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RESEARCH ARTICLE

A comprehensive evaluation of eco-productivity of the municipal solid waste service in Chile

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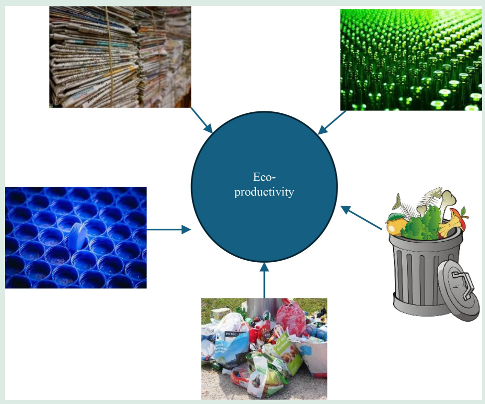
HIGHLIGHTS

- Dynamic eco-efficiency of solid waste services providers was assessed.
- Eco-productivity of Chilean municipalities improved by 1.28% per year.
- Technical progress was the main driver of eco-productivity change.



ABSTRACT: Moving toward a circular economy requires improvement of the economic and environmental performance of municipalities in their provision of municipal solid waste (MSW) services. Understanding performance changes over years is fundamental to support decision-making. This study employs the Luenberger-Hicks-Moorsteen productivity indicator to evaluate eco-productivity change and its drivers in the MSW sector in Chile over the years 2015–2019. The further use of decision tree and linear regression analysis allows exploration of the interaction between operating characteristics and eco-productivity estimations. The results of the eco-productivity assessment show that, although the Chilean MSW sector was still facing a transitional period, from 2015 to 2019, eco-productivity increased 1.28% per year. Gains in eco-productivity were due to technical progress and small gains in efficiency, whereas scale effect had an adverse impact. Other factors such as waste spending per inhabitant and the amount of waste collected and recycled per inhabitant had a significant impact on the eco-productivity of Chilean municipalities.

KEYWORDS: Solid waste, Eco-productivity change, Luenberger-Hick-Moorsteen, Recycled waste, Regression tree, Circular economy

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1 Introduction

One of the most important environmental challenges for society is the move toward a resource-efficient, circular economy, which involves reducing the generation of municipal solid waste (MSW). This has become particularly important in recent decades due to population growth, economic development, and new consumption habits or behavior (Simões et al., 2012; Fan et al., 2020; Halkos and Aslanidis, 2023). Based on World Bank estimates, the generation of waste will have reached a level of 3.40 billion tons globally by 2050 from 2.01 billion tons in 2016 (Kaza et al., 2018). Without the intervention of policy makers, waste production will continue to grow. Urban and rural areas will have to cope with an increasing demand for waste services, a lack of available landfill and environmental problems (Gastaldi et al., 2020). According to the United Nations' Sustainable Development Goals (SDGs) (Ghisellini et al., 2016; UN, 2016; Geissdoerfer et al., 2017) recycling MSW constitutes the major component of the circular economy. Solid waste services include the collection, transport and disposal of waste (Valenzuela-Levi, 2019). The management of MSW usually falls under the jurisdiction of municipalities, which need to ensure the provision of collection and recycling services that meet high standards of quality at an affordable cost (Sarra et al., 2017). In this context, it is essential to evaluate the performance of municipalities in their provision of MSW services and understand what drives this performance.

Several studies have evaluated the performance of the solid waste industry from an economic and environmental point of view. The main objective of their assessment of economic efficiency was control of the operational costs of managing a given quantity of MSW (e.g., Carvalho and Marques, 2014; Greco et al., 2015; Guerrini et al., 2017). As the environmental issues related to MSW management gained more importance, a stream of research focused on assessing the eco-efficiency of MSW service providers. This involved a joint evaluation of the economic and environmental performance of municipalities by integrating operational costs, recycled waste and unsorted waste in a synthetic index (Díaz-Villavicencio et al., 2017; Guerrini et al., 2017; Sarra et al., 2017, 2019, 2020; Expósito and Velasco, 2018; Romano and Molinos-Senante, 2020; Romano et al., 2020; Delgado-Antequera et al., 2021; Llanquileo-Melgarejo and Molinos-Senante, 2021; Llanquileo-Melgarejo et al., 2021; Amaral et al., 2022; Molinos-Senante et al., 2022; Sala-Garrido et al., 2022). Eco-efficiency provides a static evaluation of the performance of municipalities without considering their potential changes over time (Saravia-Pinilla et al., 2019). However, as many countries and regions adopt policies to improve MSW management, it becomes necessary to conduct a dynamic assessment in order to assess the impact of policies on municipal performance. Such assessments consider changes in eco-efficiency over years. To better support the decision-making process, information on the temporal dynamics of eco-efficiency is essential (Llanquileo-Melgarejo and Molinos-Senante, 2022).

Despite of the relevance of assessing eco-efficiency change over time, only a small number of studies have assessed the eco-productivity (i.e., dynamic eco-efficiency) of municipalities in MSW service provision. According to the literature, past research on this topic is limited to Lo Storto (2021), Romano et al. (2021), and Llanquileo-Melgarejo and Molinos-Senante (2022). These three studies assessed the eco-productivity changes of municipalities by computing different extensions of the Malmquist Productivity Index (MPI). Lo Storto (2021) compared the economic productivity and eco-productivity of 258 municipalities located in the Italian region of Apulia by computing global MPI. The study of Romano et al. (2021) also focused on Italian municipalities, comparing the eco-productivity of municipalities with public, private and mixed ownership waste utilities. In doing so, the Metafrontier Malmquist-Luenberger Productivity Indicator (MLPI) was computed. Finally, Llanquileo-Melgarejo and Molinos-Senante (2022) estimated the MLPI, which was subsequently broken down into eco-efficiency and technical change for a sample of Chilean municipalities.

Whereas past research evaluating the eco-productivity of municipalities in the provision of MSW notably contributed to the literature, the synthetic index used, the MPI (and its extensions), presents some notable pitfalls (Aparicio et al., 2018). First, when the units evaluated (municipalities in this study) operate under variable returns to scale, the MPI is not a correct measure of total factor productivity change (O'Donnell, 2008). Evidence about the presence of economies of scale in the provision of MSW services is mixed (Guerrini et al., 2017) and therefore, it can not be assumed that municipalities operate under constant returns to scale. Secondly, computation of the MPI requires selecting between an input or an output orientation. This means that the analyst should define whether municipalities prefer to minimise inputs to produce a given set of outputs, or if they prefer to maximise output generation given a set of inputs. According to Kerstens and Van De Woestyne (2014), and Peyrache (2014), the MPI does not properly reflect total factor productivity change from scale effects.

