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Assessing the dynamic eco-efficiency of Italian municipalities by accounting for the ownership of the entrusted waste utilities

Giulia Romano [a], María Molinos-Senante [b,*], Laura Carosi [a], Paula Llanquileo-Melgarejo [b], Ramón Sala-Garrido [c], Manuel Mocholi-Arce [c]

[a] Department of Economics and Management, University of Pisa, Via C. Ridolfi, 10, 56124, Pisa, Italy
[b] Departamento de Ingeniería Hidráulica y Ambiental, Pontificia Universidad Católica de Chile, Avda. Vicuña Mackenna, 4860, Santiago, Chile
[c] Departamento de Matemáticas para la Economía y la Empresa, Universidad de Valencia, Avda. Tarongers, S/N, Valencia, Spain

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ABSTRACT

This study evaluates and compares the dynamic eco-efficiency of municipalities with publicly owned, privately owned, and mixed ownership solid waste utilities by estimating the Meta-frontier Malmquist-Luenberger productivity index for a sample of 68 major Italian towns. On average, the eco-productivity of Italian waste service providers increased by 8% from 2016 to 2019. Although municipalities with private utilities improved their eco-productivity most, the differences among the three clusters reflecting utility ownership are not statistically significant. The results show that publicly owned waste operators drive technology and that the technological levels of private utilities have deteriorated relative to global technological progress.

1. Introduction

The increasing volume of municipal solid waste (MSW) has become one of the most critical local and national problems (Giannakitsidou et al., 2020; Ríos and Picazo-Tadeo, 2021; Romano, Marciano and Fiorelli, 2021a). The United Nations (2015) recognized the importance of improving MSW management through Goals 11 and 12 of the Sustainable Development Goals (Llanquileo-Melgarejo et al., 2021). Moreover, from a circular economy perspective, waste reduction, recycling, and reuse maximization have been identified as priorities for waste policy (Gastaldi et al., 2020).

Because MSW management significantly impacts the environment, public health, and municipal well-being, efficiency in the provision of this service is extremely important (Agovino et al. 2016; De Jaeger and Rogge, 2014; Fusco et al., 2020; Guerrini et al., 2017; Lavigne et al., 2019; Simões and Marques, 2012). As reviewed by Halkos and Petrou (2019) and Gastaldi et al. (2020), most extant studies on the performance assessment of MSW management have focused on cost efficiency (e.g., Rogge and De Jaeger, 2012, 2013; Simões et al. 2013; Simões et al., 2012; Spallini et al., 2016) or on the operational efficiency of MSW services (e.g., De Jaeger, Eyckmans, Rogge & Van Puyenbroeck, 2011; García-Sánchez, 2008; Ichinose et al., 2013). This approach ignores the environmental performance of municipalities as waste service providers (WSPs) since the waste collected or treated is used as an output variable without differentiating between recycled and unsorted waste, despite having notably different environmental impacts (Romano and Molinos-Senante, 2020). To overcome this limitation, the eco-efficiency assessments of WSPs have attracted increasing attention in recent years (e.g., Agovino, D'Uva, Garofalo and Marchesano, 2018; Díaz-Villavicencio et al., 2017;; Expósito and Velasco, 2018; Llanquileo-Melgarejo et al., 2021; Romano et al., 2020; Sarra et al., 2017). Eco-efficiency was defined by Schaltegger and Sturm (1989) as the ratio between the value-added and environmental impact; therefore, it allows the integration of economic and environmental variables in performance evaluation (Yu et al., 2020).

The literature (e.g., Calabro and Komilis, 2019; Rogge et al., 2017; Guerrini et al., 2017; Sarra et al., 2017; Tsalis et al., 2018; Llanquileo-Melgarejo and Molinos-Senante, 2021) has shown that the performance of WSPs can be influenced by several exogenous or environmental variables, such as the size of the municipality, income per capita, age of the population, male ratio, population density, tourist ratio, and WSP ownership. Within these exogenous variables, the ownership of entrusted waste utilities has been deemed significant for waste management (Esposito et al., 2020; Romano et al., 2021a; Simões

* Corresponding author.
E-mail addresses: Giulia.romano@unipi.it (G. Romano), mmolinos@uc.cl (M. Molinos-Senante), laura.carosi@unipi.it (L. Carosi), pillanquileo@uc.cl (P. Llanquileo-Melgarejo), sala@uv.es (R. Sala-Garrido), manuel.mocholi@uv.es (M. Mocholi-Arce).

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and Marques, 2012; Zaman and Lehmann, 2011) as it is also linked to the regulation of municipal waste management systems (Sarra et al., 2020). Past research on this topic has mainly focused on assessing the effects of privatization of municipal waste services on cost efficiency (e.g., Campos-Alba et al., 2019; Lombrano, 2009; Pérez-López et al., 2016; Silvestre et al., 2020; Zafra-Gómez et al., 2013) and recycling rates (e.g., Hage et al., 2018; Romano et al., 2019; Starr and Nicolson, 2015; Struk, 2017). However, the impact of utility ownership on eco-efficiency (i.e., on the joint economic and environmental performance) has hardly been investigated, although it is relevant to implementing and enhancing the circular economy. Indeed, the role of owners in defining the aims of utilities could be a key determinant (Minoja and Romano, 2021; Romano et al., 2021a). Regarding Italy, recent research has highlighted the positive role of public ownership in fostering the sustainable performance of waste utilities, owing to stronger relationships with local communities, reduced pressure on profits and dividends, and greater willingness to invest, even with delayed returns (Minoja and Romano, 2021). Indeed, Simões and Marques (2012) also highlighted that, in the wealthiest contexts, the public provision of urban waste services might provide higher efficiency than private provision. After a participated referendum in 2011 in Italy, the debate about the relevance of public provision of public services, as the management of water and urban waste, is still growing due to supposed linkage between privatization and several issues, such as the lack of investments, lower attention to social and environmental performance, and tariff increase (Romano et al., 2020).

To the best of our knowledge, only Romano et al. (2020) and Romano and Molinos-Senante (2020) analyzed the output of urban waste management in sorted and mixed waste when evaluating the influence of waste utility ownership on WSP performance. In other words, only these two previous studies have evaluated the role of ownership on WSP eco-efficiency. On the one hand, Romano et al. (2020) applied the order-m frontier approach to a sample of 220 Tuscan municipalities in Italy in 2015. This method allowed them to estimate the eco-efficiency of WSPs by considering the contexts under which they operate. The authors integrated ownership as a dummy variable. However, the results were inconclusive when municipalities were only clustered into municipalities with entrusted public or private waste utilities. Moreover, when the number of categories was enlarged, the municipalities served by the public- and mixed-owned utilities exhibited similar performances. In other words, Romano et al. (2020) did not find statistically significant evidence that municipalities with private or public utilities entrusted present different eco-efficiencies.

