15.2% of the equivalent amount treated by the best performers in the EU-28. However, there are marked differences in performance across countries: scores range from 1 (top performance) in Sweden –which treats 99.6% of its municipal waste by means of desirable operations, whether recycling or recovery– to 0.0007 in Malta, which still sends 93.2% of its waste to landfill. Generally speaking, the best performers are Nordic and Central European countries, including Sweden, Germany, Belgium, Finland and Denmark; conversely, the worst performers are mostly Eastern European countries that joined the EU from the 2000s onwards, in addition to some Southern countries such as Greece, Spain and Portugal. These results are in line with those from other studies on European countries' performance in the treatment of municipal waste that use indicators

[7] The calculations have been carried out with *DEA-Solver* software.

[8] Environmental performance in waste treatment has also been assessed by calculating the quantities of waste treated through recycling, recovery, landfill and incineration as a percentage of total waste treated, as suggested by Lavigne et al. (2019); and also by calculating the quantities of waste relative to countries' final consumption expenditure (with figures from Eurostat), as proposed by Halkos and Papageorgiou (2016). In both scenarios, the results are pretty similar to those presented in the paper, and are available to readers on request.

Table 3
Correlation between indicators of environmental performance in the treatment of municipal solid waste (*Spearman-rank coefficient*).

	Overall indicator	Recycling	Recovery
Overall indicator	1		
Recycling	0.999***	1	
Recovery	0.955***	0.952***	1

Note: *** *indicates statistical significance at 1%.*

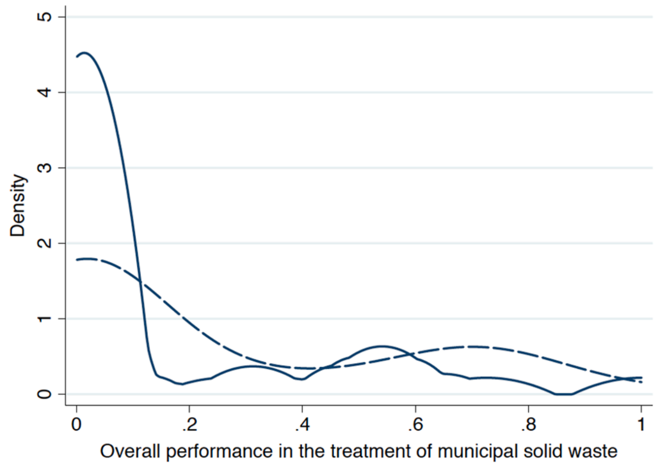

Fig. 1. Kernel densities of overall environmental performance in municipal solid waste treatment: Unweighted (solid line) and GDP-weighted (dashed line).

respectively. The interpretation of these indicators is also straightforward; i.e., the score for recycling means that, given their quantities of waste treated by means of the undesirable operations landfill and incineration as well as through recovery, countries in the EU-28 are recycling, on average, only 14.7% of the waste recycled by the best performers. Moreover, when countries are ranked according to their treatment-specific environmental performance, the ranking is largely similar to that obtained for the overall indicator. In fact, *Spearman-rank* bilateral correlations (see Conover, 1999) between our indicators of environmental performance in waste treatment in the EU-28, including treatment-specific indicators and the overall indicator, are all above 0.95 and statistically significant at 1% (Table 3). Furthermore, the results for the *Kruskal–Wallis* test (again see Conover, 1999) do not allow us to reject, at standard confidence levels, the null hypothesis that our three indicators of environmental performance are from the same population.[9] Thus, in what follows, we focus our attention on the overall indicator of environmental performance.

For a more in-depth examination of environmental performance in the treatment of municipal solid waste across the EU-28, we perform an analysis of kernel densities, both unweighted and weighted. Results are shown in Fig. 1. The main mode of the unweighted kernel distribution of environmental performance (solid line in Fig. 1) lies slightly below 0.01, and contains nearly half the countries in the sample, whereas a second mode is found around 0.55. However, unweighted kernels might present a skewed picture of environmental performance in the EU-28, as there are actually major size disparities across member states; e.g., the GDP of the German economy reached €3068.5 billion (PPP) in 2017, whereas in Malta it was just €13.7 billion (PPP). Accordingly, we have computed a weighted kernel density of environmental performance in the treatment of municipal waste in the EU-28 using countries' GDP as weightings