The current study deals with these limitations by measuring the eco-productivity change of several municipalities in the provision of MSW services, employing the Luenberger-Hicks-Moorsteen Productivity Indicator (LHMPI) developed by Briec and Kerstens (2004). This indicator integrates the Luenberger Productivity Indicator and the Hicks-Moorsteen Productivity Index. Its advantages over the MPI are as follows. The LHMPI is a difference-based indicator, which means it can identify results for variables that have a value close to zero (Briec and Kerstens, 2011). It allows for a simultaneous expansion of outputs and reduction of inputs (Luenberger, 1992). The LHMPI can break down into input and output growth (Briec et al., 2012). Moreover, it can further break down into other determinants such as technical eco-efficiency change (TEC), eco-technical change (TC) and scale eco-efficiency change (SEC) (Ang and Kerstens, 2017). Finally, it allows the inclusion of undesirable outputs, such as unsorted waste, in the modeling analysis (Baležentis et al., 2017, 2021). Despite its attractive properties, the LHMPI has never been applied in the assessment of MSW industry performance.

Against this background, the objectives of this study are threefold. The first is to assess the eco-productivity change of the municipal solid waste sector in a middle-income country such as Chile using the LHMPI. The second is to identify the main drivers of eco-productivity change by breaking down the LHMPI into TEC, TC and SEC. Finally, the third objective is to analyze the impact of operating characteristics on eco-productivity change. Thus, this study builds a regression tree to model and visualize the interaction between operational variables and eco-productivity estimations.

This study makes the following major contributions. First, it employs the LHMPI to measure the eco-productivity change of municipalities in the provision of MSW services. Secondly, the eco-productivity index breaks down into several drivers, including scale effect, which previous studies have not considered. Thirdly, it combines both non-parametric techniques and decision tree analysis to examine factors affecting the eco-performance of municipalities.

2 Materials and methods

2.1 Eco-productivity change estimation

In this section, we present the methodological approach employed to measure eco-productivity change and its determinants in several Chilean municipalities that provide MSW services. Eco-productivity change is based on the estimation of LHMPI and takes into account three types of variables: 1) the operational cost of managing MSW (input); 2) the quantity of MWS recycled (desirable outputs); and 3) the quantity of unsorted waste (undesirable output).

The measurement of productivity requires presentation of the production technology. Let us suppose that there are I total municipalities that use a set of inputs (resources), denoted x_l, to generate a set of desirable (good) outputs, denoted $y_{g,m}$. As part of this production process several undesirable (bad) outputs, $y_{b,n}$, are also generated. The production technology at any time period t, PT^t can be defined as follows (Eq. (1)):

$$PT^t = \left\{ \left(x^t, y_g^t, y_b^t \right) | x^t can\ generate \left(y_g^t, y_b^t \right) \right\}. \tag{1}$$

Distance functions can be used to represent the production technology (Chen et al., 2020). In the input-oriented case, they measure the technical efficiency of a municipality, i.e., the ability of the municipality to reduce its inputs for a given level of outputs (Coelli et al., 2005). In our case study, the technical efficiency estimated using the distance function will allow measurement of the municipality's ability to reduce the operational costs of managing MSW for a given level of MSW without differentiating recycled and unsorted waste.

Unlike the distance function, directional distance functions (DDFs), developed by Chambers et al. (1996), Chung et al. (1997) and Färe et al. (2005), allow for the simultaneous expansion of desirable outputs and contraction of inputs and undesirable outputs. Hence, DDFs are very useful in the context of eco-productivity change estimation in MSW management because municipalities are interested in recycling as much MSW as possible while at the same time reducing the amounts of operational costs and unsorted waste. The DDF at time t is defined as follows (Eq. (2)):

$$\begin{aligned} & D^t\left(x^t, y_g^t, y_b^t; g_x^t, g_{y_g}^t, g_{y_b}^t\right) = \\ & sup\left\{\beta : x^t - \beta g_x^t, y_g^t + \beta g_{y_g}^t, y_b^t - \beta g_{y_b}^t\right\}, \end{aligned} \tag{2}$$

where $g_x^t, g_{y_g}^t, g_{y_b}^t$ are the directional vectors of inputs, desirable, and undesirable outputs, respectively. In Eq. (2), β presents eco-efficiency and shows that desirable outputs will expand increase while inputs and undesirable outputs will reduce. Based on the approach by Baležentis et al. (2017, 2021) the LHMPI to estimate eco-productivity at time t can be derived as follows (Eq. (3)):

$$LHMPI^{t} = \left[D^{t}\left(x^{t}, y_{g}^{t}, y_{b}^{t}; 0, g_{y_g}^{t}, g_{y_b}^{t}\right) - D^{t}\left(x^{t}, y_{g}^{t+1}, y_{b}^{t+1}; 0, g_{y_g}^{t+1}, g_{y_b}^{t+1}\right)\right] - \left[D^{t}\left(x^{t+1}, y_{g}^{t}, y_{b}^{t}; g_{x}^{t+1}, 0, 0\right) - D^{t}\left(x^{t}, y_{g}^{t}, y_{b}^{t}; g_{x}^{t}, 0, 0\right)\right] = [LO^{t} - LI^{t}]. \quad (3)$$

The LHMPI at time t is derived from changes in outputs (keeping inputs constant) and inputs (keeping outputs constant) at time t, LO^{t} and LI^{t}, respectively. The first two terms, which consist of changes in output, measure the distance from the frontier at time period t in the direction of products (both desirable and undesirable) (Baležentis et al., 2017). The next two terms that capture the change in inputs and measure the distance of the frontier at time period t in the direction of inputs.

If $LHMPI^{t}$ takes positive values, then improvements in eco-productivity have occurred. By contrast, if $LHMPI^{t}$ is negative, then eco-productivity has deteriorated. In an analogous manner, the LHMPI at time $t+1$ can be derived based on changes in outputs and inputs at time $t+1$, LO^{t+1} and LI^{t+1}, respectively. This is provided in the equation below (Eq. (4)):

$$LHMPI^{t+1} = \left[D^{t+1}\left(x^{t+1}, y_{g}^{t}, y_{b}^{t}; 0, g_{y_g}^{t}, g_{y_b}^{t}\right) - D^{t+1}\left(x^{t+1}, y_{g}^{t+1}, y_{b}^{t+1}; 0, g_{y_g}^{t+1}, g_{y_b}^{t+1}\right)\right] - \left[D^{t+1}\left(x^{t+1}, y_{g}^{t+1}, y_{b}^{t+1}; g_{x}^{t+1}, 0, 0\right) - D^{t+1}\left(x^{t}, y_{g}^{t+1}, y_{b}^{t+1}; g_{x}^{t}, 0, 0\right)\right] = \left[LO^{t+1} - LI^{t+1}\right]. \quad (4)$$

Consequently, changes in eco-productivity between time period t and $t+1$ are derived by taking the arithmetic mean of the above productivity indicators (Eq. (5)) (Baležentis et al., 2021):

$$LHMPI^{t,t+1} = \frac{1}{2}\left(LHMPI^{t} + LHMPI^{t+1}\right) = \frac{1}{2}\left[\left(LO^{t} - LI^{t}\right) + \left(LO^{t+1} - LI^{t+1}\right)\right] = \frac{1}{2}\left[\left(LO^{t} + LO^{t+1}\right) - \left(LI^{t} + LI^{t+1}\right)\right] = \frac{1}{2}\left(LO^{t,t+1} - LI^{t,t+1}\right). \quad (5)$$

Thus, eco-productivity change depends on changes in outputs and inputs between two time periods. Eco-productivity over time improves if $LHMPI^{t,t+1} > 0$. In the case of municipalities managing MSW, this improvement could come from an increase in the quantity of MSW recycled and/or a decrease in operational costs and quantity of unsorted waste.