On the other hand, Romano and Molinos-Senante (2020) compared the eco-efficiency of a sample of 225 Tuscan municipalities in 2016 with publicly owned, mixed-ownership, and privately owned waste utilities entrusted to urban waste management services. In doing so, they applied a data envelopment analysis (DEA) meta-frontier approach. This methodology allowed the integration of group heterogeneities (i.e., ownership) for eco-efficiency assessment by considering that each group of municipalities (i.e., with public, private, and mixed waste utilities entrusted) does not share the same production frontier (Battese et al., 2004). The authors concluded that municipalities with mixed ownership of utilities exhibited the worst eco-efficiency, whereas municipalities with public utilities presented the best eco-efficiency.

Despite the novelty of Romano et al. (2020) and Romano and Molinos-Senante (2020) in analyzing the impact of ownership on the eco-efficiency of municipalities, they present notable limitations as follows. Both studies compared the eco-efficiency of WSPs during a single year (2015 and 2016, respectively) and within a specific Italian region (Tuscany). Hence, their results are insufficiently robust for global and generalizable conclusions; therefore, further research on this topic is needed. In this context, eco-efficiency provides a static evaluation of the performance of the analyzed units (WSPs in this study). In other words, it evaluates the performance of units at a given time point without considering the potential changes within them over time (Kortelainen, 2008). To better support the decision-making process, information on the temporal dynamics of eco-efficiency is essential. This type of assessment is known as eco-productivity change evaluation (Mahlberg et al., 2011). The assessment of eco-productivity change involves extending the notion of eco-efficiency to an intertemporal perspective (De Jaeger and Rogge, 2013; Refaie et al., 2016). Yang et al. (2018). Despite the potential power and impact of this approach on critical public policy decisions, to the best of our knowledge, no prior studies have evaluated the eco-productivity change of WSPs or the influence of ownership of waste utilities on this performance measure.

Against this background, the objectives of this study are twofold. The first is comparing the eco-productivity change of municipalities (WSPs) with publicly owned, mixed-ownership, and privately owned waste utilities. The Meta-frontier Malmquist-Luenberger productivity index (MMLPI) is computed for each WSP analyzed. This index allows us to estimate eco-productivity change considering the heterogeneous nature of the WSPs in terms of the management model chosen and by integrating economic costs, recycled waste, and unsorted waste as inputs, desirable outputs, and undesirable outputs, respectively, that is, evaluating the dynamic performance of WSPs by integrating both economic and environmental variables. The second objective is quantifying the drivers of the eco-productivity change of the WSPs by decomposing the MMLPI into three components according to Oh (2010): (i) efficiency change (EC), (ii) best practice gap change (BPC), and (iii) technological gap change (TGC). This information is essential for municipalities, waste utilities, and MSW regulators to develop policies to improve the economic and environmental performance of WSPs.

This study contributes to the literature on the performance assessment of WSPs by: (i) evaluating the eco-productivity change of WSPs using a 2016–2019 original database covering 68 major Italian towns of Italian provinces geographically distributed throughout the country to assess the dynamic performance of WSPs by integrating economic and environmental variables. While this topic has been previously analyzed, with several studies having assessed the eco-efficiency of municipalities as WSPs, to the best of our knowledge, no studies evaluated the eco-productivity change of WSPs. As such, this study (ii) compares the eco-productivity change of three different clusters of municipally entrusted utilities based on public, mixed, and private ownership by employing a robust and reliable index—the MMLPI (Mocholi-Arce et al., 2021) and (iii) identifies three drivers of eco-productivity change of WSPs—EC, BPC, and TGC.

2. Methodology

This section is divided into three subsections. The first is devoted to presenting the basic assumptions of the MMLPI model, which is then described in the second subsection. Finally, the third subsection describes the methods of calculating the directional distance functions required to obtain the MMLPI.

2.1. Fundamental modeling assumptions

This section reports the fundamental assumptions required for defining the MMLPI proposed by Oh (2010). Assuming there are $k = 1, \ldots, K$ WSPs during $t = 1, \ldots, T$ time periods, the production technology for WSPs producing M desirable outputs, $y \in R_+^M$, and J undesirable outputs, $b \in R_+^J$, by using N inputs, $X \in R_+^N$ is represented by the possibility set, $P(x)$, which is represented as:

$$P(x) = \{(x, y, b) |\ x\ produce\ (y, b)\}. \tag{1}$$

In addition to the production possibility set being closed, bounded, and freely disposable, the following three axioms are required:

$$If\ (x, y, b) \in P(x)\ and\ 0 \leq \theta \leq 1,\ then\ (x, \theta y, \theta b) \in P(x), \tag{2}$$

$$If (x, y, b) \in P(x) and\ y' \leq y\ then\ (x, y', b) \in P(x), \tag{3}$$

$$If\,(x,y,b) \in P(x) and\, b=0, then\; y=0. \tag{4}$$

The first axiom in Eq. (2) implies that the undesirable outputs are weakly disposable, which means that their reduction must be accompanied by the simultaneous reduction of desirable outputs. In MSW management, a reduction in the quantity of unsorted waste involves improved recycling. Eq. (3) represents the disposability axiom, which implies that desirable outputs may be reduced without reducing undesirable outputs. The last axiom (Eq. (4)) is null-jointness, which means that no desirable outputs can be produced unless undesirable outputs are also produced.

The production possibility set is well-defined from a conceptual perspective. However, it presents difficulties when applied to empirical analysis. Therefore, the directional distance function is commonly used (Choi et al. 2015), being a generalization of the Shephard distance function; however, the directional distance function allows the desirable and undesirable outputs to be treated non-proportionally by the given direction (Chung et al., 1997). The directional distance function seeks to maximize desirable output production while simultaneously reducing undesirable outputs. The directional distance function is defined as:

$$\overrightarrow{D}\left(x,y,b,\overrightarrow{g_y},\overrightarrow{g_b}\right) = \max\left\{\beta : \left(x, y+\beta\overrightarrow{g_y}, b-\beta\overrightarrow{g_b}\right) \in P(x)\right\}, \tag{5}$$

where $\overrightarrow{g} = (\overrightarrow{g_y}, \overrightarrow{g_b})$ is the vector of the directions in which both desirable and undesirable outputs should be scaled. According to Chung et al. (1997), the selected direction vector is $\overrightarrow{g} = (y, b)$, which implies that the desirable outputs increase and undesirable outputs decrease. To simplify the notation, we replace $\overrightarrow{D}(x,y,b,\overrightarrow{g_y},\overrightarrow{g_b})$ with $\overrightarrow{D}(x,y,b)$.

2.2. The Meta-frontier Malmquist-Luenberger productivity index

Before defining and decomposing the MMLPI, three benchmark technology sets should be defined: (i) contemporaneous benchmark technology, (ii) intertemporal benchmark technology, and (iii) global benchmark technology. According to Tulkens and Vanden Eeckaut (1995), these are defined as follows.