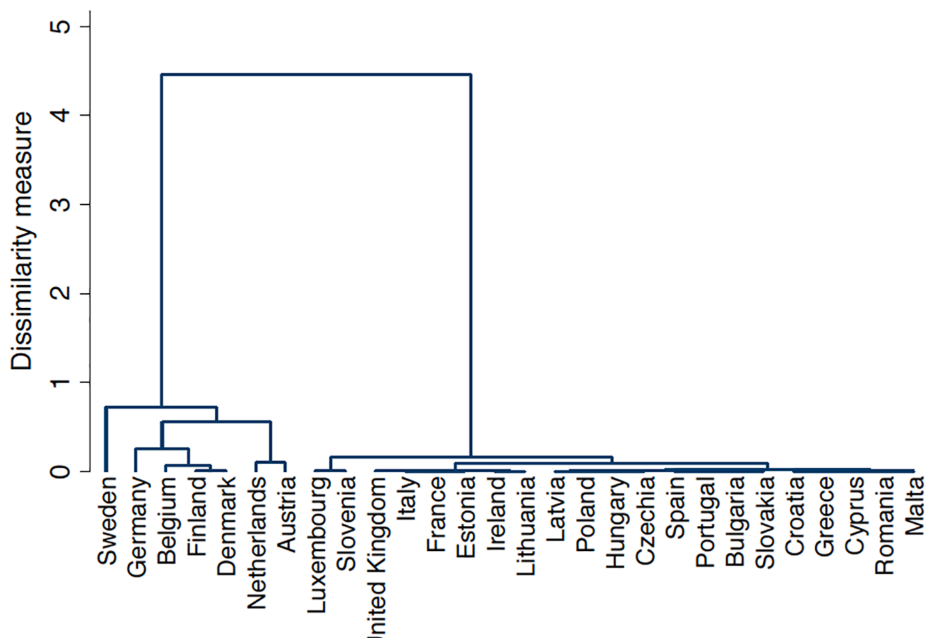

Fig. 2. Dendrogram of overall environmental performance in the treatment of municipal solid waste (Ward's linkage method).

rather different to ours, in that they do not focus on environmental issues; such studies include Callao et al. (2019), Castillo-Giménez et al. (2019a), Castillo-Giménez et al. (2019b).

On the other hand, the average scores for our two treatment-specific indicators of environmental performance in municipal solid waste treatment are 0.1476 and 0.1212 for recycling and recovery operations, (dashed line in Fig. 1). Comparing these two densities clearly highlights the fact that smaller EU-28 economies in terms of their GDP also register

[9] The computed value for the *Chi-squared* statistic of the null hypothesis of equality of populations is 3.185, with a *p-value* of 0.203.

Table 4
Groups of countries according to their environmental performance in municipal solid waste treatment.

Clusters	Countries	Environmental performance (*Overall indicator*; *0 worst – 1 best*)	
		Average	GDP-weighted average
Cluster #1	Sweden	1.0000	1.0000
Cluster #2	Germany	0.7250	0.7250
Cluster #3	Belgium, Finland and Denmark	0.5410	0.5488
Cluster #4	Netherlands and Austria	0.3123	0.3280
Cluster #5	Luxembourg, Slovenia, United Kingdom, Italy, France, Estonia, Ireland, Lithuania, Latvia, Poland, Hungary, Czechia, Spain, Portugal, Bulgaria, Slovakia, Croatia, Greece, Cyprus, Romania and Malta	0.0137	0.0153
Sub-cluster #5a	Luxembourg and Slovenia	0.0596	0.0591
Sub-cluster #5b	United Kingdom, Italy, France, Estonia, Ireland and Lithuania	0.0182	0.0205
Sub-cluster #5c	Latvia, Poland, Hungary, Czechia, Spain, Portugal, Bulgaria, Slovakia, Croatia, Greece, Cyprus, Romania and Malta	0.0046	0.0056

lower environmental performance in municipal waste treatment; in this respect, the GDP-weighted kernel distribution of performance has two modes around the values of 0.05 and 0.7.