The LHMPI shown in Eq. (5) can be further broken down into several factors (Eq. (6)):

$$LHMPI^{t,t+1} = TEC^{t,t+1} + TC^{t,t+1} + SEC^{t,t+1}. \quad (6)$$

The first part is $TEC^{t,t+1}$, which measures gains or losses in eco-technical efficiency between two time periods. It shows how close/far away to/from the eco-efficient frontier the less efficient municipalities are. In other words, it shows how much inputs and undesirable products need to reduce concurrently with an increase in desirable products in order to achieve eco-efficiency. The technical eco-efficiency change ($TEC^{t,t+1}$) component is derived through the use of DDFs as follows (Eq. (7)):

$$TEC^{t,t+1} = D^{t}\left(x^{t}, y_{g}^{t}, y_{b}^{t}; 0, g_{y_g}^{t}, g_{y_b}^{t}\right) - D^{t+1}\left(x^{t+1}, y_{g}^{t+1}, y_{b}^{t+1}; 0, g_{y_g}^{t+1}, g_{y_b}^{t+1}\right). \quad (7)$$

If a municipality achieves gains in eco-technical efficiency, i.e., $TEC^{t,t+1} > 0$, this means that it managed to reduce inputs and undesirable products while increasing the production of desirable products. It suggests that the municipality has managed to catch up with the most efficient ones and has improved its eco-productivity over time. The opposite is true when $TEC^{t,t+1} < 0$.

The second part of the eco-productivity change (Eq. (6)) is $TC^{t,t+1}$ which measures eco-technical change, the shift of the production frontier. If $TC^{t,t+1} > 0$, it means that the industry experienced technical progress. This suggests that the adoption of new technologies could have led to an expansion of desirable outputs while simultaneously reducing inputs and undesirable outputs. Technical progress leads to improvements in eco-productivity. In contrast, $TC^{t,t+1} < 0$ implies technical regress which has a negative impact on eco-productivity. Eco-technical change (TC) is derived in terms of DDFs as follows (Eq. (8)):

$$TC^{t,t+1} = \frac{1}{2}\left[\left(D^{t+1}\left(x^{t}, y_{g}^{t}, y_{b}^{t}; 0, g_{y_g}^{t}, g_{y_b}^{t}\right) - D^{t}\left(x^{t}, y_{g}^{t}, y_{b}^{t}; 0, g_{y_g}^{t}, g_{y_b}^{t}\right)\right) + \left(D^{t+1}\left(x^{t+1}, y_{g}^{t+1}, y_{b}^{t+1}; 0, g_{y_g}^{t+1}, g_{y_b}^{t+1}\right) - D^{t}\left(x^{t+1}, y_{g}^{t+1}, y_{b}^{t+1}; 0, g_{y_g}^{t+1}, g_{y_b}^{t+1}\right)\right)\right]. \quad (8)$$

The third part of the eco-productivity indicator (Eq. (6)) is the scale eco-efficiency change, $SEC^{t,t+1}$,which measures the impact of changes in scale operations on eco-productivity. If $SEC^{t,t+1} > 0$, it means that increases in the amount of desirable product (e.g., recyclable waste) collected while reducing the amount of undesirable product (e.g., unsorted waste) could lead to lower production costs and could have a positive impact on eco-productivity. In contrast, a negative scale effect could have an adverse impact on eco-productivity. $SEC^{t,t+1}$ is estimated as follows (Eq. (9)):

$$\begin{aligned} SEC^{t,t+1} &= (LHMPI^{t,t+1}) - (TEC^{t,t+1}) - (TC^{t,t+1}) = \frac{1}{2}\Big[\Big(D^t\left(x^t, y_g^t, y_{b^t}; 0, g_{y_g}^t, g_{y_b}^t\right) - D^t\left(x^t, y_g^{t+1}, y_b^{t+1}; 0, g_{y_g}^{t+1}, g_{y_b}^{t+1}\right)\Big) \\ &- \Big(D^t\left(x^{t+1}, y_g^t, y_b^t; g_x^{t+1}, 0, 0\right) - D^t\left(x^t, y_g^t, y_b^t; g_x^t, 0, 0\right)\Big)\Big] + \frac{1}{2}\Big[\Big(D^{t+1}\left(x^{t+1}, y_g^t, y_b^t; 0, g_{y_g}^t, g_{y_b}^t\right) \\ &- D^{t+1}\left(x^{t+1}, y_g^{t+1}, y_b^{t+1}; 0, g_{y_g}^{t+1}, g_{y_b}^{t+1}\right)\Big) - \Big(D^{t+1}\left(x^{t+1}, y_g^{t+1}, y_b^{t+1}; g_x^{t+1}, 0, 0\right) - D^{t+1}\left(x^t, y_g^{t+1}, y_b^{t+1}; g_x^t, 0, 0\right)\Big)\Big]. \end{aligned} \quad (9)$$

The recovery of eco-productivity components requires the estimation of DDFs. This is achieved through the use of linear programming (non-parametric) methods such as data envelopment analysis (DEA). We used DEA because it does not require the specification of a functional form such as Cobb-Douglas and translog for the underlying technology and accommodates multiple inputs and outputs (Coelli et al., 2005). DEA compares inputs and outputs across municipalities and over time in addition to measuring the efficiency of each municipality relative to the most efficient ones (Salazar-Adams, 2021).

Since this study covers several time periods where municipalities use inputs and outputs of time t using technology of time period $t+1$, and vice versa, we use the following notation for the time periods $(p,s) \in \{t,t+1\} \times \{t,t+1\}$. The following linear programming solves the output DDF (Eq. (10)) (Baležentis et al., 2017, 2021):

$$\begin{aligned} & D^s\left(x^p, y_g^p, y_b^p; 0, g_{y_g}^p, g_{y_b}^p\right) = \max\beta \\ & s.t.: \\ & \sum_{i=1}^{I} \lambda_i y_{g,i}^{m,s} \geqslant y_{g,i}^{m,p} + \beta g_{y_g}^{m,p} \forall m = 1,\ldots,M \\ & \sum_{i=1}^{I} \lambda_i y_{b,i}^{n,s} \leqslant y_{b,i}^{n,p} - \beta g_{y_b}^{n,p} \forall n = 1,\ldots,N \\ & \sum_{i=1}^{I} \lambda_i x_i^{l,s} \leqslant x_i^{l,p} \forall l = 1,..,L \\ & \sum_{i=1}^{I} \lambda_i = 1; \\ & \lambda_i \geqslant 0 \forall i = 1,\ldots,I \quad , \end{aligned} \quad (10)$$

where I is the total number of municipalities and M, N, and L represent the total number of desirable outputs, undesirable outputs and inputs, respectively. In Eq. (10), λ is a vector of intensity variables that are used to construct the production possibility frontier (Sala-Garrido et al., 2019). Moreover, β is the value of the output DDF that displays the maximum increase in desirable products and reduction in undesirable products for the direction defined by $(0, g_{y_g}^p, g_{y_b}^p)$ at time $p \in \{t, t+1\}$.