The contemporaneous benchmark technology constructs the production possibility set for group R_h at specific period t:

$$P_{R_h}^{t} = \left\{(x^t, y^t, b^t) | x^t can\ produce\ (y^t, b^t)\right\}, \quad t=1,\ldots,T. \tag{6}$$

The intertemporal benchmark technology is a single production possibility set made from observations throughout the entire period for the group R_h:

$$P_{R_h}^{I} = P_{R_h}^{1} \cup P_{R_h}^{2} \cup \ldots \cup P_{R_h}^{T} \tag{7}$$

There are H different intertemporal benchmark technologies. The WSP which is in one intertemporal benchmark technology is assumed to be unable to access different intertemporal benchmark technologies easily.

The global benchmark technology establishes a single production possibility set composed of observations throughout the entire period for all groups. For all groups involved in the assessment, the global benchmark technology is defined as:

$$P^G = P_{R_1}^{I} \cup P_{R_2}^{I} \cup \ldots . \cup P_{R_H}^{I} \tag{8}$$

Unlike the contemporaneous and intertemporal benchmark technology sets, the global benchmark covers all WSP groups (i.e., municipalities served by public, mixed, and private waste utilities).

As shown in Fig. 1, the intertemporal benchmark technology of a specific group ($P_{G_k}^{I}$) envelops its contemporaneous benchmark technologies ($P_{G_k}^{c^t}$ and $P_{G_k}^{c^{t+1}}$), while the global benchmark technology (P^G) envelops all intertemporal technologies.

The above-described benchmark technology sets allowed Oh (2010) to define the MMLPI as follows:

$$MMLPI\left(x^t, y^t, b^t, x^{t+1}, y^{t+1}, b^{t+1}\right) = \frac{1+\overrightarrow{D}^{G}(x^t, y^t, b^t)}{1+\overrightarrow{D}^{G}\left(x^{t+1}, y^{t+1}, b^{t+1}\right)}, \tag{9}$$

where $\overrightarrow{D}^{G} = (x,y,b)$ is the global directional distance function defined on the global technology set as:

$$\overrightarrow{D}^{G}(x,y,b) = \max\left\{\beta | (x, y+\beta y, b-\beta b) \in P^G\right\}, \quad s=t, t+1. \tag{10}$$

According to Oh (2010), the MMLPI can be decomposed into three components or drivers of productivity change, namely: (i) efficiency change (EC), (ii) best practice gap change (BPC), and (iii) technological gap change (TGC). The decomposition of the MMLPI is as follows:

The EC informs the extent of the gap to be closed at the contemporaneous benchmark technology at time $t+1$ relative to previous period t (Chung and Heshmati, 2015). Hence, EC is a measure of the catching-up effect in terms of technical efficiency. An EC > 1 (<1) involves efficiency improvement (deterioration). The BPC measures the change in the best practice gap ratio between the contemporaneous benchmark technology and the intertemporal benchmark technology over the two periods. BPC >1 (<1) implies that the contemporaneous benchmark technology

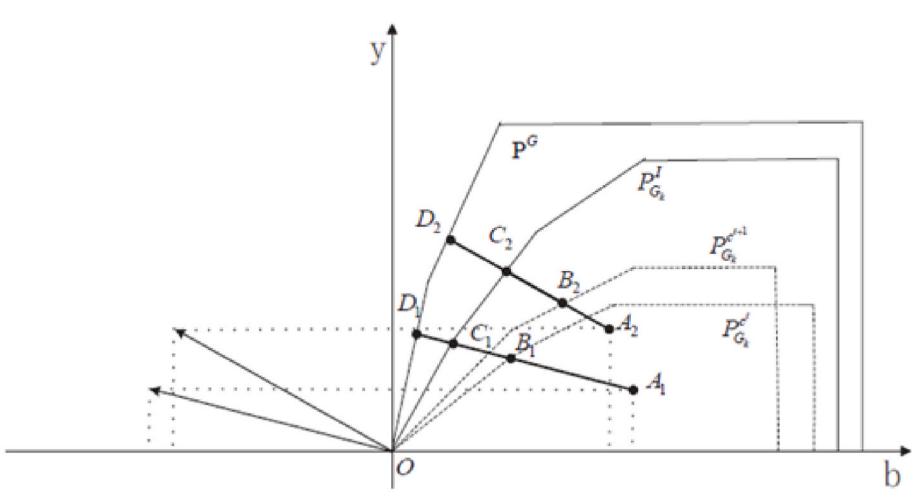

Fig. 1. Benchmark technology sets for defining the MMLPI.
Source: Adapted from Wang et al. (2018).

$$MMLPI\left(x^t,y^t,b^t,x^{t+1},b^{t+1}\right)=\frac{1+\overrightarrow{D}^G(x^t,y^t,b^t)}{1+\overrightarrow{D}^G\left(x^{t+1},y^{t+1},b^{t+1}\right)}=\frac{1+\overrightarrow{D}^t(x^t,y^t,b^t)}{1+\overrightarrow{D}^{t+1}\left(x^{t+1},y^{t+1},b^{t+1}\right)}*$$
$$\left[\frac{\dfrac{1+\overrightarrow{D}^I(x^t,y^t,b^t)}{1+\overrightarrow{D}^t(x^t,y^t,b^t)}}{\dfrac{1+\overrightarrow{D}^I\left(x^{t+1},y^{t+1},b^{t+1}\right)}{1+\overrightarrow{D}^{t+1}\left(x^{t+1},y^{t+1},b^{t+1}\right)}}\right]*\left[\frac{\dfrac{1+\overrightarrow{D}^G(x^t,y^t,b^t)}{1+\overrightarrow{D}^I(x^t,y^t,b^t)}}{\dfrac{1+\overrightarrow{D}^G\left(x^{t+1},y^{t+1},b^{t+1}\right)}{1+\overrightarrow{D}^I\left(x^{t+1},y^{t+1},b^{t+1}\right)}}\right]=\frac{1+\overrightarrow{D}^t(x^t,y^t,b^t)}{1+\overrightarrow{D}^{t+1}\left(x^{t+1},y^{t+1},b^{t+1}\right)}* \tag{11}$$
$$\left[\frac{1+\overrightarrow{D}^I(x^t,y^t,b^t)}{1+\overrightarrow{D}^t(x^t,y^t,b^t)}\Big/\frac{1+\overrightarrow{D}^I\left(x^{t+1},y^{t+1},b^{t+1}\right)}{1+\overrightarrow{D}^{t+1}\left(x^{t+1},y^{t+1},b^{t+1}\right)}\right]*\left[\frac{1+\overrightarrow{D}^G(x^t,y^t,b^t)}{1+\overrightarrow{D}^I(x^t,y^t,b^t)}\Big/\frac{1+\overrightarrow{D}^G\left(x^{t+1},y^{t+1},b^{t+1}\right)}{1+\overrightarrow{D}^I\left(x^{t+1},y^{t+1},b^{t+1}\right)}\right]=$$
$$\frac{TE^{t+1}}{TE^t}*\frac{BPR^{t+1}}{BPR^t}*\frac{TGR^{t+1}}{TGR^t}=EC*BPC*TGC$$

frontier has shifted toward (farther away from) the intertemporal benchmark technology frontier. TGC represents the "technology catching-up effect" among units (here, WSPs), which relates to changes in an intertemporal benchmark technology frontier and a global benchmark technology frontier over the two periods. TGC >1 (<1) indicates that the technical gap between a specific group and the global frontier technology has decreased (increased). Hence, the TGC provides information on the technical leadership effect of a given group. MMLPI >1 (<1) indicates that productivity improved (worsened) between t and $t+1$.

