PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE

SCHOOL OF ENGINEERING

ASSESSING ENVIRONMENTAL AND ECONOMIC PERFORMANCE OF MUNICIPAL WASTE SERVICES: AN EMPIRICAL APPLICATION FOR CHILE

PAULA IRIS LLANQUILEO MELGAREJO

Thesis submitted to the Office of Graduate Studies in partial fulfillment of the requirements for the Degree of Doctor in Engineering Sciences

Advisor:
MARÍA MOLINOS SENANTE

Santiago of Chile, January, 2024

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Dedicated to my son Elías

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OUTLINE OF THE THESIS

The key findings from the development of my doctoral project are presented in this dissertation. The outcomes were organized in four publications, which are included in the chapters that follows.

Chapter 1 – *Introduction*

It presents a description of the perspective on waste management, followed by a global context in circular economy focusing on solid waste. It concludes with a review of municipal solid waste management in Chile and the most relevant actors.

Chapter 2 – *Manuscript 1 (Published)*

P. Llanquileo-Melgarejo, M. Molinos-Senante. Evaluation of economies of scale in eco efficiency of municipal waste management: an empirical approach for Chile. *Environmental Science and Pollution Research,* 28, 28337–28348 (2021), 10.1007/s11356-021-12529-1

Chapter 3 – *Manuscript 2 (Published)*

P. Llanquileo-Melgarejo, M. Molinos-Senante, G. Romano, L. Carosi. Evaluation of the impact of separative collection and recycling of municipal solid waste on performance: an empirical application for Chile. *Sustainability*, 13 (4), 1-15 (2021), 10.3390/su13042022

Chapter 4 – *Manuscript 3 (Published)*

P. Llanquileo-Melgarejo, M. Molinos-Senante. Assessing eco-productivity change in Chilean municipal solid waste services. *Utilities Policy* (78), 101410 (2022), 10.1016/j.jup.2022.101410

Chapter 5 – *Manuscript 4 (Published)*

P. Llanquileo-Melgarejo, M. Molinos-Senante. The impact of recycling on the productivity of municipal solid waste: A comparison of the Malmquist and Malmquist-Luenberger Productivity Indexes. *International Journal of Sustainable Engineering* 16 (1), 236-247 (2023) 10.1080/19397038.2023.2256382

Chapter 6 – *General Conclusions*

The main conclusions of the dissertation are highlighted, responding to the hypotheses established at the beginning of this doctoral thesis.

Chapter 7 – *References*

RESUMEN

La recolección y manejo de los residuos sólidos urbanos (RSU) es un servicio público que impacta en el medio ambiente y la salud pública. A pesar de los esfuerzos realizados desde la política pública, a nivel global, el volumen de RSU generado ha aumentado notablemente en la última década. Es por ello que, en el contexto de economía circular, instituciones internacionales como las Naciones Unidas y la Unión Europea están impulsando la recogida selectiva y el reciclaje de residuos. Por otro lado, el aumento del volumen de RSU tiene marcadas consecuencias no solo desde el punto de vista ambiental sino también económico. Teniendo en cuenta las restricciones presupuestarias que afectan a los sectores públicos, mejorar el desempeño en la prestación de servicios de RSU ha sido identificado por los municipios como una excelente opción para mejorar la sustentabilidad en la gestión de RSU.

La evaluación del desempeño de las municipalidades en la recolección y disposición de residuos es un tópico que comenzó a estudiarse en la última década, pero aún es incipiente. La mayoría de los estudios anteriores se centraron en evaluar el desempeño económico de los municipios en la gestión de RSU sin diferenciar entre residuos reciclados y no reciclados. La revisión de la literatura sobre este tema muestra que existen tres vacíos de conocimiento: i) evaluación del impacto de la recolección separativa y reciclaje de RSU en el desempeño a través de la comparación de los indicadores de eficiencia y eco-eficiencia; ii) evaluación del cambio en el desempeño de municipios en la gestión de RSU lo largo del tiempo; iii) evaluación del desempeño económico y ambiental de los municipios chilenos en la prestación de servicios de RSU.

El objetivo principal de esta tesis es, evaluar el desempeño económico y ambiental de los municipios chilenos en la prestación de servicios de RSU. Para lograr este objetivo, se definieron los siguientes objetivos específicos: i) evaluar el impacto de la recolección selectiva y el reciclaje de RSU en el desempeño de los servicios de residuos municipales mediante la comparación de índices de eficiencia y ecoeficiencia; ii) evaluar si los cambios en las tasas de recolección selectiva y reciclaje de RSU han impactado en el desempeño ambiental y económico de los municipios a lo largo del tiempo comparando los índices de cambio de

productividad y cambio de eco-productividad y; iii) identificar los factores externos a la gestión que realizan los municipios que inciden en su desempeño medido como eficiencia, ecoeficiencia, productividad y eco-productividad. Para lograr estos objetivos, se han aplicado varios modelos de análisis envolvente de datos (DEA). DEA es una técnica no paramétrica basada en programación lineal que mide el rendimiento relativo de las unidades en función del uso de inputs para producir outputs. Permite integrar outputs deseados, que en este caso son residuos reciclados, y outputs no deseados, residuos no clasificados. Por lo tanto, este enfoque metodológico permite la evaluación conjunta del desempeño económico y ambiental de los municipios en la prestación de servicios de RSU.

De acuerdo con los objetivos planteados, esta tesis doctoral abarca 4 publicaciones científicas enfocadas en evaluar el desempeño económico y ambiental de los municipios chilenos utilizando una base de datos robusta de 2015 a 2019 cuyos principales resultados son los siguientes: i) El 40,4% de los municipios chilenos evaluados presentaron economías de escala negativas en la prestación de servicios de RSU. Este hallazgo evidencia que el tamaño actual de la operación de los municipios no es óptimo; por lo tanto, se debe promover la organización conjunta de sistemas de gestión de RSU; ii) la ecoeficiencia promedio de los municipios chilenos fue de 0,58 y el 92,3% de ellos no eran ecoeficientes; iii) la recolección selectiva y el reciclaje de RSU impactaron el desempeño de los municipios desde el punto de vista estadístico. El porcentaje de municipios ineficientes fue de 95,30% y 96,64%, según los scores de eficiencia y ecoeficiencia, respectivamente; iv) las estimaciones de cambio de productividad promedio son mayores que las asociadas a cambios en la eco-productividad para todos los años evaluados; v) los puntajes promedio agregados de cambio de productividad y cambio de eco-productividad para 2015/19 fueron 2,73 y 1,33, respectivamente, lo que revela que el desempeño de los municipios chilenos también ha mejorado desde una perspectiva ambiental; vi) Se evidenció una divergencia considerable en los puntajes de cambio de eco-productividad entre los municipios chilenos y, por lo tanto, se recomienda desarrollar e implementar políticas a escala metropolitana o regional para aprovechar las economías de escala potenciales en la recolección y el tratamiento de RSU.

Palabras Claves: Eficiencia, Eco-eficiencia, Gestión de Residuos Sólidos Municipales, Productividad, Eco-productividad, Análisis Envolvente de Datos.

ABSTRACT

The collection and management of municipal solid waste (MSW) is a public service that impacts the environment and public health. Despite efforts made through public policy globally, the volume of generated MSW has significantly increased in the last decade. Hence, in the context of a circular economy, international institutions such as the United Nations and the European Union are advocating for selective collection and recycling of waste. On the other hand, the increase in MSW volume has distinct consequences not only environmentally but also economically. Given the budget constraints affecting public sectors, improving performance in the provision of MSW services has been identified by municipalities as an excellent option for enhancing sustainability in waste management.

The assessment of municipalities' performance in waste collection and disposal is a topic that began to be studied in the last decade, but it's still in its early stages. Most prior studies focused on evaluating the economic performance of municipalities in waste provision, without differentiating between recyclable and unsorted waste. The review of literature on this topic reveals three knowledge gaps: i) assessing the impact of separate collection and recycling on municipalities´ performance by comparing efficiency and eco-efficiency; ii) evaluating changes in municipalities´ performance over time; iii) no previous studies evaluating the economic and environmental performance of Chilean municipalities in MSW services exist.

The primary objective of this thesis is to evaluate the economic and environmental performance of Chilean municipalities in the provision of MSW services. To achieve this, the following specific objectives were defined: i) assess the impact of selective collection and recycling of MSW on municipal performance through efficiency and eco-efficiency score comparison; ii) evaluate if changes in selective collection and MSW recycling rates have impacted the environmental and economic performance of municipalities over time by comparing changes in productivity and eco-productivity indices; iii) identify external factors in municipal management influencing performance metrics (efficiency, eco-efficiency, productivity, and eco-productivity) To achieve these objectives, various Data Envelopment Analysis (DEA) models have been applied. DEA is a non-parametric technique based on linear programming that measures the relative performance of units based on their use of inputs to produce outputs. It allows integrating desired outputs, in this case, recycled waste, and undesired outputs, unsorted waste. This methodological approach enables the joint evaluation of economic and environmental performance of municipalities in MSW services.

Aligned with the stated objectives, this doctoral thesis encompasses four scientific publications focused on evaluating the economic and environmental performance of Chilean municipalities using a robust database from 2015 to 2019. The key findings of the research are as follows: i) 40.4% of the evaluated Chilean municipalities exhibited negative scale economies in MSW services provision. This finding is highly relevant from a policy perspective as it underscores that the current size of municipal operations isn't optimal, thereby advocating for jointly organized waste management systems; ii) the average eco-efficiency of Chilean municipalities was 0.58, and 92.3% of them were not eco-efficient; iii) selective collection and MSW recycling statistically impacted municipality performance. The percentage of inefficient municipalities was 95.30% and 96.64% based on efficiency and eco-efficiency scores, respectively; iv) average estimates of productivity change were higher than those associated with changes in eco-productivity for all evaluated years; v) the aggregated average scores of productivity change and eco-productivity change for 2015/19 were 2.73 and 1.33, respectively, indicating that Chilean municipalities' performance has also improved environmentally; vi) a considerable divergence in eco-productivity change scores among Chilean municipalities was evident, suggesting that policymakers should develop and implement metropolitan or regional scale policies to leverage potential economies of scale in waste collection and treatment.

Keywords: Efficiency, Eco-efficiency, Municipal Solid Waste Management, Productivity, Eco-productivity, Data Envelopment Analysis.

ABBREVIATIONS

ASCC	: Agency for Sustainability and Climate Change
CORFO	: Corporation for the Promotion of Production
DEA	: Data Envelopment Analysis
DMU	: Decision Making Unit
ECH	: Efficiency Change
GDP	: Gross Domestic Product
LAs	: Local Authorities
LECH	: Luenberger Efficiency Change
LPI	: Luenberger Productivity Indicator
LTCH	: Luenberger Technical Change
MLPI	: Malmquist-Luenberger Productivity Index
MMA	: Ministry of the Environment
MPI	: Malmquist Productivity Index
MSW	: Municipal Solid Waste
OECD	: Organization for Economic Cooperation and Development
REP Law	: Extended Producer Responsibility and Promotion of Recycling
SFA	: Stochastic Frontier Analysis
SINADER	: National Waste Declaration System
SINIM	: National Municipal Information System
SOFOFA	: Factory Development Society
TCH	: Technical Change

CHAPTER 1

1. INTRODUCTION

1.1 Perspective on waste management

Solid waste management encompasses a comprehensive approach that begins with the prevention of waste generation and extends through its collection, transportation, treatment, and ultimate disposal. Inadequate waste management practices lead to substantial environmental and health challenges, as highlighted by the World Health Organization (WHO, 2021). For example, in 2016, the Central Bank (Kaza et al., 2018) reported that approximately 1,600 million tons of CO_2 equivalent were generated from solid waste management. Unmanaged or poorly managed solod waste from decades of economic growth requires urgent action at all levels of society (Kaza et al., 2018).

Focusing on municipal solid waste (MSW), despite the concerted efforts of policymakers, the quantity of MSW generated has experienced a significant surge over the past decade. Consequently, international entities such as the United Nations and the European Union are advocating for the adoption of selective waste collection and recycling practices. This emphasis on enhancing MSW management aligns with the Sustainable Development Goals outlined by the United Nations (2015). Thus, Goal 11 implies that: "by 2030, reduce the environmental impact per capita of cities, including paying special attention to air quality and municipal and other waste management".

Local Authorities (LAs) and municipalities have a pivotal role to play on a global scale in addressing the challenge of solid waste management (SWM). These entities bear the responsibility of developing the requisite infrastructure for effective MSW management, as outlined by (Zotos et al., 2009). Given the budgetary constraints often faced by the public sector, the enhancement of efficiency in the delivery of MSW services has emerged as a notable strategy. This approach holds the potential to secure the necessary resources to attain higher quality standards within the domain.

While the assessment of performance in MSW collection and disposal has gained attention in recent years, it remains an area that warrants further exploration (Pérez-López et al., 2018) highlight the relative novelty of this topic in the research landscape. The evaluation of efficiency and effectiveness in these vital aspects of waste management is gradually gaining recognition, underscoring the importance of continued investigation to develop more robust strategies and solutions.

1.2 An Overview of Circular Economy focused on Solid Waste Management

In recent times, the global momentum behind the concept of the circular economy has grown substantially. This momentum has been significantly bolstered by the proactive efforts of governments and international organizations, which have positioned the circular economy as a cornerstone of their sustainability initiatives. An illustrative example is the European Union's endorsement of the first Circular Economy Action Plan in 2015. This plan was accompanied by an array of ambitious objectives and a comprehensive roadmap comprising 54 strategic measures to accomplish them. Buoyed by the achievements of this initial endeavor, the plan received renewed emphasis five years later. In 2020, the European Union unveiled the New Circular Economy Action Plan, reinforcing its commitment to the circular economy concept. This updated plan holds a central position within the broader framework of the European Green Deal[1].

In the year 2020, Chile took a significant step towards advancing the principles of the circular economy by establishing the Global Alliance for the Circular Economy and Resource Efficiency. This collaborative initiative is under the patronage of the United Nations Environment Programme and the United Nations Industrial Development Organization. The alliance brings together an extensive range of nations, encompassing diverse countries such as Colombia, Peru, Canada, Kenya, Nigeria, South Africa, Morocco, Japan, New Zealand, Norway, and the member states of the European Union. This united front underscores the global commitment to embracing circular economy practices and fostering resource efficiency. Within the Latin American sphere, a parallel development occurred in 2020 with the formation of the Circular Economy Coalition

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[1] See: https://ec.europa.eu/environment /circular-economy/

for Latin America and the Caribbean. This coalition is dedicated to advocating for and advancing the circular economy agenda within the region. The establishment of this coalition signifies a collective effort by Latin American and Caribbean nations to drive transformative change and promote sustainable practices that align with circular economy principles.