Kernel densities provide a nice picture of the distribution of environmental performance in the treatment of municipal solid waste across the EU-28, however, they do not allow us to classify these countries into homogeneous groups according to their performance, information that could be greatly useful for European policymakers in charge of environmental policies. Thus, we have carried out a hierarchical cluster analysis in order to identify groups of countries showing similar behaviour regarding overall environmental performance in waste treatment.[10] In essence, hierarchical cluster analysis relies on establishing a hierarchical structure to assess the links between observations (see Everitt et al., 2011). Taking the Euclidean distance and its squared value as (dis)similarity measures (Lance and Williams, 1967), we have applied several clustering methods, including the simple-, complete- and average-linkage methods, in addition to the Ward's method. At first glance, the structure of the groups (or clusters) seems to be largely consistent across clustering methods; as such, for the sake of simplicity, Fig. 2 shows only the dendrogram from the commonly-used Ward's method.[11] This diagram summarizes the step-by-step procedure used to aggregate the EU-28 members into homogeneous groups, with the height of the lines representing the distance between countries or groups of countries.

Based on this dendrogram, we have identified five groups or clusters, which are listed in Table 4. Clusters #1 and #2 are made up of Sweden (the best performer in the EU-28) and Germany (with a score of 0.752), respectively; these two countries display by far the best environmental performance in municipal waste treatment of all the EU-28 members. Cluster #3 includes three countries, Belgium, Finland and Denmark, with an average performance of 0.5410, whereas the Netherlands and Austria are included in cluster #4, displaying an average performance of 0.3123. Finally, cluster #5 groups together three-quarters of the countries in the sample (21 out of 28), specifically those with the lowest performance (average of 0.0137). Given that this group contains a large number of countries with fairly different features, we have split it into three subgroups: sub-cluster #5a includes Luxembourg and Slovenia (average performance of 0.0596); the United Kingdom, Italy, France, Estonia, Ireland and Lithuania are in sub-cluster #5b (average score of 0.0182); finally, average performance in sub-cluster #5c is just 0.0046, and includes countries that joined the EU-28 from the 2000s (Latvia, Poland, Hungary, Czechia, Bulgaria, Slovakia, Croatia, Cyprus, Romania and Malta), in addition to three Southern countries (Spain, Portugal and Greece). Notably, GDP-weighted average performance scores are nearly always higher than unweighted ones, which also indicates that countries with larger economies behave better in terms of their environmental performance in waste treatment.

3.2. Can we explain environmental performance in municipal waste treatment?

In an attempt to investigate the factors that explain differences in environmental performance in municipal waste treatment across the EU-28, we have carried out a second-stage analysis in which we regress our indicator of overall performance, as the dependent variable, on a series of explanatory variables. In doing so, we use truncated regression and bootstrapping (Simar and Wilson, 2007), which allows us to account for the nature of our DEA-based performance scores and the unknown serial correlation between them. In essence, this approach requires simulating a sensible data-generating process, generating artificial bootstrap samples from this process and building standard errors and confidence intervals for the parameters of interest through bootstrapping; we have employed algorithm #1, further technical details of which as well as the implementation procedure can be found in Simar and Wilson (2007; pp. 41-42).

Regarding explanatory variables, we have identified two factors that could potentially explain performance in waste treatment: i) citizens' environmental awareness, and ii) countries' economic and legal context. These variables and their sources are described in Appendix 1, which also presents some descriptive statistics.

In order to proxy environmental awareness, we have included three variables from the Special Eurobarometer 468 '*Attitudes of European citizens towards the environment*' (EC, 2017), representing citizens' overall concern about environmental protection, and two particular concerns about waste generation and recycling. Greater public concern about the environment is expected to positively affect environmental performance in the treatment of municipal waste (Liang et al., 2018).