2.3. Calculation of the directional distance function

As illustrated by Eq. (9), to calculate the MMLPI, the directional distance function should be estimated to calculate MMLPI. In particular, to decompose the MMLPI into EC, BPC, and TGC, six directional distance functions should be estimated: $\overrightarrow{D}^G(x^s,y^s,b^s)$, $\overrightarrow{D}^I(x^s,y^s,b^s)$, $\overrightarrow{D}^s(x^s,y^s,b^s)$, where $s=t$ and $t+1$.

Two main approaches are applied to calculate the directional distance function. On the one hand, Färe et al. (2006) defined the directional distance function as a quadratic form and used linear programming. This approach allows for the easy calculation of shadow prices. However, it assumes a functional form of the directional distance function (Wang et al., 2018). On the other hand, other studies (e.g., Du et al., 2018; Färe et al., 2007; Suárez-Varela et al., 2017) employed the DEA approach, which is also based on linear programming. However, the DEA does not allow the computation of shadow prices and does not require any functional form of the directional distance function. This advantage is key to our analysis because there is no standard functional form of the production function for WSPs. Therefore, in this study, the directional distance functions were calculated by solving the following linear programming model:

$$\begin{aligned}
&\overrightarrow{D}^d\left(x^{k\acute{}s},y^{k\acute{s}},b^{k\acute{s}}\right)=\max\beta\\
&\textit{subject to}\\
&\sum_{con}\lambda^{k,s}y_m^{k,s}\geq(1+\beta)y_m^{k\acute{s}}\quad m=1,\dots,M,\\
&\sum_{con}\lambda^{k,s}b_j^{k,s}=(1-\beta)b_j^{k\acute{s}}\quad j=1,\dots,J,\\
&\sum_{con}\lambda^{k,s}x_n^{k,s}\leq x_n^{k\acute{s}}\quad n=1,\dots,N,\\
&\lambda^k\geq0
\end{aligned} \tag{12}$$

where superscript d in the objective function represents the types of directional distance functions (contemporaneous, intertemporal, and global); $\lambda^{k,s}$ is an intensity variable for constructing the production possibility set through a convex combination of observations; and the *con* under $\sum$ represents the condition for constructing a production possibility set, i.e., contemporaneous, intertemporal and global. Hence, for the contemporaneous directional distance function, $d\equiv s$ and $con\equiv\{k\in R_h\}$; for the intertemporal directional distance function, $d\equiv I$ and $con\equiv\{k\in R_h\, s\in\tau\}$, where $\tau=\{1,2,\dots,T\}$ and; for the global directional distance function $d\equiv G$ and $con\equiv\{k\in R, s\in\tau\}$, where $\tau=\{1,2,\dots,T\}$ and $R=R_1\cup R_2\cup\dots\cup R_H$.

According to Fried et al. (2008), the directional vector can be as follows: i) $g=(x,y)$; ii) $g=(0,y)$; iii) $g=(x,0)$; iv) $g=(1,-1)$; v) $g=(\overline{x},\overline{y})$, i.e., the mean values of x and y; vi) g determined from a policy directive and; vii) optimize g to minimize distance to frontier of technology. The selection of the directional vector depends on the main activity carried out by the units evaluated and the purpose of the assessment (Wang et al., 2019). The first option simultaneously scales in the inputs and output directions, whereas the second and third options scale either in the output direction or in the input direction, which in our study involve that WSPs seek only to minimize the generation of unsorted waste (bad output) or maximize the production of sorted waste (good output), respectively. In this study, the directional vector $g=(1,-1)$, i.e., the fourth option, was selected since WSPs seek the simultaneous expansion of desirable outputs (sorted waste) and reduction of undesirable outputs (unsorted waste). Considering the data used in our study, the mean value option (fifth) would involve negative independent terms. Finally, options sixth and seventh were not considered as there is no specific policy to be analyzed.

3. Case analysis

The dataset employed in this study comprises 68 large Italian municipalities whose population is greater than 14,000 people (each provincial capital) out of 107 Italian provinces over 2016–2019 and considers a population of 10,432,777 people, representing around 17.3% of the total Italian population. The municipalities evaluated belong to 19 out of the 20 Italian administrative regions. Hence, this study can be considered representative from a geographical viewpoint. The 68 municipalities were clustered according to the ownership of their entrusted waste utilities: 44% public (30 out of 68), 41% mixed (28 out of 68), and 15% private (10 out of 68).

3.1. Regulation of municipal solid waste services in Italy

In 1997, Italy issued Legislative Decree 22/97, which defined the framework for the waste management system for a decade and beyond (European Environmental Agency, 2013). Indeed, it defined the responsibilities of all actors involved in the system, with regions responsible for drawing up waste management plans and municipalities being the WSPs in charge of organizing municipal waste collection and management. Further, it introduced targets for the separate collection of municipal waste, settled the National Packaging Consortium (CONAI), and fostered the gradual introduction of a new waste tariff (EEA, 2013). Decree 22/97 was abrogated after a decade by Legislative Decree 152/2006, which incorporated most of its provisions, assuming they are still valid (EEA, 2013).

In 2018, four European Union (EU) directives came into force (2018/851/UE, 2018/850/UE, 2018/852/UE, and 2018/849/UE) amending the previous ones (Directive, 2008/98/EC on waste, 1999/31/EC on the landfill of waste, 94/62/EC on packaging and packaging waste, 2000/53/EC on end-of-life vehicles, 2006/66/EC on batteries and accumulators and waste batteries and accumulators, and 2012/19/EU on waste electrical and electronic equipment); along with the European Action Plan, they represent the "circular economy package." The new directives set targets for the preparation of the reuse and recycling of municipal waste at 55% by 2025, 60% by 2030, and 65% by 2035. For packaging waste, recycling is expected to be 65% by 2025 and 70% by 2030 for all types of packaging, with objectives differentiated by material. These EU targets should be fulfilled at the national level by each European country, including Italy, which adopted them by legislation in 2020.