The input DDF requires solution of the following linear programming model (Eq. (11)) (Baležentis et al., 2017, 2021):

$$\begin{aligned} & D^s(x^p, y_g^p, y_b^p; g_x^p, 0, 0) = \max\beta \\ & s.t.: \\ & \sum_{i=1}^{I} \lambda_i y_{g,i}^{ms} \geqslant y_{g,i}^{mp} \forall m = 1,\ldots,M \\ & \sum_{i=1}^{I} \lambda_i y_{g,i}^{n,s} \leqslant y_{b,i}^{n,p} \forall n = 1,..,N \\ & \sum_{i=1}^{I} \lambda_i x_i^{l,s} \leqslant x_i^{l,p} - \beta x_i^{l,p} \forall l = 1,..,L \\ & \sum_{i=1}^{I} \lambda_i = 1; \\ & \lambda_i \geqslant 0 \forall i = 1,\ldots,I, \end{aligned} \quad (11)$$

where β is the value of the input DDF that displays the maximum decrease in inputs for the direction defined by $(g_x^p, 0, 0)$ at time $p \in \{t, t+1\}$. In an analogous manner, the other distance functions in the eco-productivity indicator are recovered by switching the time periods $(p,s) \in \{t,t+1\} \times \{t,t+1\}$.

2.2 Factors influencing eco-productivity change of municipalities

The next step in our analysis is to gain a better understanding of the role of municipality operating characteristics, such as population density or MSW generated per capita (see next section for more details), in eco-productivity change in the provision of MSW services. To do so, we build a regression tree which allows prediction of eco-productivity change (predicted or response variable) based on a set of operating characteristics (predictors or explanatory variables).

Regression trees allow visualization of the relationship between different factors and productivity performance, further illustrating the relative importance of each. Regression trees purpose at displaying hidden insights through learning from trends in the used data to support reliable decision making (Rebai et al., 2020). The regression tree is constructed using a two-step procedure described in James et al. (2013). The first step splits the sample (observations) into K distinct and non-overlapping regions $R_1,\ldots,R_K$ (Rebai et al., 2020). The second step derives the average value of the predicted (or response) variable based on observations belonging to the particular region. In other words, the regression tree partitions the data set into smaller sub-sets (or regions) based on a set of explanatory variables which may be categorical or continuous (Nandy and Singh, 2021). Each subset generates the average value of the predicted variable, based on the observations belonging to this sub-set, by minimising the sum of squared errors (James et al., 2013). The mathematical presentation of a generic regression tree is as follows (Eq. (12)) (Rebai et al., 2020):

$$f(\xi)=\sum_{k=1}^{K}\overline{\widehat{\delta_k}}\,\Xi_{(K\in R_k)},\tag{12}$$

where ξ is a set of explanatory variables, k is the number of sub-sets and $\overline{\widehat{\delta_k}}$ denotes the mean value of the predicted variable derived for each sub-set R_k. Regression trees allow visualization of the importance of each explanatory variable on the predicted variable, i.e., eco-productivity in our study. Variables that receive a high value are ranked higher, suggesting that they play a comparatively more crucial role in predicting eco-productivity (Rebai et al., 2020).

Finally, to verify robustness, we performed a panel linear regression model (Eq. (13)) (e.g., Zhang et al., 2016; Sala-Garrido et al., 2021):

$$LHMPI_{i,t}=\gamma_0+\tau_i+\gamma\xi_{i,t}^{'}+\epsilon_{i,t},\tag{13}$$

where $LHMPI_{i,t}$ denotes the eco-productivity change indicator for each municipality at any time, t, derived from the estimation of the linear programming models. In Eq. (13), γ_0 is the constant term, whereas γ is the parameter to be estimated for a set of operating characteristics (explanatory variables) of any municipality at any time t, $\xi_{i,t}^{'}$. Additionally, $\epsilon_{i,t}$ is the error term that follows standard normal distribution. Finally, τ_i presents time-invariant unobserved heterogeneity (e.g., managerial inability) which is unit-specific. Unit-specific effects may be fixed (correlated with explanatory variables) or random (uncorrelated with explanatory variables). Thus, the linear panel regression model can be the fixed effects or the random effects model (Wooldridge, 2010). The choice of model is determined through the use of econometric tests such as the Hausman test (Greene, 2018). The final model is run using robust standard errors to control for heteroscedasticity, i.e., differences in the error variance across municipalities (Kumbhakar et al., 2015; Greene, 2018).

2.3 Case study

The empirical application conducted in this study focuses on the MSW collection and recycling services provided by 98 municipalities in Chile over the years 2015–2019. Per capita generation of MSW in Chile increased from 294.6 kg/a in 2000 to 436.6 kg/a in 2019, i.e., an increase of 48% in less than 20 years (OECD, 2023). Moreover, Chile is one of a few OECD countries where per capita MSW generation increased in the last five years (OECD, 2023). Thus, policy makers and authorities in Chile must develop and implement more effective policies to prevent MSW generation. The recycling of MSW in Chile is also an emerging field, as it is not compulsory for local authorities and municipalities to implement independent initiatives based on available municipal budget (Araya-Córdova et al., 2021). In this context, the Chilean government made some important legal changes in 2016 to improve the MSW management within the context of a circular economy. The Waste Management, Extended Producer Responsibility and Promotion of Recycling Law (the EPR Law), whose main objective was to include the valorisation of byproducts as a fundamental element in the management of solid waste and to introduce economic instruments as a tool to increase levels of waste recycling.

Local authorities in Chile are in charge of MSW management, however, the collection, transport and treatment of disposal is usually outsourced to private companies (Valenzuela-Levi, 2021). Collection of MSW is mainly door-to-door, and landfills are a very common disposal option. According to SINIA (2021), approximately 80% of solid waste in Chile is disposed of in landfills. Nevertheless, around 55% of Chilean municipalities had implemented some sort of recycling service (Valenzuela-Levi, 2019).