As for countries' economic and legal context, we have included four additional variables. The first one represents government quality, and the data come from the 2017 *European Quality of Government Index* (EQI) (Charron et al., 2014, 2016). The EQI is a composite measure based on European citizens' perceptions about corruption, impartiality and quality of governments, which ranges from −2.5 to 2.5. In this respect, higher government quality is expected to be associated to better environmental performance (Peiró-Palomino and Picazo-Tadeo, 2019). Our second variable in this category is the education level, measured as the share of the labour force with at least tertiary education. Pesonen et al. (2013) found that higher education levels positively affect environmental performance (measured through the concept of eco-efficiency); also, Díaz-Villavicencio et al. (2017) have recently shown that the higher the level of education in Spanish municipalities, the more eco-efficient their waste management. Finally, we have included two variables representing general government revenues and expenditure linked to environmental issues. The first one captures the amount of general government revenue coming from environmental taxes, as a percentage of GDP. In this respect, taxes may be used by policymakers to change the relative costs of alternative waste treatments, thus discouraging the use

[10] Several previous studies have already employed this approach to classify European countries according to their performance in the management and treatment of municipal waste, including Blumenthal (2011), Mihai and Apostol (2012), and more recently Castillo-Giménez et al. (2019b).

[11] Results for the clusters of countries obtained from the other clustering methods are available to readers on request.

Table 5
Determinants of environmental performance in municipal solid waste treatment: Results from the truncated regression.

Dependent variable: *Overall indicator of environmental performance*	Model #1	Model #2	Model #3	Model #4
Constant	0.1259*** (0.0400)	0.1263***(0.0353)	0.1267***(0.0360)	−0.5559**(0.3073)
Environmental awareness	0.0822 (0.0646)	–	0.0074 (0.0629)	−0.0135 (0.0615)
Economic and legal context	–	0.1447***(0.0473)	0.1420***(0.0522)	0.0543 (0.0680)
GDP per capita	–	–	–	0.0360**(0.0154)
GDP per capita-squared	–	–	–	−0.0004**(0.0002)
Sigma	0.2066***(0.0283)	0.1834***(0.0250)	0.1834***(0.0246)	0.1657***(0.0223)
Wald Chi-squared	1.618	9.358***	9.473***	16.250***

Notes: The number of bootstrap replications is equal to 5000 in all models. Standard errors are in brackets. ** and *** indicate statistical significance at 5% and 1%, respectively.

of less desirable operations; e.g., high environmental taxes on landfill should boost the use of more sustainable waste treatment operations such as recycling (Xevgenos et al., 2015). Moreover, revenues from environmental taxes may be devoted to sustainable waste management programmes, technologies and infrastructures (Expósito and Velasco, 2018). The second variable is general government expenditure on waste management, also measured as a percentage of GDP. It is expected that the larger the expenditure, the higher the performance.

Given the large number of explanatory variables with respect to the size of our sample, we have built a couple of aggregate indices –for environmental awareness and the legal and economic context– using factor analysis based on the principal factor method and regression scoring for prediction over all the variables (see Rencher and Christensen, 2012)[12]; these indices have been included as regressors in our second-stage estimations. Moreover, GDP per capita (measured in thousands of PPP € per capita), and its square have also been considered as further explanatory variables in order to control for countries' level of development and possible non-linear effects of this variable on environmental performance (Peiró-Palomino and Picazo-Tadeo, 2019).

Table 5 shows the results from the truncated regression for several model specifications, in which the explanatory variables are included sequentially. The dependent variable is always our indicator of overall environmental performance in the treatment of municipal solid waste; besides, 5,000 bootstrap replications have been performed in all cases.[13] In addition to a constant, Models #1 and #2 include as explanatory variables, respectively, the indices of environmental awareness and economic and legal context obtained from the factor analysis. While environmental awareness seems to have a non-significant impact on performance, the index of economic and legal context is statistically significant at 1%. These results hold when both indices are jointly included in Model #3.

Finally, Model #4 further includes GDP per capita and its square as additional regressors; both variables are statistically significant at 5%, with their estimated signs indicating a positive but decreasing effect of economic development on environmental performance in waste treatment. Moreover, the index of economic and legal context loses its significance, which seems to indicate that this variable exerts an indirect effect on environmental performance through its effect on the level of development. In particular, a favourable economic and legal context, with a high-quality government, educated citizens and appropriate environmental policies should boost economic and social development and, ultimately, translate into better environmental performance in the treatment of municipal waste. In fact, these results are entirely in line with those from Peiró-Palomino and Picazo-Tadeo (2019), who find the level of development, also measured by GDP per capita, to be the main driver of environmental performance in the EU.