In 2019, urban waste production in Italy was 30.1 million tons, with a slight decrease of 0.3% compared to 2018 (ISPRA, 2020). However, there are relevant differences among macro-areas: while municipal waste production grew in the northern regions (+0.5%), it decreased by 0.2% in the center; and 1.5% in the southern region (ISPRA, 2020).

In 2019, the separate collection rate was 61.3% of the national production, representing an increase of 3.1 points compared to the percentage of 2018 and a doubling since 2008. This environmental target, imposed by Italian law (Legislative decree n. 152/2006 and Law n. 296/2006), derived from results for regions and macro-areas; in 2019, the separate collection rate was 69.6% for the north of Italy, 58.1% for the center, and 50.6% for the southern regions (ISPRA, 2020).

Indeed, the MSW sector in Italy shows relevant differences among areas, is highly fragmented with most operators involved in only one activity (e.g., collection, treatment, tariff collection), and still lacks adequate infrastructure and suitable organization throughout the country (ARERA, 2020). Along with well-structured waste utilities with stable entrustments from the municipalities served (Minoja and Romano, 2021; Romano et al., 2021b), there are still many municipalities with temporary service entrustments of services to small utilities, which frequently creates social and environmental problems (ANAC, 2019).

Moreover, there is still a wide variety of management models available for municipalities, from direct management to in-house provision, from delegated management to mixed-owned utilities, and from delegated management to private firms. A recent report by Invitalia (2019) showed that public control prevails (in 56% of cases, of which 44% through public companies and 12% through joint majority public-owned utilities). In-house provision and public ownership are relatively more frequent for larger companies located in the center-north region of Italy, while entrustments through public tenders to private firms are more widespread in the south and often concern individual segments of urban waste service (e.g., collection, treatment, tariff collection) (Invitalia, 2019).

In 2018 the Italian Regulatory Authority for Energy, Networks and Environment (ARERA) was established to regulate the waste cycle at the national level. At the local level, urban waste management is organized based on optimal territorial areas (ATOs), delimited by regional plans.

3.2. Selection of variables for eco-productivity assessment

Following past practices in evaluating the eco-efficiency of WSPs (e.g., Guerrini et al., 2017; Llanquileo-Melgarejo et al., 2021; Sarra et al., 2017), cost variables were integrated into the assessment as inputs. In particular, three inputs were considered: (i) the total cost of managing unsorted waste per capita (EUR/capita * year), which includes the municipal costs for the collection, transport, and disposal of unsorted waste, cleaning and sweeping roads, and other costs related to the management of unsorted waste; ii) the total municipal costs of managing recycled waste per capita (EUR/capita * year), which includes the costs for the collection, transport, treatment, and recycling sorted waste; and iii) the total assets of WSP (EUR). Data on costs were collected from the Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA) database. Data on total assets were retrieved from the AIDA Bureau Van Dijk database. Given the aim of this study to evaluate the eco-productivity of municipalities, the sorted MSW per capita was included as desirable output (kg/year * person), whereas unsorted MSW per capita was considered as undesirable output (kg/year * person). The source of these data was also the ISPRA database.

The average values for 2016 and 2019 for the variables employed in this study are shown in Table 1. It illustrates that, on average, the total volume of generated MSW (sorted and unsorted waste) by the 68 Major Italian towns evaluated remained almost constant, since in 2016 it was 546.4 kg/year per capita, whereas, in 2019, it was 542.7 kg/year per capita. However, we observed an increase in the percentage of recycled MSW, as the quantity of sorted MSW increased by 16.3%, while the unsorted MSW decreased by 19.0% from 2016 to 2019. In 2016 and 2019, the municipalities whose waste utilities were mixed-owned generated total MSW above average, while the opposite is evidenced for privately-owned utilities. Nevertheless, when sorted and unsorted MSW providers are considered separately, a different pattern is observed. Municipalities with mixed-owned utilities present the highest percentage of sorted waste as, in 2016 and 2019, 60.0% and 68.4% of the MSW was collected, respectively. By contrast, for municipalities with privately-owned operators, these figures were only 35.5% and 55.2% in 2016 and 2019, respectively.

Focusing on the costs of providing waste services, Table 1 shows that, on average, the municipalities spent EUR 108.3 and 112.6 per capita annually in 2016 and 2019, respectively, to manage sorted and unsorted MSW. The average lowest total costs corresponded to mixed-owned WSPs since they were 100.0 and 103.7 EUR/year ∗ person for 2016 and 2019, respectively. By contrast, municipalities with privately-owned utilities exhibited higher total costs than average (118.7 and 130.2 EUR/year per person for 2016 and 2019, respectively). In 2016, the average total cost of managing sorted waste was 0.168 EUR/kg, whereas it was 0.230 EUR/kg for unsorted waste. By 2019, the average total cost of sorted waste remained almost constant (0.169 EUR/kg), while it notably increased for unsorted waste (0.268 EUR/kg). These figures show that managing sorted MSW is not more expensive than managing unsorted MSW.

4. Results and discussion

The average results from the MMLPI estimation (i.e., eco-productivity change) for all WSPs and their drivers are reported in Table 2 (results for each WSP are shown in Fig. 3 and the supplemental material). Data are reported for the total sample and the three groups/clusters with reference to the ownership of the utility entrusted to urban waste management by major Italian towns. Table 2 shows that the eco-productivity of all major towns increased by 8.3% during the 2016–2019 period and that all three clusters considered experienced an eco-productivity improvement during this period, with municipalities that entrusted a private waste utility reporting the highest increase (9.6% versus 6.9% for public and 9.2% for mixed). This result could be explained by taking into account the European and Italian normative framework, which impose strict targets on all municipalities in terms of sorted waste increase and unsorted waste reduction (ISPRA, 2020; Agovino et al., 2021). Results confirm the efforts made by many Italian municipalities to pave the way through improved eco-efficiency.

As reported in Fig. 2, the best and worst cases are the municipalities with privately-owned utilities entrusted to urban waste management. By

Table 1
Average values of the variables employed to evaluate the eco-productivity change of the WSPs in 68 major towns in Italy clustered by ownership of entrusted waste utility.

Variables for eco-productivity assessment	2016				2019			
	Public	Mixed	Private	Total	Public	Mixed	Private	Total
Sorted MSW (kg/year * person)	265.5	339.4	179.6	283.8	294.0	392.0	262.1	330.1
Unsorted MSW (kg/year * person)	275.8	226.2	326.8	262.6	242.0	181.0	212.8	212.6
Total cost unsorted MSW (EUR/year * person)	68.9	47.1	73.3	60.5	65.4	42.5	72.7	56.9
Total cost sorted MSW (EUR/year * person)	43.7	52.9	45.4	47.8	50.0	61.2	57.5	55.7
Total asset of the entrusted utility (10^3 EUR)	78.9	212.5	59.4	131.5	87.7	224.8	71.4	142.2

Table 2
Eco-productivity change of WSPs measured by MMLPI and its drivers (EC, BPC, and TGC-) clustered by ownership.