The data used in this study to evaluate the eco-productivity of municipalities came from the Chilean National Waste Declaration System. The selection of inputs, desirable and undesirable outputs, and operating characteristics was based on the concept of eco-efficiency[1)], the availability of statistical data, and a review of the literature on this topic (e.g., Simões et al.,

1) Eco-efficiency is a management philosophy that encourages business to search for environmental improvements that yield parallel economic benefits (World Business Council for Sustainable Development, 2024).

2010; Sarra et al., 2017; Romano and Molinos-Senante, 2020; Ríos and Picazo-Tadeo, 2021). Input was defined as the operational costs to provide MSW collection, recycling and disposal services expressed in Chilean Pesos (CLP) per year. It does not include the potential profits of selling recycled waste (Llanquileo-Melgarejo and Molinos-Senante, 2021; Llanquileo-Melgarejo et al. 2021; Molinos-Senante and Maziotis, 2021; Valenzuela-Levi, 2021). The desirable outputs were recycled MSW grouped into five categories: 1) the amount of paper and cardboard recycled; 2) the amount of glass recycled; 3) the amount of plastic recycled; 4) the amount of organic waste recycled; and 5) the amount of other recycled waste. All desirable outputs were expressed in tonnes per year (Rogge and De Jaeger, 2013; Expósito and Velasco, 2018; Valenzuela-Levi, 2019, 2021; Valenzuela-Levi et al., 2021). Undesirable output was defined as the amount of unsorted waste measured in tonnes per year (Marques and Simões, 2009; Simões et al., 2010; 2012; Guerrini et al., 2017; Delgado-Antequera et al., 2021).

Finally, several operating characteristics were employed to explore their impact on eco-productivity performance (see Table S1). The first variable was defined as population density, derived from the ratio of population to area covered by municipalities (Halkos and Petrou, 2019; Agovino et al., 2020; Romano et al., 2020). The next two variables were related to the amount of total recycled waste and total unsorted waste collected per capita (per inhabitant) (Simões et al., 2010; 2012; Valenzuela-Levi, 2019; 2021). The fourth operating characteristic was associated with waste and recycling spending per capita, derived from the ratio of operating costs to provide waste and recycling, and population (Valenzuela-Levi et al., 2021). Table 1 reports a summary of the statistics of the variables used in this study.

3 Results and discussion

3.1 Eco-productivity change estimations

Figure 1 reports the results of LHMPI estimation over the years 2015–2019. The results indicate that the eco-productivity of the municipalities evaluated in the provision of MSW services slightly improved over the study period. The annual rate of eco-productivity growth was 1.28% on average. This increase in eco-productivity was attributable to two factors: an improvement in output generation, i.e., a reduction in unsorted waste, and an increase in recycled waste of 1.50%, which offset an increase in operational costs of 0.22% on average.

Whereas the average eco-productivity change for 2015–2019 was positive, a marked decrease occurred in 2017–2018 with a regression of 1.68% in the eco-productivity of Chilean municipalities. This was due to a drop in the generation of outputs of −1.71%. This setback in eco-productivity occurred one year after adoption of the Chilean EPR Law, which meant that during 2017–2018, several municipalities were undergoing a process of transition from the previous MSW management system to the new one promoted by the Law. Subsequently, during the years 2018–2019, eco-performance of the municipal waste sector

Table 1 Descriptive statistics of the variables to evaluate eco-productivity change [a)]

Type of variable	Variables	Unit of measurement	Mean	Std. Dev.	Minimum	Maximum
Input	Total costs [b)]	CLP/a	1875568	2390822	32	14765504
Desirable outputs	Paper & cardboard	t/a	1758	9449	0.00	84263
	Glass	t/a	289	1640	0.00	30099
	Organic	t/a	484	1922	0.00	17183
	Plastic	t/a	69	624	0.00	11940
	Other recycled waste	t/a	1219	7359	0.00	114091
Undesirable output	Usorted waste	t/a	61921	424570	0.05	8371375
Operational characteristics	Population density	Inhabitants/km^2	90	168	0.08	914
	Recycled waste per inhabitant	t/inhabitant	41	112	0.00	957
	Unsorted waste per inhabitant	t/inhabitant	496	1748	0.00	34520
	Waste spending per inhabitant	CLP/inhabitant	18708	12782	0.05	93981

Note: a) Correlation coefficients between variables used for estimating productivity change and operational characteristics are shown as supplemental material; b) Total costs were expressed in 2019 prices considering the annual consumer price indexes for 2015, 2016, 2017 and 2018 which were 4.35%, 3.79%, 2.18%, and 2.32%, respectively.

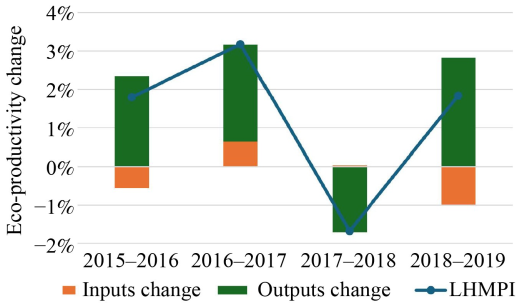

Fig. 1 Evolution of the LHMPI and contribution of inputs and outputs for Chilean municipalities in the management of MSW.

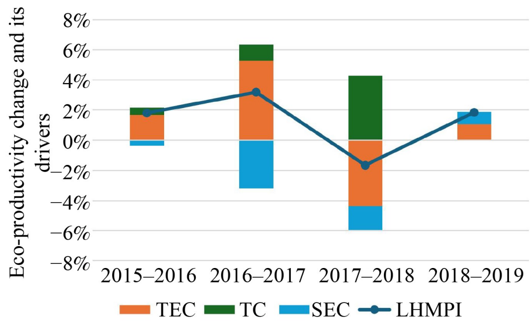

Fig. 2 Evolution of the LHMPI and its drivers for Chilean municipalities in the management of MSW.

improved. This was due to an increase in the collection and recycling of waste, which reached a level of 2.82%. However, the higher quantity of waste collected might have pushed up operational costs, which increased at a rate of 0.99% per year. This led to an improvement in eco-productivity at a rate of 1.83% per year. Overall, the results indicate that the Chilean MSW sector made some improvements in its eco-productivity over time.

At municipal level, implementation of the EPR Law had various impacts on eco-productivity. During the 2018–2019 period, 86 of the 98 municipalities analyzed (88%) improved their eco-productivity. Notably, Providencia, located in the Metropolitan Region of Santiago, the capital of Chile, exhibited the most significant advances. It achieved a LHMPI of 1.604, indicating a 60.4% increase in eco-productivity. Providencia, known for having the highest average net income in Chile, annually spends 21482 CLP per capita (≈ 29 US$) on MSW management, which closely aligns with the national average of 21003 CLP per capita (≈ 29 US$) (SINIM, 2020). The municipality's high MSW recovery rate of 9.61% is attributable to the successful implementation of five waste management programmes that effectively engage the community in various contexts. In contrast, Cerro Navia, another municipality in the Metropolitan Region of Santiago, experienced the most significant decline in eco-productivity, with an LHMPI of 0.827, reflecting a decrease of 17.3%. Its annual per capita expenditure on MSW management is substantially lower, 11336 CLP (≈ 15 US$), which is 46.0% less than the national average. Cerro Navia also has one of the lowest MSW recovery rates in the sample, at 0.36%. Despite having waste recovery programmes, these initiatives are relatively new and as yet have had no significant impact on the local population. Providencia and Cerro Navia are two examples of how implementation of the same law can have very different effects depending on the initial conditions and the local socio-economic context.