1.3 Municipal Solid Waste Management in Chile

Within Latin America and the Caribbean, only 53% of waste is appropriately managed through disposal in sanitary landfills, as indicated by the Inter-American Development Bank (IDB, 2022). In this context, Chile stands out as a regional leader, with a commendable 80.51% of waste undergoing final disposal in sanitary landfills, as reported by the Ministry of the Environment (MMA). Nonetheless, even this relatively favorable management scenario within the region does not entirely mitigate the core challenge: the substantial generation of waste coupled with inadequate disposal practices. Illustratively, the high levels of waste generation and improper disposal persist as significant issues. Over the period spanning from 2000 to 2017, the average municipal waste generated per individual witnessed a notable increase of 49%, escalating from 294 to 439 kilograms per person (OECD)[2].

The situation concerning final waste disposal presents particular challenges. In 2017, it was projected that the average remaining operational lifespan of landfills in Chile was a mere 12 years (SUBDERE, 2017). This raises concern, especially when considering that the establishment of new landfills is a complex process that typically takes over a decade to materialize. Adding to these concerns, a recent study indicates that Chile currently grapples with 3,735 illegal waste disposal sites. Of these, 3,492 are classified as micro-dumps, occupying areas less than 1 hectare, while 243 are categorized as illegal dumps spanning more than 1 hectare (Ossio and Faúndez, 2021). These sites contribute to severe environmental issues and negatively impact the quality of life for the communities residing nearby.

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[2] See: https://data.oecd.org/waste/municipal-waste.htm.

Simultaneously, Chile exhibits noteworthy shortcomings in the domain of recycling. For instance, in 2018, the overall recycling rate across the country reached a mere 22%. Even more striking, the recycling rate for municipal waste remained below 2%. This stands in stark contrast to other countries where both recycling rates can exceed 50%. Given these disparities, there is an evident imperative to progress in these domains. The circular economy presents a wealth of strategies to tackle these complex challenges comprehensively and holistically.

The enactment of Law No. 20,920, known as the Framework for Waste Management, Extended Producer Responsibility, and Promotion of Recycling (REP Law), in 2016 marked the inception of a transformative process in Chile. This legislation heralds a new era of institutional advancement in the realm of the circular economy, particularly with regards to recycling. Under the ambit of this law, a significant shift in the country's approach to waste management is underway. The REP Law mandates that producers of priority products take on the responsibility for organizing and financing the management of waste generated by these products at the end of their useful life. This encompasses a structured system where producers are bound by predefined collection and recovery targets outlined in corresponding decrees. This legal framework represents a dynamic stride towards fostering circular economy practices, propelling Chile towards heightened levels of environmental stewardship and sustainable waste management.

The MMA is a pivotal stakeholder that has ardently embraced the momentum of the circular economy model. To effectively integrate this focus into its institutional framework and galvanize its agenda, the MMA established the Circular Economy Office in 2018. This entity succeeds the former Office of Waste and stands as a testament to the government's commitment to advancing circular economy principles. Furthermore, the MMA has played a proactive role in supporting the progression of various legislative initiatives in alignment with this agenda. In addition to the REP Law mentioned earlier, the MMA has been involved in the formulation and passage of several other laws. One such example is the legislation that prohibits the distribution of single-use plastic bags across the entire national territory. Another noteworthy initiative is the project that seeks to amend Law No. 21,100 to prohibit the distribution and sale of specific plastic items, which has recently secured approval from the Senate and is now undergoing the Presidential signature process.

In addition to the MMA's efforts, the Corporation for the Promotion of Production (CORFO) has been a proactive driving force in advancing the circular economy in Chile since 2018. CORFO has displayed remarkable enthusiasm in promoting circular economy principles through various mechanisms. This includes championing the cause through competitive funds designed to support projects aligned with circular economy ideals. With no fewer than 10 dedicated calls for such projects conducted thus far, CORFO has significantly bolstered the adoption of circular practices in the country. Furthermore, CORFO has been instrumental in fostering collaboration and synergy within the circular economy landscape. The corporation has facilitated the creation of networks aimed at nurturing the growth and diffusion of circular economy initiatives. Simultaneously, CORFO has dedicated its efforts to designing and implementing comprehensive training programs that equip stakeholders with the knowledge and skills required to thrive in the circular economy paradigm.

Complementing these endeavors, the Agency for Sustainability and Climate Change (ASCC) has also embarked on a mission to champion the circular economy agenda. The ASCC's commitment is evident in its active promotion of no less than 12 Clean Production Agreements centered around various circular economy themes.

Furthermore, a notable trend is emerging in which numerous prominent companies across Chile are proactively spearheading efforts to transition towards more circular operational models. Alongside this, several key business associations are fervently championing initiatives centered around the circular economy. These collaborative endeavors illustrate the growing commitment within the private sector to adopt sustainable practices that align with circular economy principles. Among them are:

- SOFOFA's[3] Scale 360 project;

[3] Factory Development Society is the trade union association of companies, unions of the Chilean industrial sector.

- The development of the Circular Economy Strategy in Construction by the Chilean Chamber of Construction.
- The APL for Electrical and Electronic Devices of the Chamber of Commerce of Santiago.
- The APL Zero Waste to Elimination of Business Action; and
- The growing number of companies that have joined the National Association of the Recycling Industry reflects the dynamism of this activity in the country.

Chile generates annual amount of approximately 8 million tons of municipal solid waste (MSW), as reported by the Ministry of the Environment (MMA, 2022a). This figure underscores the significant scale of waste generation within the country. In the context of waste generation rates, Figure 1-1 illustrates a comparative overview of Waste Generation Rates across the Latin America and the Caribbean Region, measured in kilograms per capita per day. Notably, in the case of Chile, the daily per capita waste generation amounts to 1.15 kilograms. This statistic positions Chile's waste generation rate above the regional average of 0.9 kilograms and even surpasses the global average of 0.74 kilograms per capita per day. This data emphasizes the need for concerted efforts to address waste management challenges and transition towards more sustainable waste practices in order to align with global trends and objectives.

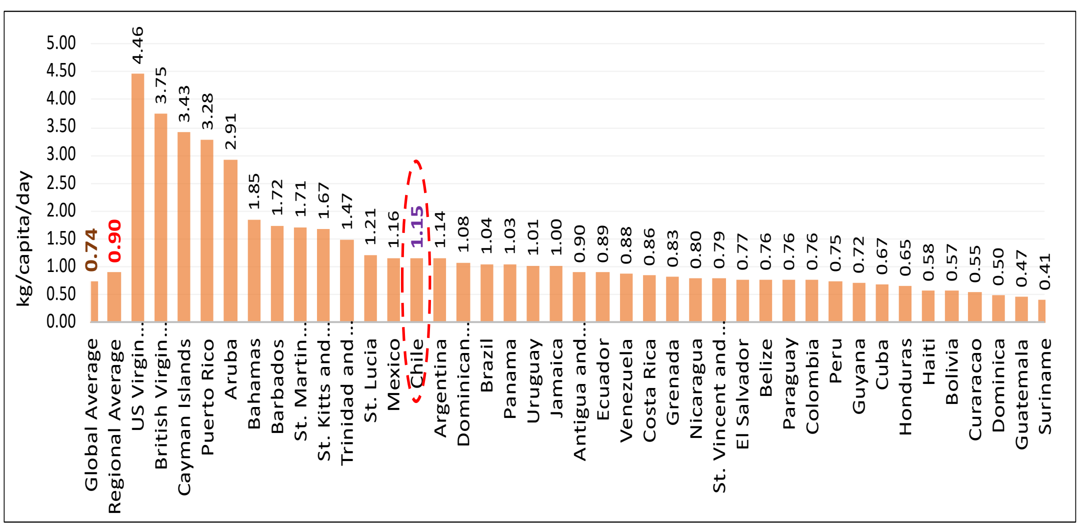

Figure 1-1: Waste Generation Rates: Latin America and the Caribbean Region (kg/capita/day). Source: Own elaboration from Report World Bank (2018): What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050 (Kaza et al., 2018).

Certainly, within the context of the Metropolitan Region of Chile, Figure 1-2 provides a visual representation of the variations in waste generation rates across different communes within the region. This illustration serves to highlight the differences in the amount of waste generated by each commune, thereby offering insights into the local dynamics of waste generation within the Metropolitan Region.

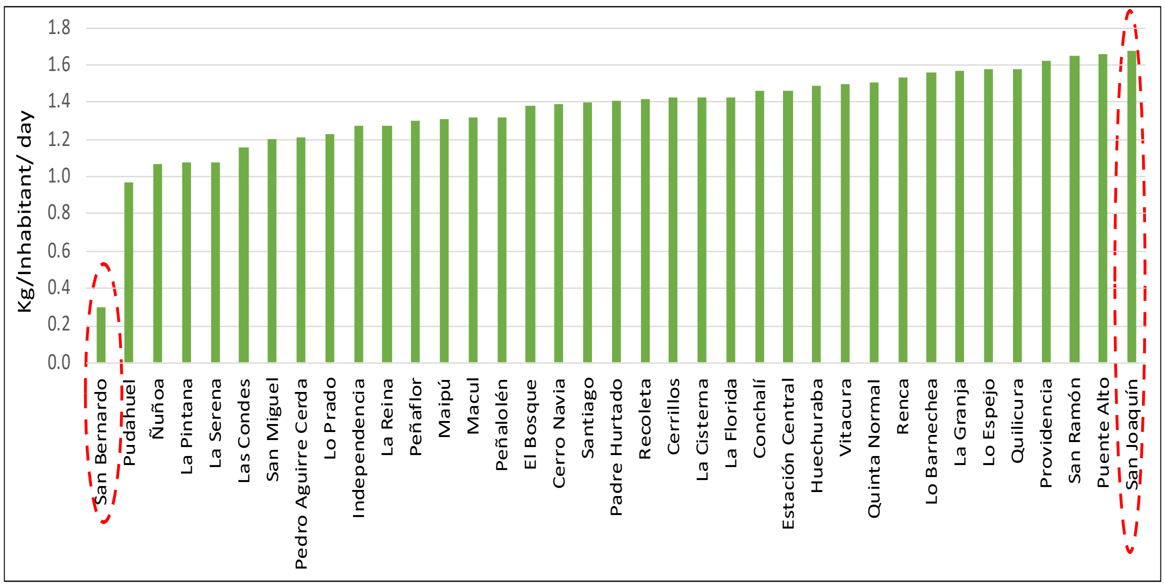

Figure 1-2: Municipal solid waste from Metropolitan Region, Chile (Kg/Inhabitant/day). Source: Own elaboration from Registro de Emisiones y Transferencias de Contaminantes (RETC), Chile.

Indeed, disparities among communes in the Metropolitan Region of Chile extend beyond waste generation and encompass differences in the costs associated with waste management. Figure 1-3 visually represents these significant variations in terms of the costs incurred for solid waste management by each commune.

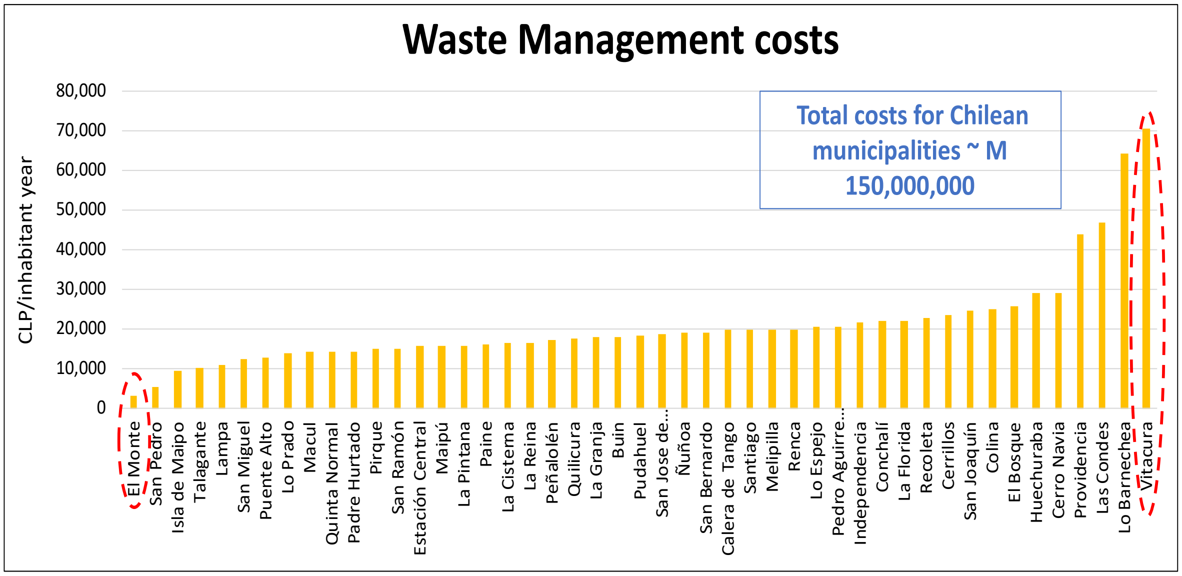

Figure 1-3: Municipal waste management annual costs per capita for the Municipalities of the Metropolitan Region, Chile. Source: Own elaboration from Census (2017) and SINIM (2017) data.

1.4 Problem Statement and gaps in literature

The assessment of performance in the collection and disposal of MSW has gained research attention over the past decade, yet it remains relatively unexplored, as highlighted by Pérez-López et al. (2016). A review of the literature evidences that most empirical studies in this area have been focused on specific countries such as the United States, Italy, and Portugal (Sarra et al., 2017). Notably, this topic has scarcely been investigated for Chilean municipalities. Evaluating performance metrics like efficiency, eco-efficiency, productivity change, and eco-productivity change provides valuable insights into how municipalities are managing MSW from both economic and environmental standpoints. Furthermore, prior research has underscored the importance of considering external factors that can influence the performance of municipalities in waste management services. For instance, studies (Guerrini et al., 2017; Sarra et al., 2017) have highlighted external variables affecting Italian municipalities' performance, including population density, age distribution, geographical characteristics, waste generation levels, collection methods, socioeconomic status, and commune size, among others. Extending this analysis to the Chilean context can shed light on the unique dynamics and factors influencing waste management performance in the country's municipalities.