Waste Utilities	MMLPI	EC	BPC	TGC	Municipalities with MMLPI>1 (%)
Public	1.069	1.094	0.980	1.020	76.7
Mixed	1.092	1.051	1.040	1.010	35.7
Private	1.096	1.162	1.154	0.885	50.0
All	1.083	1.087	1.030	0.996	73.5

contrast, the public WSPs presented a more homogeneous behavior, as the amplitude between the maximum and minimum MMLPI was the smallest among the three groups. As shown in Fig. 2, for the three clusters, the minimum MMLPI was below 1.0, which means that not all municipalities improved their eco-productivities during 2016–2019. This result highlights the need to increase utilities and municipalities efforts to improve their results (Romano et al., 2019; Sarra et al., 2017; Romano and Molinos-Senante, 2020). Indeed, in October 2019, the national regulator (ARERA) approved a new tariff method for urban waste management to further support municipalities and waste utilities to improve their waste management performance (ARERA, 2020). Table 1 shows that only half of the municipalities with private ownership and about one-third with mixed ownership improved their eco-productivity, whereas 76.7% of the public WSPs presented a positive performance evolution. Despite the differences in the average MMLPI values among the three groups of waste utilities according to ownership, from a statistical viewpoint, they are not significant, as the p-value of the Kruskal-Wallis test was 0.6119. Thus, the null hypothesis, which states that the three groups of WSPs (public, mixed, and private) originate from the same populations, cannot be rejected. In other words, the differences in eco-productivity changes among the evaluated groups of Italian waste utilities were not statistically significant.

To better understand what fostered the change in eco-productivity in the urban waste management of Major Italian towns, we look at the MMLPI components: EC, BPC, and TGC. The average results indicate that the EC and BPC components contributed positively to the changes in productivity from 2016 to 2019.

EC (average value 1.087) contributed more than BPC (average value 1.03) to the productivity improvements, while TGC contributed slightly negatively to the eco-productivity change (average value 0.996). These results suggest that municipalities achieved improvements in average technical efficiency and that technical changes were experienced during the studied period. The average efficiency improvement was moderate, at 8.7% per year. As shown in Fig. 4 and the supplemental material, 52.9% (36 out of 68), 16.2% (11 out of 68), and 30.9 (21 out of 68) of the Italian WSPs evaluated improved, not changed, and decreased EC, respectively, over the study period. Considering that EC measures the catch-up effect, this finding illustrates that most major Italian municipalities moved closer to the most efficient ones. This result seems to confirm previous research that highlighted the importance of promoting and spreading best practices in urban waste management (Romano et al., 2021a; Di Foggia and Beccarello, 2021). By contrast, the municipalities whose EC was smaller than 1 experienced a lag in the catch-up

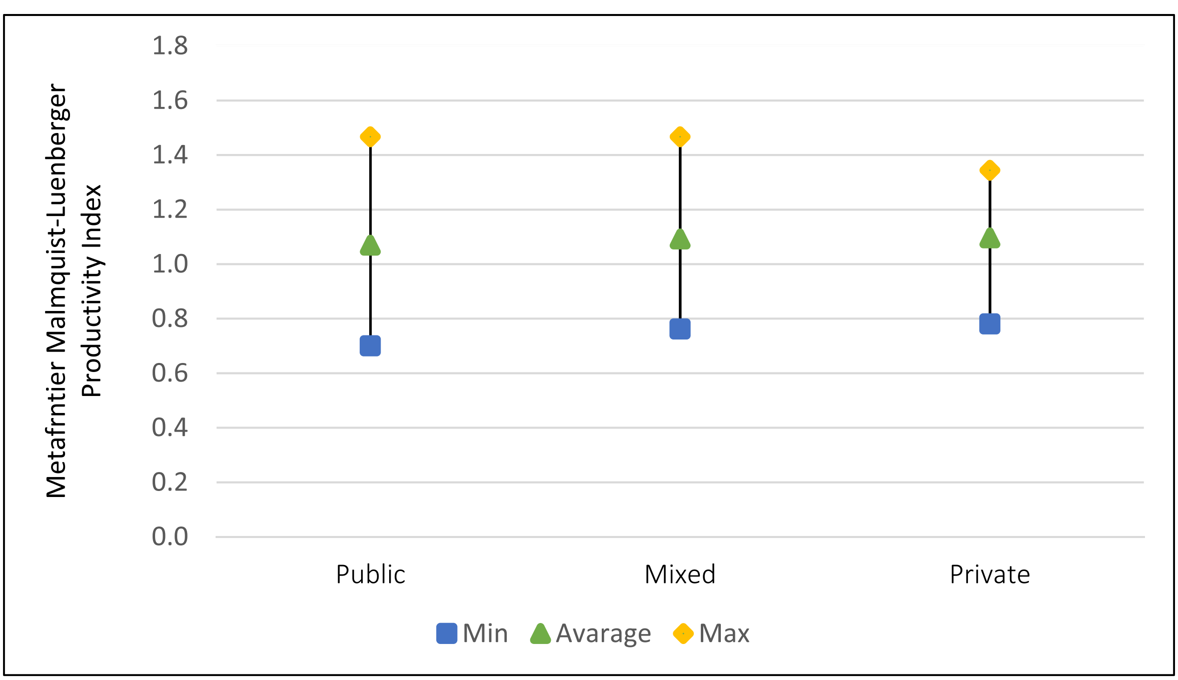

Fig. 2. Statistical values of eco-productivity change of municipalities (WSPs) served by entrusted public, mixed, and private waste utilities.