To gain better understanding of what drove eco-productivity in the MSW sector, we need to look into the results of its components: TEC, TC and SEC. Figure 2 shows the results of this breakdown. We observe that, on average, eco-productivity improvements from 2015 to 2019 were attributable to small gains in TEC and TC, whose annual progress was 0.90% and 1.45%, respectively. By contrast, average SEC was −1.08% contributing negatively to eco-productivity change. This finding suggests that, over time, less eco-efficient municipalities improved their average performance to approach that of the most efficient ones in the sector. This means that, on average, municipalities made efforts to recycle more solid waste while simultaneously attempting to reduce unsorted waste and operational costs.

Considerable gains in technical efficiency were observed during the first two time periods. The annual rates of TEC were 1.67% and 5.26% during the 2015–2016 and 2016–2017 periods, respectively. However, this upward trend was interrupted in the following year, in which TEC deteriorated by 4.37%, reflecting the difficulties experienced by municipalities in adopting the requirements established by the new Chilean MSW Law. The situation improved the following year when, on average, the sector improved its managerial practices, reporting gains in efficiency at a level of 1.05% per annum.

While on average less efficient municipalities made efforts to catch up with the most efficient ones in the industry, technical progress was apparent. The values for TC were positive from 2015 to 2018, whereas values show a slight decrease (−0.05%) for 2018–2019. The positive TC could be attributable to the adoption of alternative strategies, implemented by municipalities to increase the selective collection of MSW that facilitated its recycling. According to Chilean Environmental Ministry (MMA) estimations, in order to reach the objectives of the EPR Law, it would be necessary to multiply the number of recycling centers by three in the four years after its implementation (MMA, 2018). Technical progress peaked during the period 2017–2018 as it improved at a rate of 4.28% per annum, i.e., one year after adoption of the Chilean EPR law.

Any gains in TEC and TC were lost due to the negative scale effect. The SEC followed a negative trend throughout the whole period, except for the year 2018–2019 (0.83%). This means that increases in the scale of operations involving the collection and recycling of larger amounts of MSW might have led to higher production costs. Studies have previously researched the presence of economies of scale in the provision of MSW services, reaching divergent conclusions. On the one hand, Carvalho and Marques (2014), Pérez-López et al. (2018); Romano and Molinos-Senante (2020) found that municipalities with large populations are the most eco-efficient in managing MSW services. By contrast, Guerrini et al. (2017) concluded that smaller municipalities tended to be more efficient. Within the Chilean context, Llanquileo-Melgarejo and Molinos-Senante (2021) estimated that 40.4% of the Chilean municipalities evaluated (n = 142) presented positive economies of scale, whereas 59.6% of them presented negative economies of scale. In our case study, a negative trend in SEC suggests that on average municipalities had moved away from their most productive scale size. Therefore, any proportional increases in the generation of MSW could lead to disproportionate increases in costs.

Overall, results indicate that on average, municipalities improved their eco-performance over time due to small gains in running their daily business while adopting new approaches to promote separative collection of MSW and improving its recycling. Less productive municipalities could seek to improve their eco-performance by optimizing the scale of their operations. It is expected that this will occur in future years because, based on extended producer responsibility, private contractors could participate in the MSW collection and recycling systems, increasing the operational scale of municipalities.

To illustrate the different aspects of eco-productivity change across different Chilean regions, Table 2 displays region-specific results. As a general observation, the average annual rate of eco-productivity growth varied across the regions. The highest rate of eco-productivity growth was achieved by the Coquimbo region in central Chile, whereas we find the lowest rate of eco-productivity change in the Los Rios region, which is located in southern Chile. Moreover, there is no clear trend regarding the aspect that has most impact on eco-productivity. There are regions such as Coquimbo where the major driver of eco-performance was gains in technical efficiency, whereas in other regions, such as La Araucania, TC was the only positive contributor to eco-productivity. This illustrates the lack of a national common strategy for promoting MSW recycling until enactment of the recent EPR Law. In this context, each municipality adopted its own approach to MSW management, which led to divergent results.

The best performing group included regions that had an annual eco-productivity rate that was higher than average (1.28%). This group included regions located in southern and central Chile. For this group, average eco-productivity increased by 4.65%, which was mainly attributable to TEC gains, at an average level of 4.17%. This group experienced a small progress in TC, which was an average 0.35% per year, whereas scale effect was small but positive. This finding suggests that the

Table 2 Annual growth rate of eco-productivity change and its components by Chilean region

Variable	Fixed effects				Random effects			
	Coef.	St. Err.	Z-stat	p-value	Coef.	St. Err.	Z-stat	p-value
Constant	1.893	1.423	1.330	0.185	1.245	0.117	**10.603**	0.000
Recyclabe waste per capita	0.047	0.014	**3.310**	0.001	0.030	0.008	**3.659**	0.000
Unsorted waste per capita	−0.059	0.027	**−2.178**	0.03	−0.021	0.013	***−1.645***	0.099
Waste spending per capita	−0.059	0.066	−0.901	0.368	−0.023	0.014	***−1.639***	0.101
Populaton density	−0.002	0.382	−0.006	0.995	0.011	0.010	1.124	0.261
R^2	0.47				0.47			
X^2 stat	4.95			0.4	**20.36**			0.000
					Hausman test			
					Ho: preferred model RE			
					X^2 stat	7.49	p-value	0.112

Notes: Dependent variable is LHMPI. Bold (bold italic) are statistically significant from zero at 5% (10%) significance level.

best performing municipalities made considerable efforts to improve their managerial practices. Eco-performance could further improve by becoming more technologically innovative in waste management and by optimizing the scale of operations.

The second group presented in Table 2 consists of municipalities that performed close to or lower than industry eco-productivity. This group reported an annual eco-productivity rate of 0.52% which was attributable to TC and TEC. The rate of technical progress was 1.57% per year, whereas gains in efficiency were at the level of 0.26% per year. This finding suggests that this group of municipalities adopted new technologies to improve eco-performance. Moreover, less eco-efficient municipalities made some efforts to catch up with the most eco-efficient ones in the industry. Any gains in efficiency and technical change were lost due to the negative scale effect. This means that collection of more waste from more customers might have increased production costs, leading to lower levels of productivity. On average, this group of municipalities could become more eco-productive by serving smaller areas and improving their managerial practices.