Given the absence of prior studies assessing the performance of Chilean municipalities in municipal waste services, there exists a notable gap in the existing literature. A comprehensive literature review highlights three principal gaps in this research domain:

a. Previous studies have primarily evaluated either the efficiency or the eco-efficiency of municipalities in MSW management. However, these studies have not compared both performance metrics, which means that there is a lack of understanding regarding the implications of separate waste collection and recycling on municipal performance.

b. Most performance assessments have been conducted at specific points in time and have not taken into account the changes in municipalities' productivity over time. Furthermore, none of these limited prior studies have integrated the analysis of non-recyclable waste.

c. There is a distinct absence of research that evaluates both the economic and environmental performance of Chilean municipalities concerning the provision of MSW services.

1.5 Research Question and Hypotheses

1.5.1 Main research question

Do, and to what extent, selective collection, MSW recycling, and external factors impact municipalities' performance in providing MSW services?

1.5.2 Main hypothesis

The selective collection and recycling of MSW together with to external factors such as population density, population size, tourism rate, geographical area served, among others, affect the economic and environmental performance of municipalities in the provision of MSW services.

- **H_1:** Selective collection and recycling of MSW affects the economic and environmental performance of municipalities in the provision of MSW services.

- **H_2:** The improvement in the rate of selective collection and recycling over time of MSW has implied significant changes in the environmental and economic productivity of the municipalities in the provision of MSW services.

- **H_3:** In addition to the management carried out by the municipalities, are there multiple external factors that affect their economic and environmental performance in the provision of MSW services.

1.6 Objectives

The **main objective** of this dissertation is to evaluate the economic and environmental performance of Chilean municipalities in providing MSW services.
The specific objectives of the dissertation are as follows:

- **SO_1:** To evaluate the impact of the selective collection and recycling of MSW on the performance of the municipalities in the management of MSW by comparing efficiency and eco-efficiency indices;

- **SO_2:** To evaluate whether changes in the rates of selective collection and recycling of MSW have impacted the environmental and economic performance of the municipalities over time by comparing the rates of change in productivity and eco-productivity;

- **SO_3:** To identify external factors to the management carried out by the municipalities that affect their performance measured as efficiency, eco-efficiency, productivity and eco-productivity.

1.7 Case Study

The empirical applications conducted in this dissertation focused on Chilean municipalities (see Figure 1-4) evaluated between 2014 and 2019[4].

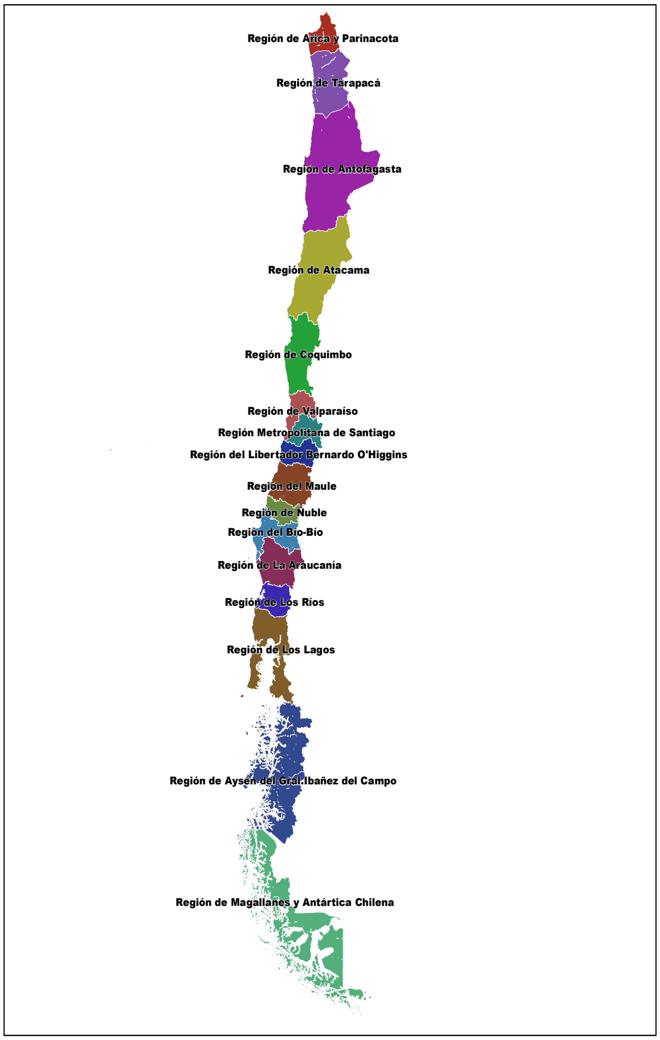

Figure 1-4: Study area.
Regions of Chile (Names are in Spanish).

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[4] For each written paper, different numbers of municipalities were used due to the availability of data and the variables used; each was representative of the Chilean population.

The national databases used to obtain the required statistical information were: i) SINADER (National Waste Declaration System), ii) SINIM (National Municipal Information System), and iii) 2017 Census. SINADER is a national digital platform that records multiple data related to the management of MSW of Chilean municipalities. This database contains information from 310 of the 345 Chilean municipalities for the 16 national regions, which implies that the empirical applications of this thesis will be representative of Chile. This database contains relevant and available information between 2014 and 2019, such as i) annual quantity of MSW produced categorized as organic matter, paper, plastic, glass, and metals, among others; and ii) type of treatment or disposal system, such as incineration, composting, recycling or landfill.

SINIM is one of the main Chilean databases and includes around 300 indicators for the 345 Chilean municipalities between 2011 and 2022. The indicators are grouped into categories that include socioeconomic variables of the population, geographical conditions of the municipality and; municipal operating expenses for the provision of essential services that include the management of MSW. Finally, the 2017 Census also contains demographic and socioeconomic data of the municipalities, which are relevant for the management of the MSW.

1.8 Methodological Approach and Thesis Organization

To achieve research's main and specific objectives, a methodology has been developed that consists of a set of work packages (WPs), which are described below and will lead to tasks and papers associated with the specific objectives described above. The proposed dissertation is based on the following WPs (see Figure 1-5):

- **WP_0:** Development and validation of the database for Chilean municipalities.
- **WP_1:** Evaluation of the impact of selective collection and recycling of MSW on economic and environmental performance.
- **WP_2:** Evaluation of the change in the environmental and economic performance of the municipalities in the collection and treatment of the MSW.
- **WP_3:** Identification of influential external factors affecting the performance of municipal waste services.

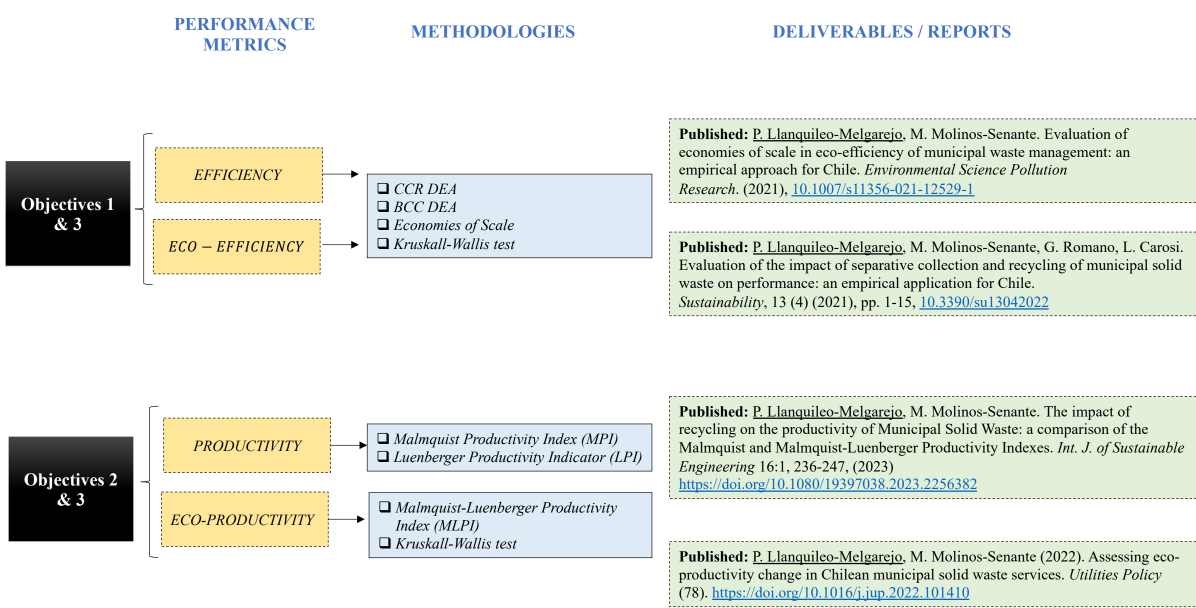

Figure 1-5: Summary of the research proposal. Own elaboration.

1.8.1 WP_0: Development and validation of the database for Chilean municipalities

Task 0.1: Database on MSW generation and management by municipalities

The SINADER and SINIM databases were used for this task. SINADER provides the following information for 310 Chilean municipalities (345 in total):

- Type of MSW produced as metals, organic matter, plastic paper, glass, and electronic waste.
- Type of treatment or disposal system such as compost, incineration, recycling or landfill.
- Amount of each type of MSW is produced annually.
- Data available between 2014 and 2019.

SINIM presents the following main characteristics:

- Information of 300 Chilean municipalities (345 in total)
- Data available between 2011 and 2018.
- Socio-economic variables of the population.
- Geographic conditions of the municipality.
- Operational costs of the municipalities to provide basic services, which include MSW management.

Task 0.2: Database on exogenous variables influencing economic and environmental performance

In addition to SINIM database, the Census 2017 was used to characterize the socioeconomics and geographic conditions of the municipalities evaluated. It provides essential information for the excellent design of public policies and private and public decision making. It allows to count and characterize the population in a moment: magnitude, distribution, and composition of the population (sex, age, education, migration, among others).

Task 0.3: Outliers identification

The three databases (SINADER, SINIM, CENSO 2017) were used to comprehensively characterized most Chilean municipalities from a socioeconomic and management perspective of MSW. Because more than 300 units (municipalities) were evaluated and many variables were considered in this study, a method based on the average and standard deviation was used to detect outliers.

Outliers' identification is essential to evaluate the units' performance using non-parametric methods such as Data Envelopment Analysis (DEA) due to its deterministic nature. Outliers can affect the efficiency and productivity results since they act as pairs of other units (Ananda, 2019). As a result of this exhaustive data collection process a complete characterization of Chilean municipalities on the management of MSW was obtained, which is essential to developing the following WPs.

1.8.2 WP1: Evaluation of the impact of selective collection and recycling of MSW on economic and environmental performance

Task 1.1 Evaluation of the efficiency of municipalities in the collection and treatment of MSW

The objective of this task is to evaluate the efficiency of municipalities in the provision of MSW services. In doing so, each municipality's efficiency score was calculated. Regarding the methodology, two DEA approaches were used: i) DEA_CRS and ii) DEA_VRS. DEA_CRS assumes constant returns to scale and was proposed by (Charnes et al., 1978) whereas DEA_VRS involves variable returns to scale and was developed by (Banker et al., 1984). Both methodologies have been extensively studied in the literature on waste management in developed countries by authors such as (Agovino et al., 2018; Ichinose et al., 2013; Simoes and Marques, 2012; Pérez-López et al., 2016; Yang et al., 2018). DEA_CRS and DEA_VRS models measure the maximum radial reduction in all inputs that would increase the unit's efficiency to the level of the most efficient units in the study set (Hernández-Sancho et al., 2011). That is, they measure the overall efficiency for each DMU studied. Because in this task the aim was evaluate the efficiency of municipalities only the economics and quantity of MSW generated was integrated in the assessment.

Task 1.2 Evaluation of the eco-efficiency of municipalities in the collection and treatment of MSW

In the evaluation of the performance of municipal waste services, recyclable waste such as paper, plastic, glass and organic matter can be considered desirable products, whereas unsorted waste is an undesirable output (Díaz-Villavicencio et al., 2017). The consideration of desirable and undesirable outputs describes the main difference between the evaluation of efficiency, which only considers inputs and outputs, and eco-efficiency, which differentiates outputs and desirable (recycled waste) and undesirable (unsorted waste). The main advantage of considering undesirable outputs in performance evaluation is that an inefficient DMU can improve its performance by reducing undesirable outputs and inputs and increasing desirable outputs (Chang et al., 2013). For MSW services, this means that a municipality can improve its eco-efficiency by reducing the volume of unsorted waste and increasing the volume of recycled waste. From a methodological point of view, to evaluate eco-efficiency, the same DEA models applied in Task 1.1 but integrating undesirable outputs were used. This methodological approach allowed us the joint evaluation of the environmental and economic performance of the municipalities in the collection and treatment of MSW.

Task 1.3 Comparison of efficiency and eco-efficiency scores

To verify the impact of selective collection and recycling on the performance of municipalities, it is necessary to compare the efficiency and eco-efficiency scores for each municipality, i.e., comparing performance scores obtained in Task 1.1 and Task 1.2. To verify if there were statistically significant differences between both performance scores (efficiency and eco-efficiency) the non-parametric tests of Mann-Whitney and Kruskal-Wallis were used to compare the average of 2 samples and three or more samples, respectively (Molinos-Senante and Guzmán, 2018).

1.8.3 WP_2: Evaluation of the change over time in the municipalities' environmental and economic performance in the MSW collection and treatment

Task 2.1 Evaluation of the change in the productivity of the municipalities in the collection and treatment of MSW

This task was devoted to evaluating productivity change over time of the municipalities in the collection and treatment of the MSW. Concerning this issue, the literature is very limited and only Simoes et al. (2012); Pérez-López et al. (2018) and Lo Storto (2021) evaluated the productivity change of municipalities in the provision of MSW services by using the Malmquist Productivity Index (MPI). However, this index has two significant drawbacks: i) it is necessary to choose between an input orientation or an orientation output (Williams et al., 2011) and ii) MPI relates efficiency change (ECH) and technical change (TCH) through multiplication (Cook et al., 2010). To overcome these disadvantages, there is an alternative indicator, the Luenberger Productivity Indicator (LPI), which has shown to have significant advantages over the MPI: i) the LPI relates ECH and TCH through addition; ii) it can simultaneously focus on increasing outputs and decreasing inputs. (Boussemart et al., 2003) showed that the MPI overestimates the productivity change, unlike the LPI, concluding that the LPI is superior to the MPI. Because in the framework of MSW services, there are no previous studies evaluating the productivity change using the LPI, this methodological approach was used contribution to the current vein of literature.