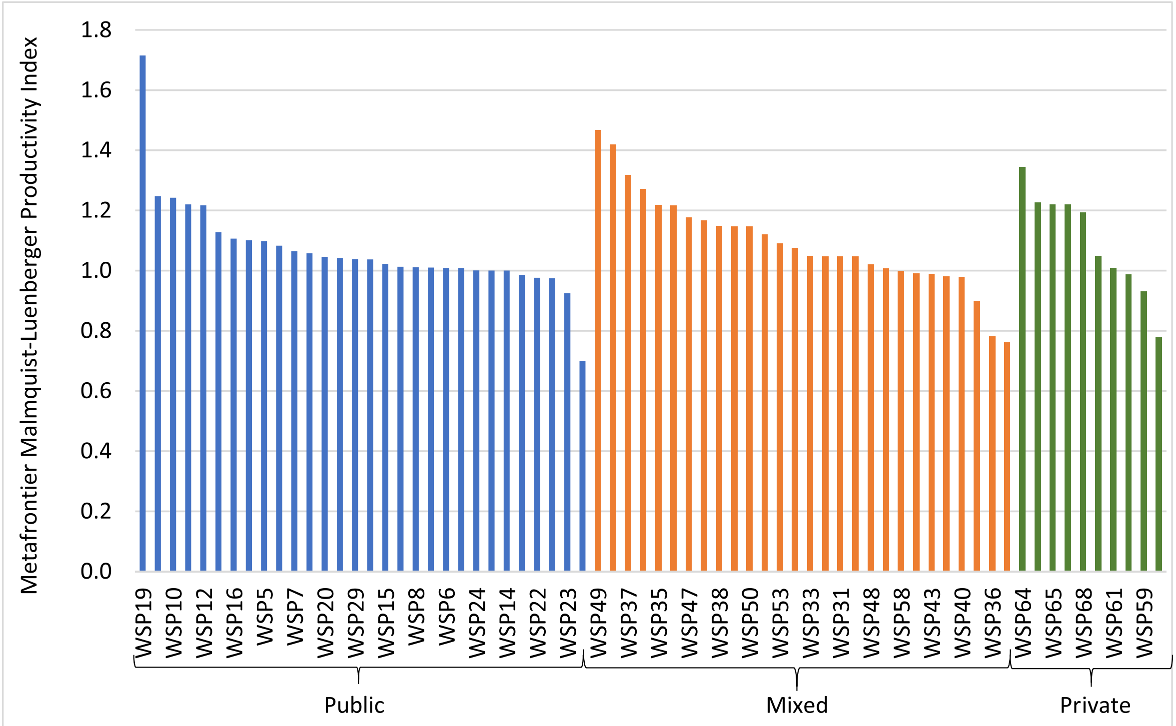

Fig. 3. Eco-productivity change of municipalities (WSPs) served by entrusted public, mixed, and private waste utilities.

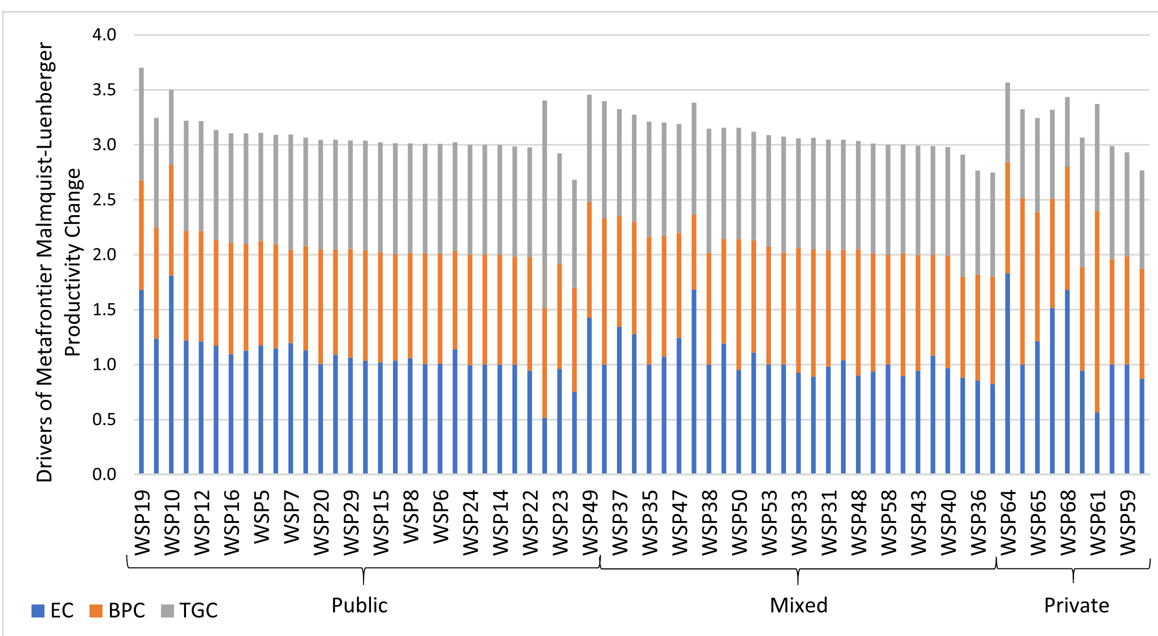

Fig. 4. Drivers of eco-productivity change of public, mixed, and private waste service providers (WSPs).

index; therefore, they need to manage their day-to-day operations better to save costs and increase the volume of recycled MSW.

The BPC results (Table 2 and Fig. 4) show that, on average, the evaluated WSPs increased their technical change by 3% per year. In particular, 25 out of the 68 waste utilities (36.8%) exhibited values smaller than 1 for BPC, whereas 36 out of 68 (52.9%) had values higher than 1. The remaining WSPs evaluated (7 out of 68, or 10.3%) exhibited BPC values equal to 1. Considering that BPC is an innovation factor (Mocholi-Arce et al., 2021), the results show that more than one-third of the WSPs evaluated require further investments in technology that allow the contemporaneous technology to shift closer to the intertemporal technology. This objective can be achieved by adopting the best practices for separate collection and MSW recycling, as suggested by increasingly relevant strategies such as the “zero waste” one (Connett, 2013; Romano et al., 2020, 2021a) and by recent case studies (Minoja and Romano, 2021; Castigliego et al., 2021). Agovino et al. (2021) confirmed a convergence process for the sorted waste in Italy, even if the convergence speed among macro-area is still different, with the northern regions performing better than the Central and the Southern. The third driver of the MMLPI is the TGC, which provides information about the "technology catching-up impact" (Bansal et al., 2021). The average value for the 68 evaluated WSPs was below 1 (0.996), being the driver that contributed less and negatively to eco-productivity change over the study period. Fig. 4 illustrates that 25 out of 68 waste utilities (36.8%) improved their TGC, whereas 29 out of 68 (42.6%) lagged according to this eco-productivity driver. This finding implies that, for most of the evaluated WSPs, the gap in technology between the intertemporal technology and the global technology was improved or remained constant. This result corroborates the finding of the Italian Regulatory Authority (ARERA, 2020) in terms of the need to strengthen the attention to infrastructures, encourage plant development, and disseminate new technologies. From the cluster results, the data show that municipalities with public utilities entrusted with waste management services are better able than those with mixed or private operators to close the gap for the contemporaneous benchmark technology in 2019 relative to 2016 (see Fig. 4). This result confirms Italian case studies outcomes (Minoja and Romano, 2021; Romano et al., 2021a): public ownership appears to be more suitable than private ownership for improving intellectual capital (i.e. intellectual material, knowledge, experience, intellectual property, and so on) and innovative investments, "owing to lower pressure on profits and dividends, willingness to invest with delayed returns, and stronger relationships with the community" (Minoja and Romano, 2021: 123,213). Moreover, as Simões and Marques (2012) highlighted, the results confirm that "public provision yields better results in the richest countries".