The worst performing group includes regions that reported negative rates of eco-productivity change on average per year. Specifically, the average eco-productivity growth ranged from −0.30% to −1.04% per year. On average, this group of regions reported a decrease in eco-productivity of 0.71%. The TEC was the only component that negatively contributed to eco-productivity change. Any gains in TC and SEC were lost due to the negative TEC. This finding suggests that the worst performing group could improve its eco-performance by becoming more efficient from a production point of view, i.e., by improving the way daily operations are run. Improvements in technical efficiency should be a priority for the regions located in southern Chile, who reported losses in technical efficiency ranging from 3.97% in La Araucania to 7.44% in Los Rios. The Metropolitan region, which includes the capital of Santiago, reported an annual productivity rate of 0.30% per year. Taking into account that the Metropolitan region consists of 32 municipalities, this region could improve its eco-performance by controlling production costs while increasing collection and recycling waste services, in addition to optimizing its scale of operations.

3.2 Operational variables influencing the eco-productivity change of Chilean municipalities

After estimating the eco-productivity change of Chilean municipalities in the provision of MSW services, it is of great interest to understand the role of other operating environment characteristics that could influence performance. Figure 3 shows the results of this analysis. The bottom of each branch of the regression tree reports the average eco-productivity indicator, which is estimated based on the percentage of each of the observations in this specific branch (Rebai et al., 2020). Conclusions show that recyclable waste per capita (Rcwaste per cap), unsorted waste per capita (Uswaste per cap) and waste spending per capita (Cost per cap) are the major determinants predicting eco-productivity. Population density did have an impact on eco-performance, but of a smaller magnitude (see Fig. S1 in Supplemental material).

According to the results shown in Fig. 3, if municipalities increase the collection of recyclable waste per inhabitant by more than 28 t/a, they could achieve an annual eco-productivity indicator (HLMPI) of 1.2, or equivalently, increase the rate of eco-productivity by 2% per year. It is estimated that average predicted eco-productivity could reach even higher annual rates if waste spending per inhabitant were less than 9600 Chilean pesos per year. In this case, predictions suggest the annual rate of productivity will reach the level of 6%. In contrast, if waste spending per capita were more than 9600 Chilean pesos per year, then on average municipalities could improve eco-productivity by collecting more than 366 t of unsorted waste. In this case, mean productivity might increase less than 3% per year. A collection of less than 366 t of unsorted waste could potentially lead to an increase in productivity of 1% per year.

If recyclable waste is between 5.2 and 28 t, it is estimated that eco-productivity could reach an average level of 0.94. Low levels of eco-productivity could also be achieved if municipalities collected less than 1 tonne of recyclable waste. It is predicted that municipalities could experience a negative eco-productivity rate of 2% per year (or 0.98) on average. Negative rates of eco-productivity could be reported if municipalities collected between 1 and 5.2 tonnes of recyclable waste. However, eco-performance could improve if municipalities made efforts to collect between 366 and 396 tonnes of unsorted waste. In this case, it is estimated that municipal sector productivity could potentially increase by 3% per year.

Overall, the results indicate that on average municipalities need to control waste spending, the amount of recyclable water, and unsorted waste per inhabitant to improve eco-performance. Findings suggest that on average, gains in eco-productivity could reach 6% per year if municipalities recycled more than 28 tonnes of waste per year, and waste spending per

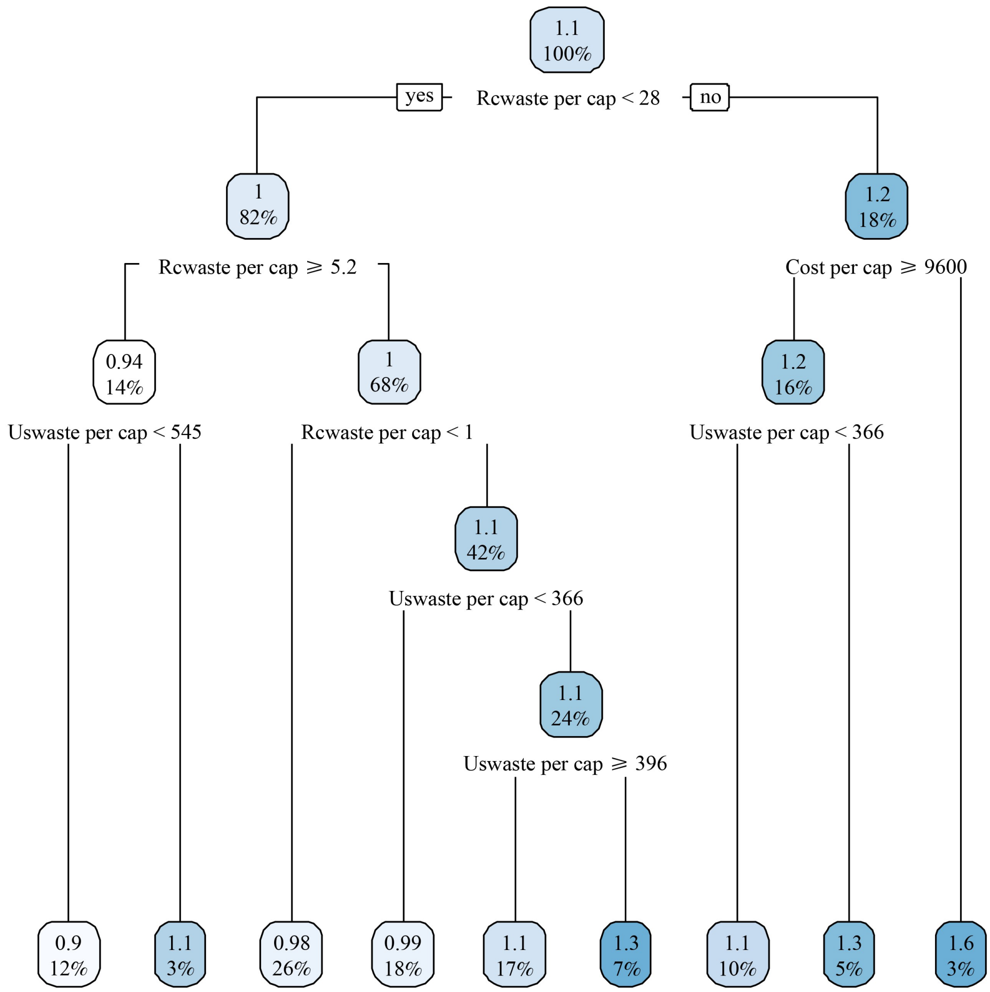

Fig. 3 Regression tree (predicted variable is LHMPI).