[12] For the sake of space, details on the implementation of the factor analysis are not included in the paper, but they are available to readers on request.

[13] The estimations have been carried out with *Stata* software, and the *Simarwilson* module developed by Tauchmann (2016).

4. Summary, conclusions and policy issues

Environmentally sustainable development is a key aspiration of modern societies' citizens. Among the many pillars of environmental sustainability, preventing municipal solid waste is an overriding priority for legislation and environmental policies in developed countries. Going beyond that, appropriate solid waste management is also a necessary condition for achieving environmental sustainability. In response to growing demands for indicators that can help policymakers to improve the design of their environmental policies, the first contribution of this paper is the proposal of an indicator for assessing environmental performance in the treatment of municipal solid waste. The indicator, which is calculated using Data Envelopment Analysis (DEA) techniques, is formulated as a ratio between an aggregate indicator of desirable waste treatment operations and an aggregate indicator of undesirable ones. One advantage of using this technique is that the weightings of desirable and undesirable waste treatments are data-driven, so that no additional exogenous information is required. Moreover, an outstanding feature of our indicator is that it jointly accounts for both desirable and undesirable treatments, which helps provide a comprehensive picture of overall environmental performance in municipal waste treatment; notwithstanding, treatment-specific indicators of performance are also provided.

As a second contribution, our composite indicators are empirically illustrated with an application to assessing environmental performance in municipal waste treatment by European Union-28 (EU-28) members. In this empirical illustration, which relies on data from the year 2017, recycling and recovery are seen as environmentally desirable waste treatments, whereas landfill and incineration are undesirable ones. Our results reveal a worryingly low level of average performance, with huge differences across the EU-28. In this respect, Sweden is the top performer, followed by Central and Northern European countries such as Germany, Belgium, Finland and Denmark. At the opposite end of the spectrum, most of the Eastern European countries that joined the EU-28 from the 2000s onwards, in addition to Southern and Mediterranean countries such as Spain, Portugal and Greece, are among the worst environmental performers in the treatment of waste. In a second stage of our research, we have examined some potential determinants of environmental performance in municipal solid waste treatment, finding economic development to be the main determinant.

We hope that these empirical results from the application of our indicators can provide European policymakers with relevant information, helping them to improve the design of their environmental policies, particularly those targeted at improving environmental performance in the treatment of municipal solid waste. In this respect, and given the broad differences in performance found across the EU-28, our belief is that further harmonized legislation is urgently needed to boost performance, including environmental taxes on landfill or even the prohibition of this municipal waste treatment. Moreover, campaigns aimed at raising European citizens' awareness of the major environmental benefits derived from practices such as recycling and reuse could also significantly contribute to achieving the goal of environmental sustainability.

CRediT authorship contribution statement

Ana-María Ríos: Conceptualization, Data curation, Formal analysis, Writing - original draft. **Andrés J. Picazo-Tadeo:** Formal analysis, Methodology, Supervision, Writing - review & editing.

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.

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Appendix 1. . Second-stage variables: Description, sources and descriptive statistics

Variable	Description	Source	Mean	Standard deviation
Environmental awareness				
Environmental protection concern	Percentage of respondents who consider that environmental protection is very important	Special Eurobarometer 468: Attitudes of European citizens towards the environment (EC, 2017)	57.8	12.7
Waste concern	Percentage of respondents who choose the 'increase in the amount of waste' as one of the four environmental problems that most concern them		42.9	10.6
Recycling concern	Percentage of respondents who say they have separated most of the waste for recycling in the last six months		62.3	16.1
Economic and legal context				
Government quality	European quality of government (EQI) index. The data are standardized with a mean of zero, and higher scores indicating higher quality	Quality of Government Institute of Gothenburg University (2017)	0.01	0.98
Education attainment	Share of labour force with at least tertiary education (*percentage*); 2017	Eurostat	35.2	7.9
Environmental taxes	General government environmental tax revenues (*percentage* of GDP); 2017	Eurostat	2.61	0.68
Waste expenditures	General government expenditure on waste management (*percentage* of GDP); 2017	Eurostat	0.28	0.21
Other variables				
GDP per capita	GDP per inhabitant in thousands of € in *Purchasing Power Parity* (PPP); 2017.	Eurostat	29.98	12.37

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