Task 2.2 Evaluation of the change in the eco-productivity of the municipalities in the collection and treatment of MSW

The literature review showed that no previous studies evaluated municipalities' eco-productivity change in the provision of waste services. In other words, no previous studies evaluate the productivity change of municipalities in the provision of MSW by integrating simultaneously unsorted waste as undesirable output and recyclable waste as desirable outputs. The Malmquist-Luenberger Productivity Indicator (MLPI) (Chung et al., 1997) was applied to overcome this literature gap. This methodological approach provides an eco-productivity change score for each municipality analyzed, considering recyclable waste, unsorted waste and costs as desirable outputs, undesirable outputs and inputs, respectively.

Task 2.3 Comparison of productivity and eco-productivity change scores

Following the same methodological approach proposed in Task 1.3, the results obtained using the conventional measurement of productivity change (Task 2.1) were compared with the scores integrating undesirable outputs (Task 2.2). Comparative analysis allowed us to analyze whether adopting better environmental practices (selective collection and recycling) in the management of MSW impacts the municipalities' performance in the provision of MSW services. This information is relevant to support public policies as it provides information to promote selective collection and recycling in Chilean municipalities.

1.8.4 WP3: Identification of influential external factors affecting the performance of municipal waste services

Task 3.1 Identification of external factors affecting the performance of municipal waste services

As a result of WP1 and WP2, the performance of municipalities in the provision of waste services was evaluated. However, from a policy perspective, it is important to explain why a municipality is (or not) efficient, eco-efficient, productive, or eco-productive. In this task, external factors to the management carried out by the municipalities that might affect the performance of municipalities on the provision of waste services were analyzed. These factors cannot be considered inputs or outputs in the DEA assessment since they are not directly controllable by the municipalities. According to literature (Guerrini et al., 2017; Sarra et al., 2017), external factors to be analyzed are the size of the commune, density population, age range, tourism, geographical characteristics, and amount of waste generated, collection methods, socioeconomic level. Information for each municipality about these variables was compiled as part of Task 0.1. From a methodological point of view, some previous studies have employed parametric methodologies (Fernández-Aracil et al., 2018), i.e., econometric models in which the dependent variable is the performance index and the independent variables are the external factors evaluated. However, this approach presents problems related to multicollinearity; therefore, a non-parametric methodology was applied. Municipalities evaluated were grouped based on factors suspected to affect their performance. Subsequently, the Mann-Whitney non-parametric test was used to compare the mean of 2 samples and the Kruskal-Wallis test when there are three or more samples. The null hypothesis tested will be that the K samples are derived from the same population. This assessment considered efficiency, eco-efficiency, productivity change and eco-productivity change as performance metrics.

CHAPTER 2

2. EVALUATION OF ECONOMIES OF SCALE IN ECO-EFFICIENCY OF MUNICIPAL WASTE MANAGEMENT: AN EMPIRICAL APPROACH FOR CHILE

2.1 Introduction

The increase in the production of MSW in recent decades has been mainly linked to the economic development of countries and has become one of the most serious problems facing modern society (Marques and Simoes, 2009; Di Foggia and Beccarello, 2018). In this context, several countries have developed waste management policies aimed at increasing resource efficiency and reducing the negative impact of waste on the environment and citizens' health (Romano and Molinos-Senante, 2020). Currently, the management of MSW is included as part of Goal 11 (Sustainable Cities and Communities) of the Sustainable Development Goals proposed by the United Nations (2015). As demonstrated by (Schroeder et al., 2019) and (Cavaleiro de Ferreira and Fuso-Nerini, 2019), the ambitious Sustainable Development Goals can be accomplished by facilitating the practices of the circular economy. The European Commission defines the circular economy "as a system where the values of products, materials and resources are maintained in the economy for as long as possible, and the generation of waste is minimised" (European Commission, 2015). Thus, in the circular economy context, improving the eco-efficiency of MSW management occupies a prominent role.

The concept of eco-efficiency was first defined by (Schaltegger and Sturm, 1989) as the ratio between the value added and the environmental impact. It entails producing more goods and services with fewer resources and a minimal environmental impact (Koskela and Vehmas, 2012). In recent years, eco-efficiency has been popularised as a management philosophy that encourages companies and public services to balance their economic and environmental performances (WBCSD, 2000). However, despite the usefulness of evaluating the eco-efficiency of MSW services, most previous studies benchmarking the performance of MSW service providers have focused on evaluating the cost efficiency by employing the total costs of the service as the input and tons of MSW collected as the output (e.g., Chen 2008; Rogge and De Jaeger, 2012; Vishwakarma et al., 2012; Yang et al., 2018). This approach considers both recyclables and unsorted wastes as outputs, despite the fact that they have notably different environmental impacts. In other words, this approach ignores the environmental performance of DMUs in the provision of MSW services. In contrast, eco-efficiency assessment integrates both economic and environmental variables in the performance evaluation (Gómez et al., 2018). Thus, to evaluate the eco-efficiency of MSW services, (Courcelle et al., 1998) have suggested the use of recyclable waste as a desirable output and unsorted waste as an undesirable output. Nevertheless, to the best of our knowledge, only (Diaz-Villavicencio et al., 2017; Sarra et al. (2017, 2019, 2020); Guerrini et al., 2017; Expósito and Velasco, 2018 and Romano and Molinos-Senante et al., 2020) have evaluated the eco-efficiency of waste services. It should be highlighted that the empirical applications conducted by these studies focused only on Italian and Spanish MSW service providers, i.e., there is no information regarding the eco-efficiency of MSW services outside of these two countries. An alternative approach was applied by (Marques et al., 2012) who estimated the efficiency of a sample of Portuguese recycling companies. In this study, they applied several non-parametric models to compare the recycling and economic efficiency. In a first set of models, efficiency was estimated considering operational expenditure as input and amount of glass, paper and plastic collected as outputs. The economic efficiency assessment considered capital expenditure as input whereas outputs were the total economic revenue financial transfers from the Socieda de Ponto Verde.

To improve the management of MSW, scale-related economies are a relevant issue for waste service providers (Sarra et al., 2020). In this context, some previous studies have analysed the presence of economies of scale in the provision of waste services (e.g., Bel and Fageda, 2006; Bel and Mur, 2009; Bartlomiej, 2016; Caldas et al., 2019; Ferraresi, 2018; Sarra et al., 2019, 2020). With the exception of Sarra et al., (2019, 2020), these previous studies have focused on the economics of the provision of MSW services excluding the environmental performance of the service providers. Thus, the presence of economies of scale of the MSW services when eco-efficiency is employed as a metric of their performance remains as open issue. Hence, for benchmarking the eco-efficiency of DMUs providing MSW services, investigation into whether they present economies of scale is needed.

In addition to the management carried out by the service providers, past research on benchmarking the performance of municipal waste services has found that there are some exogenous variables, such as population size, population density, tourism, etc., that have an impact on the efficiency of MSW services (e.g., Simoes and Marques, 2012; Carvalho et al., 2015; Caldas et al., 2019; Guerrini et al., 2017; Halkos and Petrou, 2018), showing divergent results. Moreover, previous studies on eco-efficiency assessment and economies of scale analysis have mainly focused on European countries. Thus, the previous research is limited and inconclusive, warranting the need for further research with metrics that take into account environmental issues, i.e., considering eco-efficiency as a metric of performance.

The objectives of this study were threefold. The first was to evaluate the eco-efficiency of MSW services provided by a sample of municipalities, i.e., assessment of their performance considering not just economic costs and quantity of waste managed but differentiating recycled and unsorted wastes as they have different environmental impacts. The second objective was to investigate whether the eco-efficiency of MSW services is affected by economies of scale, i.e., evaluation of their scale eco-efficiency. This information is essential for local policymakers to develop policies that take advantage of inter-municipal cooperation with the aim of improving eco-efficiency in the management of MSW (Silvestre et al., 2020). The third objective of this study was to explore some exogenous variables that could have an impact on the eco-efficiency of MSW services. This approach was used to benchmark the performance of a sample of Chilean municipalities providing MSW services to 62% of the Chilean population. Hence, this study is quite representative of the country. The Chilean example is very interesting because, unlike European countries, waste management policies are incipient in most Latin American countries. Hence, knowledge about the topics addressed in this study will be very useful for the design of effective policies for improving MSW management that are aligned with the principles of the circular economy and the Sustainable Development Goals.

Chile has the highest per capita Gross Domestic Product (GDP) among Latin American countries (World Bank, 2019) and is part of the Organization for Economic Cooperation and Development (OECD) since 2010. Hence, municipal recycling services have been promoted in recent years, defining national goals for municipal recycling or taxes on landfills (Valenzuela-Levi., 2019). The main regulation that regulates waste management in Chile was implemented in 2016 and is known as Recycling and Extended Producer Responsibility Law. This law establishes that all producers or importers of "priority products" must take charge of the goods once their useful life ends. In other words, these "useless" products must return to the industries where they were manufactured, or to the warehouses where their distribution began. The Law establishes collection and recovery goals differentiated by types of waste (Ministerio de Medio Ambiente, 2016). The standard defined by the Law focuses on preventing and recovering waste in all its aspects (Ministerio de Medio Ambiente, 2016). However, before the adaptation of this Law, municipal recycling services emerged without a national recycling policy (a complete revision of the Chilean regulatory framework for waste management can be consult at (Vásquez, 2011). In this context, in the past recycling was introduced thanks to autonomous initiatives of the municipal authorities (Valenzuela-Levi., 2019).

The document is organized as follows. After the introduction, Section 2 describes the methodology, where the estimation of eco-efficiency scores, analysis of economies of scale and factors affecting eco-efficiency is detailed. Then, in Section 3, the sample and data are described. Section 4 presents and discusses the results. Finally, Section 5 highlights the conclusions of this paper.

2.2. Methodology

The methodological approach followed in this work was divided into three stages: First, the eco-efficiency of MSW services for each municipality analysed was evaluated. Second, the presence of economies of scale in the provision of MSW services for each municipality under study (Chilean municipalities) was assessed. Finally, the effects of external factors on the performance of municipalities providing MSW services were analysed using the Kruskal–Wallis non-parametric method.

2.2.1 Estimation of eco-efficiency scores

To evaluate the eco-efficiency of MSW services, the data envelopment analysis (DEA) method was employed (Boetti et al., 2012; Simões and Marques, 2012; Guerrini et al., 2017; Sarra et al., 2017; Romano and Molinos-Senante, 2020). It is a non-parametric technique based on linear programming that estimates the efficient production frontier, which is then used to measure the relative eco-efficiency of a set of DMUs. Hence, DEA methodology provides a measure of the relative performance of the DMUs based on the use of inputs to produce outputs (Banker et al., 1984; Charnes et al., 1978). The three main positive features of DEA to evaluate the eco-efficiency of MSW services are as follows: i) it does not require information about input and output prices; ii) it does not require the functional form of the efficient frontier to be defined (Molinos-Senante and Guzmán, 2018) and iii) it allows desirable outputs (recyclable wastes), undesirable outputs (unsorted waste) and inputs (economic costs) to be integrated in a single index for the performance assessment (Molinos-Senante et al., 2016). Hence, this methodological approach allows the joint economic and environmental performance of municipalities providing MSW services to be evaluated.

Subsequently, the DEA model employed to compute the eco-efficiency scores, i.e., the DEA method integrating unsorted waste as an undesirable output, is presented. The notation used is as follows: $x \in \Re_{+}^{M}$ denotes the vector of inputs, $y \in \Re_{+}^{S}$ is the vector of desirable outputs and $b \in \Re_{+}^{H}$ is the vector of undesirable outputs.

The production possibility set of desirable and undesirable outputs given the level of inputs is defined as follows:

$$P(x) = \{(y, b): x \; can \; produce \; (y, b)\} \qquad (2.1)$$

The input distance function, including undesirable outputs, is defined as follows:

$$D(x, y, b) = min_{\theta}\{\theta > 0: x\theta \in P(x)\} \qquad (2.2)$$

Following (Färe et al., 1994), for each DMU (municipality in this study) j, the linear program to be solved to compute the eco-efficiency scores assuming constant returns to scale (CRS) is (Eq. 2.3):

$$
\begin{aligned}
& Min\ \theta^{CRS} \\
& s.t. \\
& \textstyle\sum_{j=1}^{N} \lambda_j x_{ij} \leq \theta x_{i0} && 1 \leq i \leq M \\
& \textstyle\sum_{j=1}^{N} \lambda_j y_{rj} \geq y_{r0} && 1 \leq r \leq S \\
& \textstyle\sum_{j=1}^{N} \lambda_j b_{zj} = b_{z0} && 1 \leq z \leq H \\
& \lambda_j \geq 0 && 1 \leq j \leq N
\end{aligned}
\tag{2.3}
$$

In the case of variable returns to scale (VRS) technology, the linear program to be solved to estimate the eco-efficiency scores for each unit j is (Eq. 2.4):

$$
\begin{aligned}
& Min\ \theta^{VRS} \\
& s.t. \\
& \textstyle\sum_{j=1}^{N} \lambda_j x_{ij} \leq \theta x_{i0} && 1 \leq i \leq M \\
& \textstyle\sum_{j=1}^{N} \lambda_j y_{rj} \geq y_{r0} && 1 \leq r \leq S \\
& \textstyle\sum_{j=1}^{N} \lambda_j b_{zj} = b_{z0} && 1 \leq z \leq H \\
& \textstyle\sum_{j=1}^{N} \lambda_j = 1 \\
& \lambda_j \geq 0 && 1 \leq j \leq N
\end{aligned}
\tag{2.4}
$$

where θ^{CRS} and θ^{VRS} indicate the eco-efficiency scores of the DMUs evaluated, assuming constant and variable returns to scale technology, respectively. In both cases, $\theta \in (0, 1]$ and a DMU is eco-efficient if θ equals unity, whereas it is inefficient if $0 < \theta \leq 1$. The difference between the eco-efficiency score and the value of 1 represents the input savings required by the unit to be eco-efficient; M is the number of inputs used; S is the number of desirable outputs generated; H is the number of undesirable outputs involved; N is the number of municipalities analysed; and λ_j is a set of intensity variables that represents the weighting of each DMU analysed.