Table 3 Estimates of random effects model to identify operational variables affecting eco-productivity change with robust standard errors

Variable	Coef.	Rob. Std. Err.	Z-stat	*p*-value
Constant	1.245	0.066	**18.746**	0.000
Recyclable waste per capita	0.030	0.008	**4.058**	0.000
Unsorted waste per capita	−0.021	0.012	***−1.745***	0.081
Waste spending per cap	−0.023	0.010	**−2.193**	0.028
Populaton density	0.011	0.006	***1.819***	0.069
R^2	0.47			
X^2 (5)	**27.09**			0.000

Notes: Dependent variable is LHMPI. Bold (bold italic) are statistically significant from zero at 5% (10%) significance level.

inhabitant were less than 9600 CLP per year.

Finally, to check robustness, we performed a panel linear regression to quantify the impact of operating characteristics on eco-productivity growth. Table 3 shows the results of running the random effects model using robust errors. We found that all operating characteristics had a statistically significant influence on eco-productivity. The amount of recyclable waste per capita and waste spending per capita were the main drivers, as shown by the magnitude of the estimated coefficients, followed by unsorted waste per capita and population density. A 1% increase in the amount of recyclable waste per capita could lead to an average increase in eco-productivity of 0.030%. This finding implies that recycling more waste could improve industry performance. The higher the waste spending per inhabitant the lower productivity could be. The same applies when higher amounts of unsorted waste per inhabitant are collected. On average, and maintaining the other factors constant, a 1% increase in waste spending per capita and unsorted waste per capita could reduce eco-productivity by 0.023% and 0.021%, respectively.

Population density had a positive and statistically significant impact on eco-productivity. This means that the more densely populated areas could be more eco-productive than areas that are less densely populated. This could be attributable to the fact that densely populated areas might have more frequent schedules for waste collection or may have developed more efficient waste management practices for waste collection and recycling. Thus, the costs to provide collection and recycling services could be lower in those areas than in less densely populated ones. This result is consistent with past research (e.g., De Jaeger et al., 2011; Vishwakarma et al., 2012; Expósito and Velasco, 2018; Romano and Molinos-Senante, 2020) which found that higher population density causes lower costs and therefore, better performance. Overall, the results of the linear regression and the regression tree are consistent, demonstrating the substantial impact of operating characteristics on the eco-productivity change of municipalities in MSW management.

Findings show an emerging effect on economic and environmental performance of Chilean municipalities, restricted to the time period analyzed, as a consequence of implementation of the Chilean EPR Law. Indeed, on average, municipalities tend to improve their eco-productivity because of increased MSW recycling, albeit at the expense of higher economic costs. In the context of Chile, where the solid waste recycling rate is very low, less than 5% (Valenzuela-Levi, 2021), it is not possible to recommend that municipalities adjust their waste management policies to reduce costs. Nevertheless, significant efforts must be made to continue improving MSW recycling rates. Some actions that can be undertaken include: 1) establishing diverse recycling programmes that cover a wide range of materials, in addition to waste collection methods adapted to local socio-economic conditions; 2) undertaking educational campaigns aimed at raising public awareness of recycling practices; 3) investing in waste-to-energy plants that convert non-recyclable waste into electricity or heat. Whereas this is not the best approach to valorise MSW, it will enable a reduction in landfill usage, which is currently around 80% (SINIA, 2021); 4) fostering collaboration between municipalities and private companies to invest in waste management infrastructure and share best practices; and 5) promoting markets for products made from recycled materials. This can include government procurement policies that prioritise recycled-content products.

There were notable differences in eco-productivity across Chile's regions, underscoring the need for region-specific policies. Such policies should be customised to match the distinct socio-economic and geographic characteristics of each region. For instance, in predominantly rural areas or ones with a strong agricultural economy, the focus could be on the valorisation of organic materials. In contrast, regions with a developed recycling market might benefit from prioritising the valorisation of other types of waste. Achieving this requires the establishment of robust partnerships between public entities, the private sector and local communities.

4 Conclusions

Moving toward a resource-efficient, circular economy is critical from supply, security and environmental perspectives. Sustainable waste and materials management is part of the 2030 Agenda for Sustainable Development. Consequently, the measurement of eco-productivity and its determinants is essential because it allows policy makers to identify areas for improvement so that MSW management services are provided in an efficient, sustainable manner.

This study evaluates the eco-productivity change of the municipal solid waste sector in Chile over the years 2015–2019. Thus, our study assesses performance change over years and integrates both economic and environmental variables. The study takes LHMPI, which is broken down into TEC, TC and SEC, as the performance index. In brief, the main findings are as follows. First, we find that the municipal solid waste sector achieved small gains in eco-productivity over time. The rate of productivity growth was 1.28% on average per year, which was mainly attributable to improvements in the management of MSW (1.50%) and small reductions in operational costs (0.22%). The evolution of the LHMPI over years is consistent with the policies adopted by the Chilean government in the framework of the EPR Law. Secondly, TEC and TC had a positive influence on the eco-productivity of Chilean municipalities, whereas the scale effect had an adverse impact. This is due to the efforts made by municipalities to promote separate waste collection and therefore, an increase in MSW recycling. However, any gains in efficiency and technical change were lost due to the inability of municipalities to optimise the scale of their operations, as indicated by the negative scale effect. Thirdly, regression tree results indicated that the per capital collection of recyclable waste and unsorted waste, in addition to waste spending had the most impact on predicting eco-productivity. Population density had a smaller impact on eco-performance. These findings were corroborated by performing a linear regression.

The findings of our study could be of great interest to policy makers. Our study measures the eco-productivity of the municipal solid waste sector and its determinants over time. Policy makers will be able to understand what drives performance and identify practices to improve it. In the Chilean context, the estimation of the LHMPI allows evaluation of the EPR Law's impact on the eco-performance of municipalities. Furthermore, policy makers can identify the best and worst performing municipalities at regional level. Since different factors may affect productivity across groups and regions, more target-oriented practices could be promoted by policy makers to improve eco-performance. Finally, our empirical approach highlighted that several other factors beyond TC and TEC could exist. These were related to the amount of money spent per inhabitant or the quantity of waste recycled per inhabitant. We also show that higher population density might be associated with lower collection and recycling costs than in less densely populated areas. Understanding what drives eco-performance could support the decision making of businesses, promote efficient and sustainable waste management, and encourage a circular economy.

While this study presents significant insights, it also has limitations. The primary limitation is the study's short timeframe, covering only the years 2015–2019, restricted by the availability of data. Improving the MSW industry's eco-productivity requires investment in new facilities and time to change the public's attitudes to waste generation and recycling. Additionally, this study only considers the two years following the enactment of Chile's EPR Law. Typically, the impact of new laws and regulations on industry performance takes time to materialise. Therefore, future research, contingent on data availability, would benefit from extending the analysis over a longer period. A further limitation of this study pertains to the operating variables that influence eco-productivity estimations, which were limited by the data available. Future research in this area should consider examining the effect of additional, currently unavailable, environmental variables, which might include factors such as levels of tourism, size of the municipality, or annual gross domestic product per capita, in order to gain a more comprehensive understanding of the eco-productivity of municipalities.

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