Further, the private cluster experienced the best result in terms of BPC (1.154 versus 1.040 mixed and 0.980 public); as BPC is considered as relative innovation effect, the result suggests that, when municipalities with entrusted private utilities are evaluated within their cluster, they experienced the highest technical progress over the study period. The values lower than 1 of the BPC for the municipalities with public operators entrusted to the waste management service highlight that during the 2016–2019 period, their contemporaneous frontier shifted toward generating more desirable and less undesirable outputs. This finding implies that the municipalities' efforts with public waste utilities, in accordance with the targets imposed by the European and national regulations, were not enough to improve technical change.

The TGC component of the MMLPI, that is, the "technology catching-up effect," deserves further comments and analysis. It exhibits a different behavior among clusters, shedding light on the peculiarities of the three groups. Specifically, the largest TGC was reported for public waste utilities, with an average value of 2% per year.

This finding demonstrates that the technical gap between the public group and the global frontier technology decreased slightly in 2019 compared to 2016. By contrast, TGC for the private cluster showed that the gap in technology between the intertemporal technology for this cluster and global technology increased. Therefore, the private sector experienced a significant (11.5%) reduction in technical leadership.

Indeed, the municipalities with privately-owned waste utilities (private cluster) in 2016 had the lowest rate of sorted waste among major towns (Table 1); further, previous research (Romano et al., 2019) based on 2012–2015 data for one Italian region (Tuscany) highlighted that the municipalities with privately-owned waste utilities produce more waste pro capita than the municipalities with public or mixed-owned operators and that the municipalities that directly manage the service or entrust it to public firms that have higher rates of separate collection than the others. Therefore, the significant technological advancement of private and mixed-owned waste utilities could be linked to the need to increase the separate collection rates and reduce unsorted waste in the served territories to reduce the differences from the municipalities served by publicly owned operators. In other words, if the EC and BPC indexes keep track of private firms' efforts to improve their performance, TGC reveals the weaknesses of private operators relative to public and mixed.

The results for private waste operators show that the technical gap between these firms and the global frontier technology increased, highlighting the need to foster the invention and adoption of new technologies able to increase the separate and reduce the unsorted waste collection. Technology appears to be driven by publicly owned waste operators (Minoja and Romano, 2021), and the technological levels of private utilities have deteriorated relative to global technological progress, further supporting the debate about remunicipalisation in public service provision (Albalate et al., 2021; Clifton et al., 2019; Romano et al., 2021a). This unfavorable technological situation of private waste operators should induce municipalities that entrust the services to private operators to impose strict targets for both desirable (separately collected waste) and undesirable (unsorted waste) outputs, fostering technical investment in technologies and innovation to improve separate collection (e.g., RFID technology for pay-as-you-throw tariff) and to reduce unsorted waste (e.g., increase separate waste collection frequency).

5. Conclusions

Improving MSW management is a critical issue for local and national authorities to enhance the circular economy and sustainability, increase the quality of life in communities, and reduce health risks. In this context, the ownership of waste utilities is relevant for defining their strategies and their economic and environmental targets, as it might influence their performance. Previous studies (Romano et al., 2020; Romano and Molinos-Senante, 2020) have evaluated the impact of Tuscan WSP ownership on eco-efficiency. However, the information provided by these studies is limited, as eco-efficiency is a static evaluation of the performance; that is, it only considers the performance of WSPs during a single year; further, the focus on a since the region is too narrow to derive generalizable results. This study evaluated the temporal dynamics of eco-efficiency to overcome these limitations and provide more robust conclusions. In other words, it analyzed the eco-productivity changes of WSPs. To analyze the influence of ownership on the eco-productivity change of WSPs, the MMLPI was estimated and decomposed into three drivers: EC, TGC, and BPC.

An empirical application for a sample of 68 major Italian towns was conducted over the 2016–2019 period to illustrate the usefulness of the applied methodological approach. The main results are as follows. First, on average, Italian waste utilities assessed increased their eco-productivity by 8.3% during this period. This finding supports the efforts of WSPs to simultaneously reduce operational costs and increase the volume of recycled MSW. Second, the three WSP clusters (private, public, and mixed ownership utilities) improved their eco-productivities over time, with privately- and mixed-owned WSPs showing the most notable increases.

Nevertheless, the differences in eco-productivity change estimations among the three groups of Italian WSPs evaluated were not statistically significant. Accordingly, the ownership of WSPs does not have a significant impact on the evolution of their economic and environmental performance, as measured by the MMLPI. Third, the EC and BPC drivers positively contributed to eco-productivity change, which means that technical efficiency increased, and the innovation effect of WSPs contributed positively to the eco-productivity change. However, the WSPs with entrusted public utilities still have room to improve their dynamic eco-efficiencies by implementing innovative practices in their operations and management.

Finally, the "technology catching-up effect" exhibits different results among clusters: while the technical gap between the public group and the global frontier technology slightly decreased in 2019 compared to 2016, the private cluster showed an increase. Therefore, the private sector experienced a relevant (11.5%) reduction in technical leadership, thus requiring strict controls from WSPs to foster significant technological advancement. Since European and national targets request to increase the separate collection rates and reduce unsorted waste, the existing differences from the municipalities served by publicly owned operators should be covered by the municipalities that totally or partly privatized their urban waste service management. In other words, although private firms have made efforts to improve their performances, the TGC component of the MMLPI reveals the weaknesses of private operators compared to public and mixed ones in terms of the technical gap between these firms and the global frontier technology. For this reason, the municipalities that entrust these services to private operators should impose strict targets for separate collection and unsorted waste reduction by fostering technical investment in technologies and organizational innovation.

A limitation of this study is the relatively low number of private WSPs assessed (15%) compared with the number of public (44%) and mixed (41%) WSPs. Although this study employs DEA meta-frontier approach, dynamic eco-efficiency scores might be affected by the differences in the size of the groups evaluated. As the results are influenced by the low number of private WSPs considered in the study, they must be interpreted cautiously in developing policy. Hence, further research might involve using robust methods such as DEA order-m or DEA order-α to minimize potential bias in the results and, therefore, in the comparison of groups of WSPs. Previous studies have revealed that some exogenous variables, such as population, population density, average age, and tourism, might influence the performance of WSPs. Hence, further research is required to extend the analysis conducted to evaluate the influence of several exogenous or environmental variables on the eco-productivity change of Italian WSPs. The literature illustrates that conditional frontier analysis extends the non-parametric production technology to robustly account for outliers in the data and allow measuring the effect of environmental variables on the dynamic eco-efficiency of units. Moreover, future studies could cluster WSPs based on their management model, for example, door-to-door collection, in-house provision, and delegated management, to evaluate its impact on the performance of WSPs.

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 A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jup.2021.101311.

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