2.2.2 Analysis of economies of scale

In order to analyse the economies of scale in the provision of MSW services, the direction of returns to scale was analysed as described by (Marques and De Witte, 2011). As illustrated in Eqs. (2.3) and (2.4), the eco-efficiency scores can be calculated by assuming either CRS or VRS technology. Under CRS technology, the eco-efficiency score is the product of scale eco-efficiency and pure technical eco-efficiency, since the CRS approach assumes that all DMUs operate at an optimal level (Charnes et al.,1978). In contrast, the VRS approach measures only eco-efficiency, since it compares DMUs with similar scales Banker et al., (1984). According to (Molinos-Senante and Guzmán, 2018), when a DMU presents a CRS eco-efficiency score (θ^{CRS}) equal to the VRS eco-efficiency score (θ^{VRS}), its scale eco-efficiency (SEE) is equal to unity given that:

$$SEE\ (x, y) = \frac{\theta^{CRS}}{\theta^{VRS}} \tag{2.5}$$

If $SEE = 1$, then the evaluated DMU operates under CRS technology. In contrast, if $SEE < 1$, the evaluated DMU operates under VRS technology.

According to previous studies (Marques and De Witte, 2011; Carvalho and Marques, 2014; Molinos-Senante and Guzmán, 2018), when a unit operates under VRS technology, i.e., $SEE < 1$, it can have either increasing returns to scale (IRS) or decreasing returns to scale (DRS). IRS is associated with positive economies of scale as desirable outputs increase by more than the proportional change in inputs (Carvalho et al., 2015). In contrast, DRS involves negative economies of scale as it implies that desirable outputs increase by less than the proportional change in inputs (Guerrini and Romano, 2013).

Given that one of the objectives of this study was to evaluate the presence of economies in the provision of MSW services, whether DMUs (municipalities) operate under IRS or DRS technology was further evaluated. In doing so, an additional DEA model assuming non-increasing returns to scale (NIRS) was solved, providing an additional eco-efficiency score (θ^{NIRS}) (Cooper et al., 2011), which is as follows:

$$
\begin{aligned}
& Min\ \ \theta^{NIRS} \\
& s.t. \\
& \textstyle\sum_{j=1}^{N} \lambda_j x_{ij} \leq \theta x_{i0} && 1 \leq i \leq M \\
& \textstyle\sum_{j=1}^{N} \lambda_j y_{rj} \geq y_{r0} && 1 \leq r \leq S \\
& \textstyle\sum_{j=1}^{N} \lambda_j b_{zj} = b_{z0} && 1 \leq z \leq H \\
& \textstyle\sum_{j=1}^{N} \lambda_j \leq 1 \\
& \lambda_j \geq 0 && 1 \leq j \leq N
\end{aligned}
\tag{2.6}
$$

As stated by Hwang et al. (2016), on the one hand, a unit operates under DRS technology, i.e., presents negative economies of scale, when $\theta^{NIRS} = \theta^{VRS}$. On the other hand, a unit operates under IRS technology, i.e., exhibits positive economies of scale, when $\theta^{NIRS} \neq \theta^{VRS}$.

2.2.3 Factors affecting eco-efficiency

The previous stages allowed the level of eco-efficiency in the provision of MSW by each municipality evaluated to be identified. However, there are some external factors affecting the management of MSW, also known as environmental variables, that could impact their eco-efficiency. These factors cannot be considered as inputs or outputs, since they are not directly controllable by the municipalities.

There are several alternative methodological approaches available to identify the factors that affect the eco-efficiency scores. Some previous studies (Fernández-Aracil et al., 2018) have employed parametric methodologies i.e., econometric models in which the dependent variable is the performance index and the independent variables are the external factors evaluated (Simões and Marques, 2011). However, this approach presents problems related to multicollinearity; therefore, a non-parametric methodology was applied in this study. The municipalities evaluated were grouped based on factors that were suspected to affect their eco-efficiency and were tested for statistically significant differences in the distribution of the eco-efficiency scores among the groups of municipalities (Guerrini et al. 2017; Sarra et al., 2017; Romano and Molinos-Senante, 2020). The non-parametric Kruskal–Wallis test was applied. The null hypothesis tested was that the K samples are derived from the same population. The null hypothesis could be rejected at a 95% significance level when the p-value was less than or equal to 0.05. The external factors were used to analyse the eco-efficiency of the MSW services. It should be noted that other studies (e.g., Simões et al., 2010; Romano et al., 2019; Ferreira et al., 2020) used alternative methodologies such as double bootstrap and order-m/order-α to evaluate the influence of exogenous variables in the performance of MSW service providers.

2.2.4 Sample description and data

The sample used for this empirical application corresponds to 142 out of 345 Chilean municipalities. These 142 municipalities correspond to 11,697,868 inhabitants (62%) of a total population of 18,729,160 people in Chile (Chilean Census, 2017). Information about MSW management is available from the SINADER database. For 2018, which is the most recent year with available data, information regarding 310 municipalities was obtained. However, to conduct this study, only those municipalities that recycle some MSW were considered in the eco-efficiency assessment. Hence, according to the SINADER database, in 2018, 54.2% (168 out of 310) of Chilean municipalities did not recycle any MSW.

Based on past research on the performance of waste service management (e.g., Marques and Simoes, 2009; Simoes et al., 2010; Exposito and Velasco, 2018; Romano et al., 2019), the total annual cost of the provision of MSW services by each municipality was integrated in the eco-efficiency assessment as the input. This variable was collected from the SINIM for 2018. It is one of the main Chilean databases and includes approximately 300 indicators for the 345 Chilean municipalities. The total cost indicator is defined as the expenditures made by each municipality, including cleaning services, waste collection and waste treatment. It is expressed in Chilean pesos/year. As this study evaluated the performance of municipalities providing MSW services using eco-efficiency as a metric, unsorted waste (tons/year) was considered as an undesirable output (Sarra et al., 2017; Expósito and Velasco, 2018). On the other hand, recyclable wastes (tons/year) were integrated as desirable outputs and were categorised as follows: i) paper and cardboard, ii) glass, iii) plastic, iv) organic waste and v) other inorganic recycled waste (Marques et al., 2012; Diaz-Villavicencio et al., 2017).

Hence, the eco-efficiency assessment conducted in this study involved one input, one undesirable output and five desirable outputs. Information about waste generation (unsorted water and recycled waste) was collected from the SINADER database for 2018.

To select the potential exogenous variables affecting the eco-efficiency scores, three criteria were considered: i) the features of the MSW sector in Chile, ii) the available information for the municipalities evaluated and iii) the extant literature (e.g., Sarra et al., 2017; Calabro and Komilis, 2019; Romano and Molinos-Senante, 2020). The following variables were considered: i) the population served, which is defined as the number of inhabitants of the municipality; ii) the municipality size, expressed in km^2. This variable does not involve all areas of the municipality but focuses on the urban area where the MSW services are provided; iii) the population density, which is expressed as the number of people per km^2 of urban area of the municipality; iv) the tourism ranking, proposed by the Studies and Territory Division of the Undersecretariat of Tourism together with the Destinations Unit, Territory and Environment, of the Sub-directorate of the Development of National Tourism Service (Sernatur, for its acronym in Spanish), and it considers 15 variables; v) the amount of waste generated per capita, which was estimated as the ratio between the kg of waste generated and the number inhabitants of each municipality and vi) the annual gross domestic product (GDP) per capita.

The main statistics of the variables used to estimate the eco-efficiency scores of the sample of Chilean municipalities and the exogenous variables affecting the eco-efficiency scores are shown in Table 2-1.

Table 2-1: Basic statistics of the variables considered to evaluate eco-efficiency

	Variables	*Unit of measure*	*Average*	*Standard deviation*	*Minimum*	*Maximum*
Input	Total costs	CLP/year	1,719,437	2,548,504	764	14,765,504
Desirable Output	Paper and paperboard	Tons/year	106	559	0	6,023
	Glass	Tons/year	188	417	0	2,759
	Plastics	Tons/year	32	164	0	1,842
	Organic waste	Tons/year	185	1,157	0	13,089
	Other inorganic waste	Tons/year	6,387	65,149	0	775,267
Undesirable Outputs	Unsorted waste	Tons/year	36,225	52,875	223	360,451
Environmental Variables	Population Density	Inhabit./Km^2	1,380	3,444	3	18,221
	Municipality size	Km^2	858	1,998	7	14,616
	Population Served	Inhabitants	82,379	107,514	880	633,021
	Tourism	-	0.0665	0.1406	0.0008	1.0000
	Annual waste generated per capita	Kg/Inhabit*year	837.00	4818.97	80.05	57802.78
	Annual gross domestic product per capita	Million CLP/year	116	197	13	1889

2.3. Results and Discussion

2.3.1 Evaluation of eco-efficiency and economies of scale

To evaluate the eco-efficiency of MSW services provided by each evaluated municipality, the first step was to investigate the technology they use in the management of their waste, i.e., whether they operate under CRS or VRS technology. In doing so and according to the methodological approach described in section 2, the DEA-CRS and DEA-VRS models (equations 2.3 and 2.4) were solved for each municipality evaluated. Figure 2-1 shows the SEE for the 142 Chilean municipalities evaluated. The eco-efficiency scores of each municipality, assuming CRS, VRS and NIRS technology, are shown in the supplemental material. Accordingly, 6 out of 142 (4.2%) of the municipalities operate under CRS as the SEE value equals unity, whereas 96% of the municipalities exhibit VRS technology (i.e., the SEE value is less than unity).

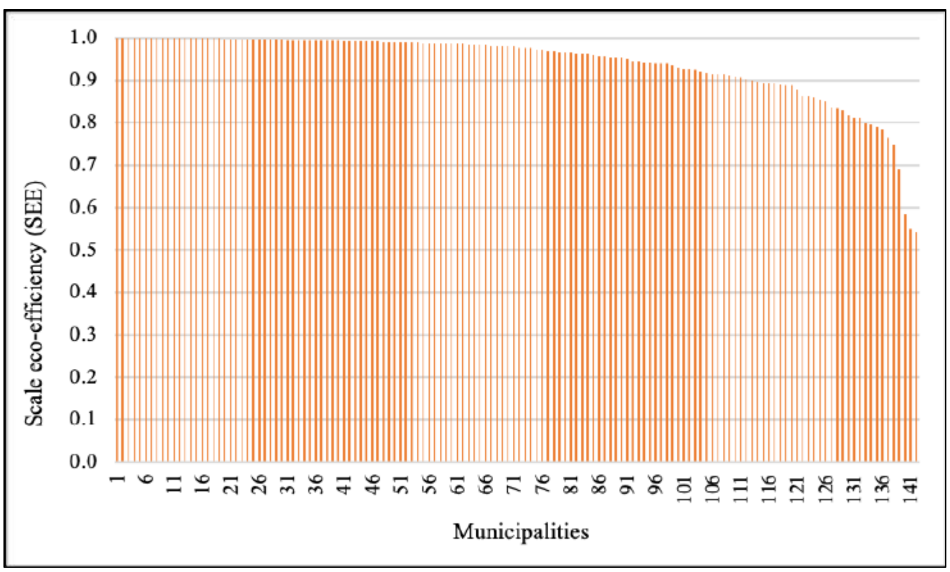

Figure 2-1: Scale eco-efficiency (SEE) in the provision of solid waste services for each Chilean municipality evaluated.

This finding indicates that only 4% of the municipalities evaluated present a scale of operation in which the inputs used and outputs generated are proportional. In contrast, 96% of the evaluated municipalities have economies or diseconomies of scale in their solid waste management. Therefore, the next step was to investigate whether the municipalities that operate under VRS technology present DRS or IRS technology, that is, if they exhibit negative or positive economies of scale, respectively. The eco-efficiency scores were estimated assuming NIRS. The difference between θ^{NIRS} and θ^{VRS} for each municipality is shown in Figure 2-2. It was found that 55 out of 136 (40.4%) of the municipalities present IRS technology, indicating that they have positive economies of scale. From a management point of view, this means that these municipalities take advantage of their size of operation as the greater the quantity of wastes managed, the lower the cost per unit. On the other hand, 81 out of 136 (59.6%) of the evaluated municipalities operate under DRS technology, demonstrating that these municipalities present negative economies of scale in the management of MSW.

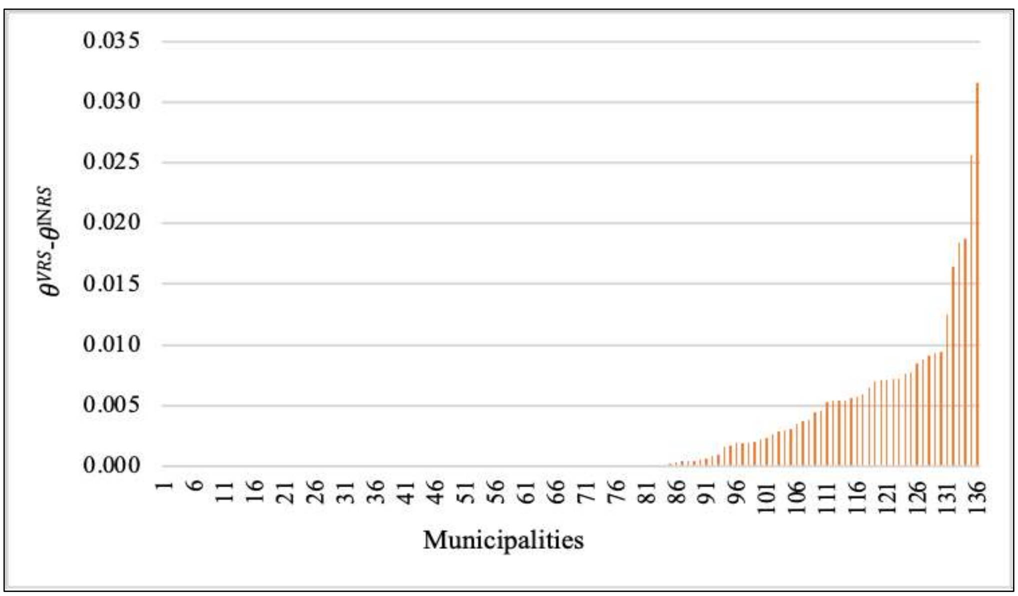

Figure 2-2: Difference of eco-efficiency scores in the provision of solid waste services for each Chilean municipality evaluated assuming variable returns to scale (VRS) and non-increasing returns to scale (NIRS).

The geographic distribution of the municipalities operating under CRS, DRS and IRS technology is shown in Figure 2-3. This figure illustrates that in northern Chile, very few municipalities recycle MSW; therefore, they were not considered in this study. Among the ones that do recycle waste, most of them operate under DRS technology, i.e., present negative economies of scale. In other words, the quantity of MSW recycled is not optimal.

In the central zone of Chile, where most Chileans live, the municipalities exhibit both positive and negative economies of scale. Actually, some of the municipalities are continous, suggesting that mergers or alliances among municipalities for the provision of MSW services will be beneficial in terms of the eco-efficiency. It should be noted that the area south of the metropolitan area of Santiago, which concentrates one-third of the total population of Chile, was not integrated in this study as municipalities located in this area formally do not recycle MSW. In this context, the municipalities evaluated within the metropolitan area of Santiago exhibit negative economies of scale, indicating that their operational size does not favour their eco-efficiency in the provision of MSW services; therefore, some policies should be implemented to change the current management of MSW. Finally, most of the municipalities located in southern Chile present positive economies of scale, which is very relevant as some of them are located in rather isolated areas.

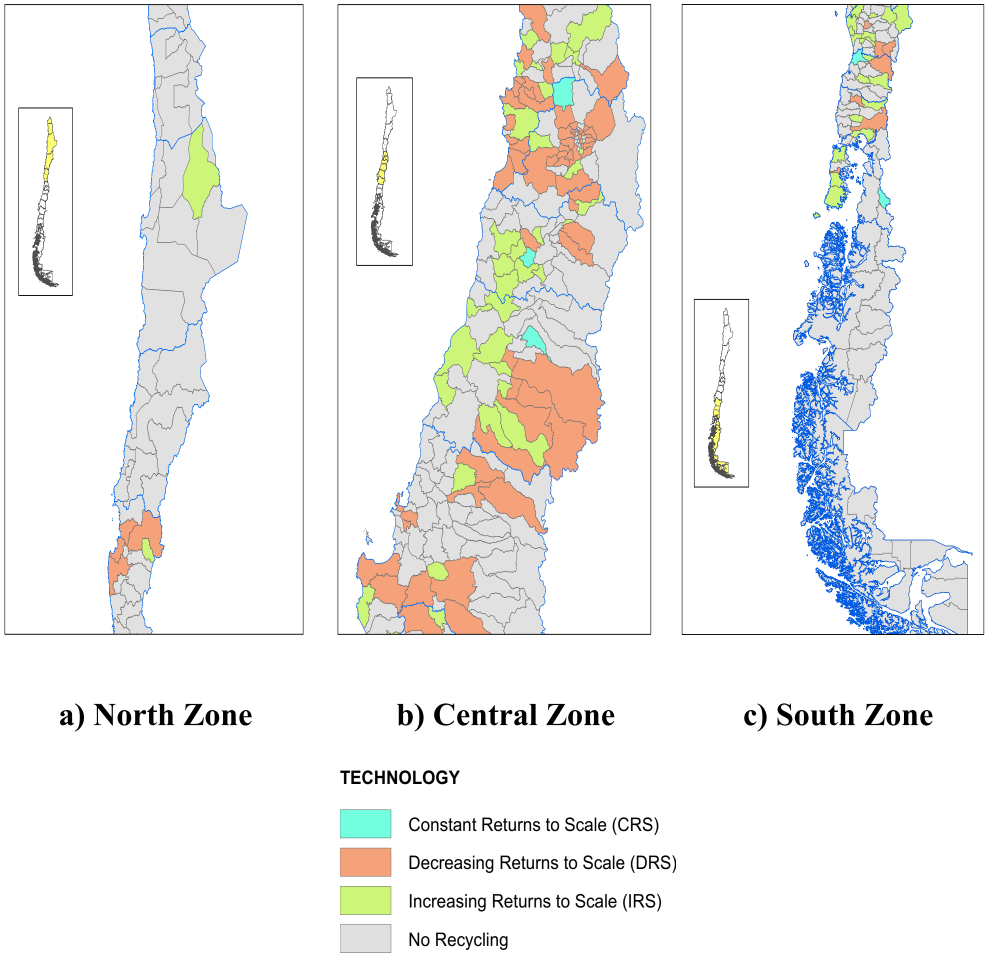

Figure 2-3: Maps of Chilean municipalities exhibiting CRS, DRS and IRS technology in eco-efficiency assessment for the provision of MSW service.

Focusing on the eco-efficiency scores under VRS technology, Table 2-2 shows the main statistics of the eco-efficiency scores of the 142 Chilean municipalities evaluated. The mean eco-efficiency score is 0.58, indicating that the municipalities can save an average of 42% of the current cost by keeping the same amount of MSW managed (both recycled and unsorted wastes). The results estimated for Chilean municipalities are on the same order of magnitude as for the Tuscan municipalities reported by (Romano and Molinos-Senante, 2020). They reported mean eco-efficiency scores of 0.697, 0.677 and 0.523 for public, private and mixed firms providing MSW services. However, they are greater than the ones reported by (Sarra et al., 2017) for a sample of Italian municipalities as well as a sample of Spanish municipalities (Diaz-Villavicencio et al., 2017). In contrast, the average eco-efficiency of the MSW services provided by Chilean municipalities evaluated (0.58) is slightly lower than that estimated by (Expósito-Velasco et al., 2018) for Spanish regions, whose average value was 0.792. At the municipal level, the results illustrate that only 11 out of the 142 Chilean municipalities evaluated (7.74%) are eco-efficient, i.e., they comprise the best practice benchmark. Conversely, 131 out of 142 (92.25%) are not eco-efficient. Based on these results, most of the municipalities have room to improve their eco-efficiency in the management of MSW. Moreover, as shown in Figure 2-5, most of the municipalities evaluated (108/142, 76.1%) present an eco-efficiency score ranging between 0.5 and 0.6, followed by 18 municipalities whose eco-efficiency is between 0.6 and 0.7. This finding indicates that the majority of the municipalities studied can improve their waste management process by at least 50% in comparison with the current status. On the other hand, only 11 out of the 142 municipalities evaluated are eco-efficient; that is, they are the best ones in terms of eco-efficiency in the management of MSW.

Table 2-2. Main statistics of eco-efficiency scores of the Chilean municipalities evaluated.

Metric	*Eco-efficiency score*
Average	0.58
SD	0.14
Maximum	1.00
Minimun	0.50
Percentage of eco-efficient municipalities	7.74%
Percentage of inefficient municipalities	92.25%

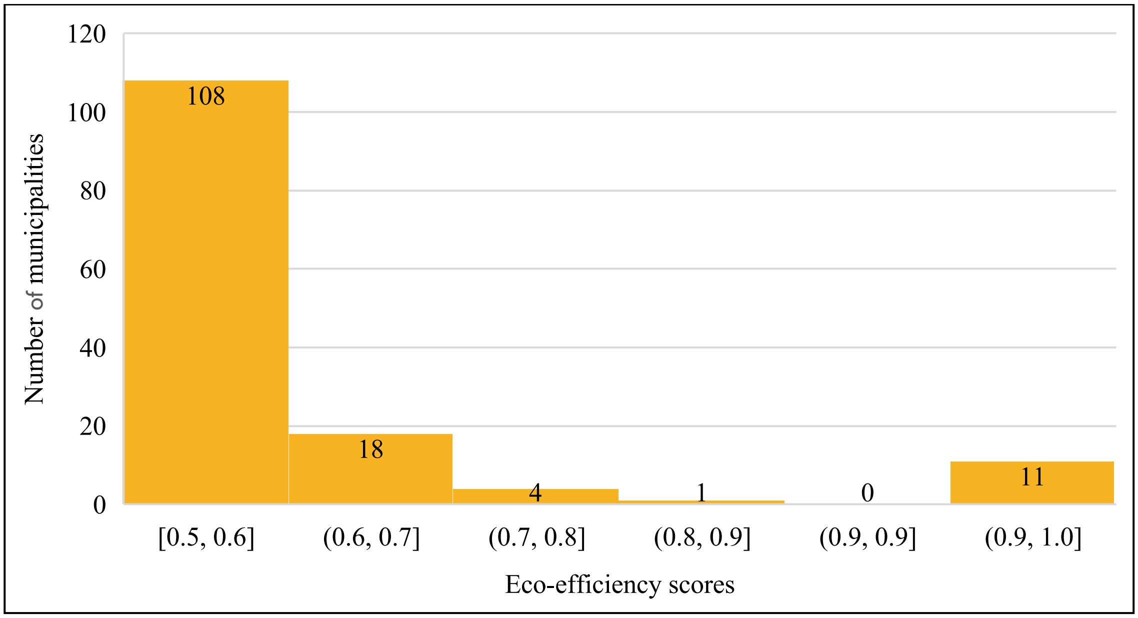

Figure 2-4: Histogram of the eco-efficiency scores of the municipalities evaluated.

Figure 2-5 shows the eco-efficiency scores for the Chilean municipalities evaluated for the northern, central and southern areas of the country. The 11 eco-efficient municipalities are not concentrated in a single area, but they are geographically distributed across Chile. Actually, of the few municipalities evaluated in the northern part of the country, only one of them is eco-efficient. As expected, due to larger number of municipalities evaluated, most of the eco-efficient municipalities (7/11, 63.6%) are located in the central area of Chile; and four of these municipalities belong to the metropolitan area of Santiago. Finally, 2 out of the 11 eco-efficient municipalities are located in the southern area of the country. The geographical and environmental conditions of these eco-efficient municipalities are very variable. For example, the minimum and maximum populations are 880 and 400,869 people, respectively. Hence, it was important to conduct the second stage of analysis to identify potential exogenous factors affecting the eco-efficiency of MSW services.

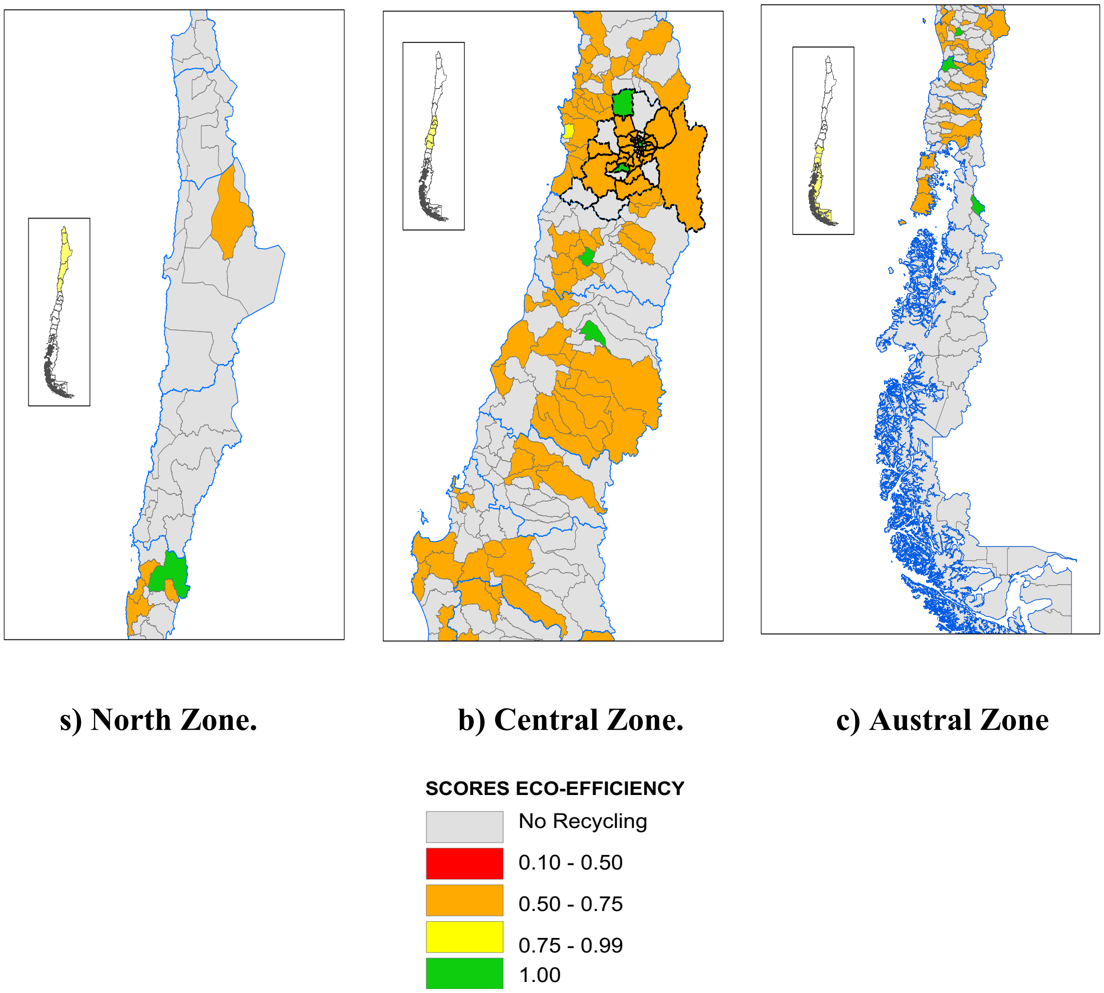

Figure 2-5: Maps of Chilean municipalities and their eco-efficiency scores.

2.3.2 Factors affecting the eco-efficiency of MSW services provided by Chilean municipalities

Once the eco-efficiency scores of the 142 Chilean municipalities evaluated were computed, the exogenous variables were explored as potential determinants of the eco-efficiency scores. Table 2-3 shows the average eco-efficiency scores, the percentage of eco-efficient municipalities and the p-values of the Kruskal–Wallis test for each group of municipalities, according to the five exogenous variables explored. The 142 municipalities were classified into groups according to the average values of each exogenous variable.

First, according to (Sarra et al., 2017; Pérez-Gómez et al., 2018; Romano and Molinos-Senante, 2020), the population of the municipality was investigated as a potential determinant of eco-efficiency of MSW services. Although the average eco-efficiency scores among the three groups of municipalities are small, according to the p-value of the Kruskal–Wallis test, the differences among them are statistically significant. This finding indicates that municipalities with a population greater than 70,000 present an average eco-efficiency score that is larger than that of the medium and small municipalities. This result is consistent with previous research (Carvalho and Marques, 2014; Pérez-López et al., 2018; Romano and Molinos -Senante, 2020), which also concluded that the population served is a determinant of the efficiency of MSW services. Nevertheless, past research also has demonstrated contrary results. For example, (Guerrini et al., 2017) and (Expósito and Velasco, 2018) have found that the size of the served population does not have a significant impact on the eco-efficiency of MSW services provided by a sample of Italian municipalities and Spanish regions, respectively. Regarding the second variable evaluated, municipal size, the p-value of the Kruskal–Wallis test (>0.05) shows that this variable does not have a statistically significant impact on the eco-efficiency of MSW services provided by Chilean municipalities. The average eco-efficiency scores are fairly similar among the three groups of municipalities evaluated. This finding is consistent with the eco-efficiency results reported in section 4.1, revealing that 40.4% of the municipalities evaluated present positive economies of scale, whereas 59.6% of them present negative economies of scale. In other words, the impact of the economy of scale in the provision of MSW services by Chilean municipalities is inconclusive. In contrast, some previous research (e.g., Sarra et al., 2017; Fidelis and Colmenero, 2018) has concluded that the collection area has an impact on the performance of MSW service providers.

Regarding the influence of the population density on eco-efficiency, the results shown in Table 2-3 illustrate that municipalities with a large population density (> 170 people/km^2) are the most eco-efficient. In contrast, municipalities with a moderate-to-low population density present lower average scores of eco-efficiency. The Kruskal–Wallis test led us to reject the hypothesis of equality of means for eco-efficiency with 95% significance based on the three groups, since the p-value was <0.05. This finding indicates that the population density significantly affects the eco-efficiency of MSW services. Similar conclusions have been reported by (Guerrini et al.,

2017) for a sample of Italian municipalities. However, other past research (e.g., Marques and Simoes, 2009; De Jaeger et al., 2011; Expósito and Velasco, 2018) is inconclusive about the impact of the population density on the performance of the MSW service providers.

According to previous studies (e.g., Bosch et al., 2000; García-Sanchez, 2008; Guerrini et al., 2017), the impact of tourism on the eco-efficiency MSW services was investigated. However, the results for the empirical application conducted in this study are divergent from previous ones. In the current study, it was found that municipalities with a higher tourism ranking are the most eco-efficient. The Kruskal–Wallis test results indicate that the differences in the eco-efficiency scores for the three groups of municipalities are statistically significant, demonstrating that tourism has a positive impact on the management of MSW services. It should be noted that in most areas of Chile, tourism is a developing industry and not as advanced as in the case studies analysed by (Guerrini et al., 2017) and (Romano and Molinos-Senante, 2020).

The next factor evaluated in this study was the amount of waste generated per capita. The results listed in Table 2-3 reveal that the largest average eco-efficiency scores correspond to the largest waste production, i.e., the municipalities with waste generation greater than 800 kg per capita per year have higher eco-efficiency scores. The p-value of the Kruskal–Wallis test (<0.05) shows that this variable has a significant effect on the eco-efficiency of the MSW services. This finding illustrates that the fixed costs of managing MSW in Chile are high; therefore, as the amount of waste generated increases, municipalities become more eco-efficient. This is due to the fact that MSW is managed independently by each municipality in Chile. In order to reduce fixed costs and to improve the eco-efficiency of MSW services, it is necessary that municipalities collaborate and develop alliances. Finally, the last external factor evaluated was the annual GDP per capita. Table 2-3 shows that the largest mean eco-efficiency score corresponds to those municipalities with a GDP per capita larger than CLP[5] 100 million per year. The p-value of the Kruskal-Wallis test is 0.03 which reveals that this variable has a significant effect on MSW services' eco-efficiency. This finding evidence that municipalities with larger economic

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[5] On 7th January 2021, US$ 1 = CLP 696 and € 1 = CLP 856

resources can adopt policies to promote waste recycling among their inhabitants. Given that recycling is still incipient in Chile, these policies can be costly and therefore, require significant financial resources. This information is very relevant for policy makers at regional and national level as additional economic resources should be devoted to achieving the goals of the Chilean Recycling Law adopted in 2016.

Table 2-3: Number of municipalities per group, mean eco-efficiency score, % eco-efficient municipalities and p-value for each environmental variable.

Variables	*Number of Municipalities*	*Average eco-efficiency*	*% municipalities eco-efficient*	*p-value*
Population served (Inhabitant)				
< 18,500	46	0.581	11	
18,500-70,000	48	0.563	4	0.018
> 70,000	48	0.598	8	
Municipal size (Km²)				
< 11,200	40	0.579	8	
11,200-18,700	53	0.582	8	0.295
> 18,700	49	0.580	6	
Population Density (Inhabitant/Km²)				
< 30	46	0.578	11	
30-170	48	0.565	4	0.049
> 170	48	0.598	8	
Tourism Ranking				
< 0.0105	46	0.555	7	
0.0105-0.0445	48	0.576	8	0.001
> 0.0445	48	0.609	8	
Waste per capita (Kg waste generated / inhabitant*year)				
< 600	129	0.575	4	
600-800	6	0.535	33	0.040
> 800	7	0.729	57	
Annual per capita gross domestic product (CLP M$)				
< 49	42	0.539	1	
49-100	60	0.579	5	0.003
> 100	39	0.629	5	

2.4 Conclusions

The management of MSW is a basic service provided at the municipal level and is part of the Sustainable Development Goals. In a circular economy context, it is necessary that municipalities evaluate their eco-efficiency in the provision of MSW services. In other words, the assessment of the performance of MSW services should integrate both economic and environmental variables. Moreover, in Latin American countries such as Chile, regulations regarding MSW, and recycling incentives and targets are emerging. Hence, it is relevant to evaluate the presence of economies of scale and exogenous variables affecting the eco-efficiency of MSW services. To shed light on this relevant topic, this study evaluated the eco-efficiency of MSW services provided by a sample of Chilean municipalities using the DEA method. In the performance assessment, the total cost as the input, unsorted waste as an undesirable output and five types of recycled waste as desirable outputs were integrated. The results from the empirical application illustrate that 40.4% of the municipalities evaluated presented negative economies of scale. This finding is very relevant from a policy perspective, since it provides evidence that the current size of the operation of the municipalities is not optimum; therefore, joint organization of systems of MSW management should be promoted. It was also found that the average eco-efficiency score was 0.58 and that 92.3% of the municipalities were not eco-efficient. These results reveal that the management of MSW in Chile has not been addressed from a holistic perspective embracing economic and environmental issues. Thus, the regulator and municipalities need to introduce effective policies to promote the recycling of MSW. Finally, it was demonstrated that 5 out of 6 of the exogenous variables evaluated (population served, population density, tourism, waste generated per capita and annual GDP per capita) significantly affect the eco-efficiency of MSW services.

From a policy perspective, the results of this study are very relevant to support and adopt specific actions by policy-makers. Firstly, it has been evidenced that in most of the cases, the local scale, which is the one adopted in Chile, is not adequate to promote solid waste recycling. In this sense, initiatives at the metropolitan or regional level should be promoted. Secondly, eco-efficient municipalities are heterogeneously distributed through the country which evidences those regional policies have not been adopted yet. This issue is very relevant for a large country like Chile. Moreover, notable differences among neighboring municipalities, in terms of eco-efficiency in the management of MSW, have been revealed.

The identification of factors affecting eco-efficiency scores is also relevant for policy makers. Thus, the fact that municipalities with the largest number of inhabitants are the most eco-efficient supports the need to develop waste management policies on a larger scale than the local one. It has also been evidenced that tourism does not always imply negative impacts from the perspective of waste management, which is associated with educational campaigns and promotion of MSW recycling that should be carried out in all municipalities (not only on those municipalities with more tourism). The identification of annual GDP per capita as a variable affecting the eco-efficiency of municipalities evidences the impact of economic issues on MSW management and also suggests that to improve eco-efficiency, an inter-municipal fund should be created where municipalities with fewer economic resources could receive contributions from the richest ones contributing to enhancing MSW recycling issues across the country.

CHAPTER 3

3. EVALUATION OF THE IMPACT OF SEPARATIVE COLLECTION AND RECYCLING OF MUNICIPAL SOLID WASTE ON PERFORMANCE: AN EMPIRICAL APPLICATION FOR CHILE

3.1. Introduction

In recent years, there has been an increase in the production of municipal solid waste (MSW), which has been linked with the economic development of the countries, population growth and the increase in the density of the urban population (Daskalopoulos et al., 1998). In many countries, the management of MSW has become one of the most serious problems facing modern society (Marques and Simoes, 2009; Di Foggia and Beccarello, 2018). This is one of the reasons why the European Union (EU) has paid considerable attention to waste management policies intending to increase resource efficiency and reduce the negative impact of waste on the environment and the health of citizens. In other words, the EU is promoting the circular economy, defined as "a system where the values of products, materials and resources are kept in the economy for as long as possible and the generation of waste is minimized" (European Commission, 2015) in the framework of waste management. At global level, the importance of MSW management is included within Goal 11 (Sustainable Cities and Communities) of the Sustainable Development Goals (SDG) proposed by the United Nations (2015). As it was evidenced by (Cavaleiro de Ferreira and Fuso-Nerini, 2019) and (Schroeder et al., 2019), the accomplishment of the SDG can be eased by the good practices of circular economy.

Moreover, improving the efficiency in the management of municipal waste services is necessary to reduce its associated costs, provide a better quality of service, comply with the requirements established both worldwide and local and, reduce the fees for citizens (Romano and Molinos-Senante, 2020). The concept of efficiency has been studied and used from an economic perspective to evaluate the performance of units from several topics (Cooper et al., 2011). It is defined as the relation between outputs produced and inputs used by the units (municipalities in this case study) evaluated; it is a relative measure since it compares the performance among the units evaluated. However, as environmental concerns have grown, it has been evidenced the necessity of integrating environmental variables in efficiency assessment (Korhonen and Luptacik, 2004). In this context, it was proposed the concept of eco-efficiency which is defined as the production of more goods (outputs) and services, with fewer resources (inputs) and with less environmental impact (Beltrán-Esteve et al., 2017). The prefix ´eco´ represents the environmental and economic performance, and therefore, the assessment of the eco-efficiency involves considering environmental and economic variables (Gómez et al., 2018).

In the framework of MSW management, previous studies have evaluated the efficiency and eco-efficiency of the provision of municipal waste collection services separately and independently (e.g., Marques and Simoes, 2009; Rogge and De Jaeger, 2012; Pérez-López et al., 2016; Guerrini et al., 2017; Yang et al., 2018). However, to the best of our knowledge, there are no studies where both metrics (efficiency and eco-efficiency) have been compared, which is relevantt to develop public policies in the framework of the circular economy. According to the literature (Guerrini et al. 2017; Sarra et al., 2017; Expósito and Velasco 2017; Agovino et al. 2018; Halkos and Petrou 2019; Romano and Molinos Senante, 2020), some external factors to the management carried out for municipalities, such as are population density, age range, geographical characteristics, amount of waste generated, socioeconomic level, size of the commune, among others, impact on the performance (efficiency) of the provision of municipal waste services. However, since there are no studies comparing efficiency and eco-efficiency metrics in the provision of municipal solid waste service, there is no information about the impact of external factors on efficiency and eco-efficiency differences.

Against this background, the main objective of this work is to evaluate the impact of selective collection and recycling of MSW on the performance of municipalities in the provision of MSW services. In doing so, two synthetic indices such as efficiency and eco-efficiency were estimated and compared. The second objective of this study is to explore the impact of exogenous variables on efficiency and eco-efficiency differences. The empirical application focused on a large sample of Chilean municipalities since recently, the country is doing notable efforts to improve recycling rates of MSW.

The contribution of this research to the literature is the comparison between the concepts of efficiency and eco-efficiency. In doing so, to evaluate eco-efficiency, an undesirable output (unsorted waste) was integrated into the evaluation of the municipalities' performance in the provision of MSW services. This approach makes it possible to estimate eco-efficiency which, unlike the conventional evaluation of efficiency, integrates not only economic but also environmental variables. This topic is very relevant to support the decision-making of municipalities since it provides information on the compensation between the environmental performance of municipalities in the provision of MSW services. Moreover, the identification of factors affecting differences in efficiency and eco-efficiency scores provides relevant information to understand why some municipalities present relevant differences in its performance based on the two metrics considered in the assessment.

3.2. Material and methods

The methodological approach applied in this paper was divided into two stages. First, based on previous research (e.g., Perez-Lopez et al., 2016; Guerrini et al., 2017; Marques et al., 2017; Yang et al., 2018) the efficiency and eco-efficiency of municipalities in the collection and treatment of MSW was evaluated using data envelopment analysis (DEA) method. Both metrics were employed to assess the impact of selective collection and recycling on the performance of municipalities in the provision of MSW services. Second, a non-parametric test was employed to identified exogenous factors affecting differences in efficiency and eco-efficiency scores for each municipality evaluated.

3.2.1 Efficiency and eco-efficiency assessment

Assuming a production process in which, from an input vector $x \in \Re_+^M$, a vector of desirable outputs $y \in \Re_+^S$ results is obtained using the T technology. The set of production possibilities is defined as follows:

$$P(x) = \{(x, y): x\ can\ produce\ y\} \tag{3.1}$$

The input distance function is defined as:

$$D(x, y) = min_{\theta}\{\theta > 0: x\theta\ \in P(x)\} \tag{3.2}$$

Following (Charnes et al., 1978), for each unit j (a municipality in this study), a linear program has to be solved to calculate its efficiency score (see Eq. 3.3). Based on previous studies (e.g., Sarra et al., 2017; Romano and Molinos-Senante, 2020), an input orientation assuming variable returns to scale (VRS) was employed. It should be noted that municipalities cannot directly control the amount of MSW that is generated and therefore, input orientation is more adequate.

$$\begin{aligned}
&Min\ \theta^{VRS} \\
&s.t. \\
&\textstyle\sum_{j=1}^{N} \lambda_j x_{ij} \leq \theta x_{i0} && 1 \leq i \leq M \\
&\textstyle\sum_{j=1}^{N} \lambda_j y_{rj} \geq y_{r0} && 1 \leq r \leq S \\
&\textstyle\sum_{j=1}^{N} \lambda_j = 1 \\
&\lambda_j \geq 0 && 1 \leq j \leq N
\end{aligned} \tag{3.3}$$

where θ^{VRS} indicates the efficiency score of each unit evaluated; M is the number of inputs used; S is the number of outputs generated; N is the number of units analyzed, and λ_j is a set of intensity variables which represent the weighting of each analyzed municipalities j in the composition of the efficient frontier. $\theta^{VRS} \in (0, 1]$ and a unit is efficient if its efficiency score (θ^{VRS}) equals unity, whereas it is inefficient if $0 < \theta \leq 1$.

For evaluating eco-efficiency of municipalities in the provision of MSW services, the following methodology was employed. Assuming a production process where from an input $x\ \in\ \mathfrak{R}_+^N$, a vector of desirable outputs $y\ \in\ \mathfrak{R}_+^M$ and another vector of undesirable outputs $b\ \in\ \mathfrak{R}_+^H$ are obtained using the technology T, the production possibility set of desirable and undesirable outputs is defined as follows:

$$P^{*}(x) = \{(y, b): x\ can\ produce\ (y, b)\} \tag{3.4}$$

The input distance function, including undesirable outputs, is defined as follows:

$$D(x, y, b) = min_{\theta}\{\theta > 0: x\theta\ \in P^{*}(x)\} \tag{3.5}$$

Following (Färe et al., 1994), for each unit j, the linear program to be solved to compute the eco-efficiency scores assuming also input orientation and VRS technology is as follows:

$$
\begin{aligned}
& Min\ \theta^{VRS*} \\
& s.t. \\
& \textstyle\sum_{j=1}^{N} \lambda_j x_{ij} \leq \theta^{*} x_{i0} && 1 \leq i \leq M \\
& \textstyle\sum_{j=1}^{N} \lambda_j y_{rj} \geq y_{r0} && 1 \leq r \leq S \\
& \textstyle\sum_{j=1}^{N} \lambda_j b_{zj} = b_{z0} && 1 \leq z \leq H \\
& \textstyle\sum_{j=1}^{N} \lambda_j = 1 \\
& \lambda_j \geq 0 && 1 \leq j \leq N
\end{aligned}
\tag{3.6}
$$

where θ^{VRS*} indicates the eco-efficiency score of the unit evaluated; M is the number of inputs used; S is the number of desirable outputs generated, H is the number of undesirable outputs involved in the assessment; N is the number of municipalities analyzed, and λ_j is a set of intensity variables which represent the weighting of each analyzed municipalities j in the composition of the efficient frontier. As in the case of efficiency assessment, $\theta^{VRS*} \in (0, 1]$ and a unit is eco-efficientif θ^{VRS*} equals unity, whereas it is inefficient if $0 \leq \theta^{VRS*} < 1$.

A limitation in any DEA model is the number of units (municipalities) analyzed in relation to the number of inputs and outputs considered in the assessment. To avoid relative efficiency discrimination problems, "Cooper's rule" must be meet. This means that the number of units (municipalities) to be evaluated must be greater than or equal to $max\,\{m\,x\,s;\ 3\,(m\ +\ s)\}$ where m is the number of inputs and s is the number of outputs involved in the evaluation (Molinos-Senante et al., 2016). Considering that the evaluated municipalities in this study are 298 and one input and five outputs (desirable and undesirable) were considered, then it is concluded that this study does comply with the Cooper rule.

To evaluate whether the differences between the efficiency and eco-efficiency indices are statistically significant, the non-parametric test of Mann-Whitney test was applied. The null hypothesis (H_0) states that the groups come from the same populations. H_0 can be rejected with a significance level of 95% if the p-value is equal to or less than 0.05, which means that the differences in the efficiency and eco-efficiency scores for the municipalities evaluated are statistically significant.

3.2.2 Factors affecting efficiency and eco-efficiency differences

Eqs (3.3) and (3.6) previously described allowed us to estimate efficiency and eco-efficiency scores in the provision of MSW for each evaluated municipality. However, there are some external factors that might affect the management of MSW, also known as environmental variables, that could impact efficiency and eco-efficiency differences. These factors cannot be considered as inputs or outputs in efficiency and eco-efficiency assessment since they are not directly controllable by the municipalities.

To evaluate the impact of exogenous variables on the performance of units, some previous studies have used parametric methodologies (Fernández-Aracil et al., 2018), that is, econometric models in which the dependent variable is the performance index, and the independent variables are the external factors evaluated. However, this approach presents problems related to multicollinearity (Marques and Simões, 2009) and, therefore, a non-parametric test has also bee be applied (Simões et al., 2010; Simões and Marques, 2012; Díaz-Villavicencio et al., 2017; Romano and Molinos Senante, 2020).

To apply a non-parametric approach, the evaluated municipalities were grouped according to the external factors that could affect their performance, based on previous studies (Guerrini et al., 2017; Sarra et al., 2017; Romano and Molinos-Senante, 2020). Subsequently, the non-parametric Kruskal-Wallis test was employed in which the null hypothesis tested was that the K samples are derived from the same population. The null hypothesis could be rejected at a significance level of 95% when the p-value is less than or equal to 0.05.

The Kruskal Wallis test is given by (Theodorsson-Norheim, 1986):

$$\mathrm{T} = 12/[N\,(N+1)]\sum_{i=1}^{k}\frac{Ri^2}{Ni} - 3(N+1) \tag{3.7}$$

Where: N is the total number of observations; R_i is the rank for an individual sample; K is the number of groups and N_i is the number of observations in group i.

The differences in efficiency and eco-efficiency scores were estimated in relative terms using the following equation:

$$Relative\ difference\ (\%) = \frac{Eco\text{−}efficiency\ score - Efficiency\ score}{Efficiency\ score} * 100 \tag{3.8}$$

3.2.3 Sample Description

The sample used for this empirical application corresponds to 298 out of 345 Chilean municipalities, considering 2018 as a case study. These 298 municipalities involve 14,716,132 inhabitants of a total population of 18,729,160 (79%) people in Chile (Census of Chile, 2017).

Based on previous research on the performance of waste service management (Marques and Simoes, 2009; Simoes et al., 2010; Expósito and Velasco, 2018; Romano et al., 2019), the total annual cost of MSW provision services of each municipality was integrated into the efficiency and eco-efficiency evaluation as an input. Information on MSW management is available in the database of the National Waste Declaration System (SINADER, acronym in Spanish), corresponding to the year 2018. Recyclable waste (Tons/year) were integrated as desirable outputs and are classified into: i) paper and cardboard, ii) glass, iii) plastic, iv) organic waste (Villavicencio et al., 2017; Romano and Molinos-Senante et al., 2020). While for the eco-efficiency evaluation, ursorted waste (Tons/year) was included as undesirable output (see Tables 3-1 and 3-2).

To select the exogenous variables that might affect efficiency and eco-efficiency differences, three criteria were considered: i) the characteristics of the MSW sector in Chile, ii) the information available for the evaluated municipalities and iii) the existing literature (e.g., Sarra et al. al., 2017; Calabro and Komilis, 2019; Romano and Molinos-Senante, 2020). According to these criteria, the following variables were considered: i) the urban population, which is defined as the total number of the communal urban population; ii) the size of the municipality, expressed in km^2. It should be noted that this variable does not involve all area of the municipality but focuses on the urban area where MSW services are provided; iii) population density, which is expressed as the number of inhabitants per km^2 of urban area of the municipality; iv) the tourism index proposed by the Division of Studies and Territory of the Undersecretariat of Tourism (Sernatur, for its acronym in Spanish) which embraces s 15 variables and; v) the amount of waste generated per capita which was estimated as the relationship between the kg of waste generated and the number of inhabitants of each municipality.

The main statistical variables to estimate the efficiency and eco-efficiency scores of Chilean municipalities and the exogenous variables analysed are shown in Table 3-1 and Table 3-2.

Table 3-1: Variables used as inputs and outputs to evaluate efficiency and eco-efficiency of municipalities in MSW management.

Efficiency Assessment	***Eco-efficiency Assessment***
Inputs: i) total costs of MSW collection and disposal (CLP/year)	**Inputs:** i) total costs of MSW collection and disposal (CLP/year)
Output: i) quantity of MSW collected and disposed (ton/year)	**Desirable Outputs:** i) quantity of paper collected and recycled (ton/year); ii) quantity of glass collected and recycled (ton/year); iii) quantity of plastic collected ar recycled (ton/year); iv) quantity of organic matter collected and recycled (ton/year).
	Undesirable Output: unsorted waste (ton/year)

Table 3-2: Basic statistics of the variables considered to evaluate efficiency and eco-efficiency.

	Variables	*Unit of measure*	*Average*	*Standard Deviation*	*Minimum*	*Maximum*
Input	Total costs	CLP/year	1,173,068	2,051,970	98	14,765,504
Desirable output	Paper recycled	Tons/year	51	389	0	6,023
	Glass recycled	Tons/year	89	302	0	2,759
	Plastics recycled	Tons/year	15	114	0	1,842
	Organic waste recycled	Tons/year	88	803	0	13,089
Undesirable Outputs	Unsorted waste	Tons/year	25,967	43,074	3	360,451
Environmental Variables	Population Density	Inhabit./Km^2	1,117	3,272	0	18,221
	Municipality size	Km^2	1,831	4,747	7	49,924
	Population Served	Inhabitants	49,383	87,729	633	568,094
	Tourism Index	-	0.048	0.107	0.000	1.000
	Annual waste generated per capita	Kg/Inhabit*year	1,240	10,192	0,430	176,500

3. 3 Results and Discussion

3.3.1 Efficiency and eco-efficiency estimation

The efficiency and eco-efficiency scores of the 298 Chilean municipalities were estimated using Eqs. (3.3) and (3.6), respectively. Table 3-3 shows the main statistical characteristics of the results. The complete sample of Chilean municipalities illustrated that when the efficiency evaluation excludes separate waste collection (recycling), the mean efficiency score was 0.26. This means that, on average, the evaluated municipalities could reduce their inputs (total costs) by 74% if they were operated as efficient municipalities. In this scenario, only 14 out of the 298 municipalities were efficient, which corresponds to 4.70% of them. In a very similar way, when the selective collection and recycling of MSW was integrated into the evaluation, the number of eco-efficient municipalities is 13 which represents 4.36% of the sample. By contrast, the mean eco-efficiency score increased to 0.54. This finding means that municipalities perform better when the evaluation integrates the collection and recycling of MSW. This finding evidence that, on average, municipalities are making economic efforts to increase the percentage of selective waste collection and recycling.

Table 3-3: Main statistics of the efficiency and eco-efficiency scores of the Chilean municipalities evaluated.

Metric	***Efficiency score (θ^{VRS})***	***Eco-efficiency score (θ^{VRS*})***
Average	0.26	0.54
Standard deviation	0.23	0.11
Maximum	1.00	1.00
Minimum	0.00	0.50
Efficient municipalities (%)	4.70	4.36
Inefficient municipalities (%)	95.30	96.64

The histogram in Figure 3-1 shows the distribution of the efficiency and eco-efficiency scores of the 298 Chilean municipalities evaluated. When comparing the efficiency and eco-efficiency scores, the impact of selective collection and recycling on the performance of municipalities is verified as the p-value of the Mann-Whitney test was lower than 0.05. It is illustrated that most of the municipalities, that is, 181 out of 248 (73%) have a poor performance since their efficiency scores are lower than 0.2, this implies that these municipalities can save around 80% of their operating costs if they are managed more efficiently. On the other hand, 261 municipalities presented eco-efficiency scores between 0.4 and 0.6; that is, in some cases, there is more than a 50% improvement in their costs, also considering non-recycled waste.

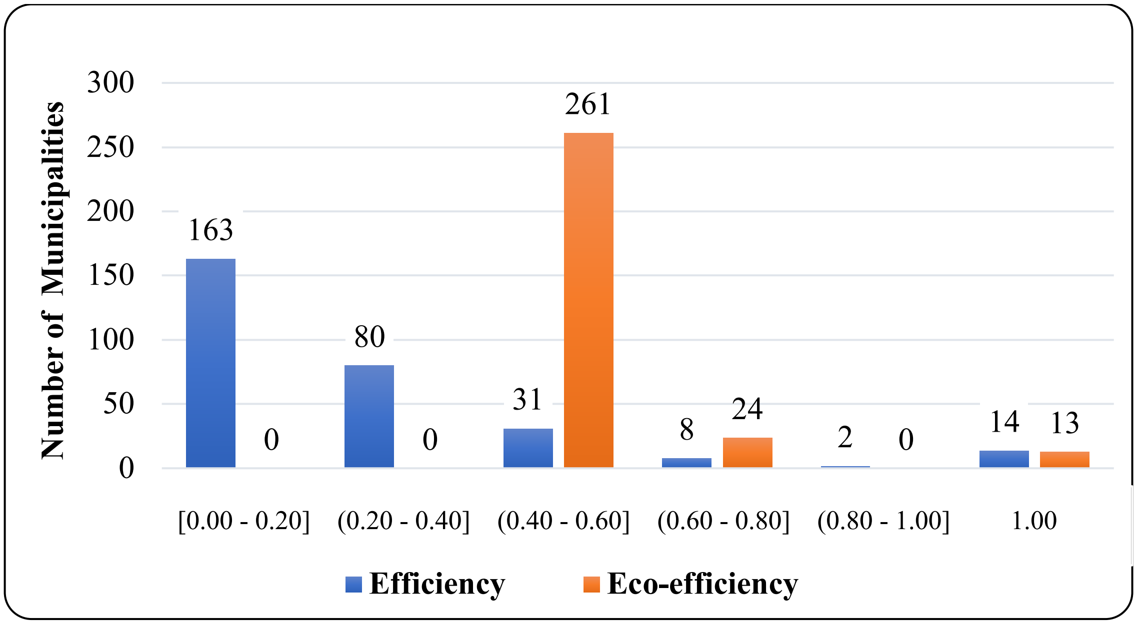

Figure 3-1: Histogram of the efficiency and eco-efficiency scores of the Chilean municipalities evaluated.

To further analyze the difference between efficiency and eco-efficiency scores, the histogram shown in Figure 3-2 illustrates that 112 municipalities have an eco-efficiency and efficiency difference between 0.40 and 0.50. This positive value means that municipalities have better performance when the assessment differentiates desirable and undesirable outputs, i.e., recycled and unsorted waste.

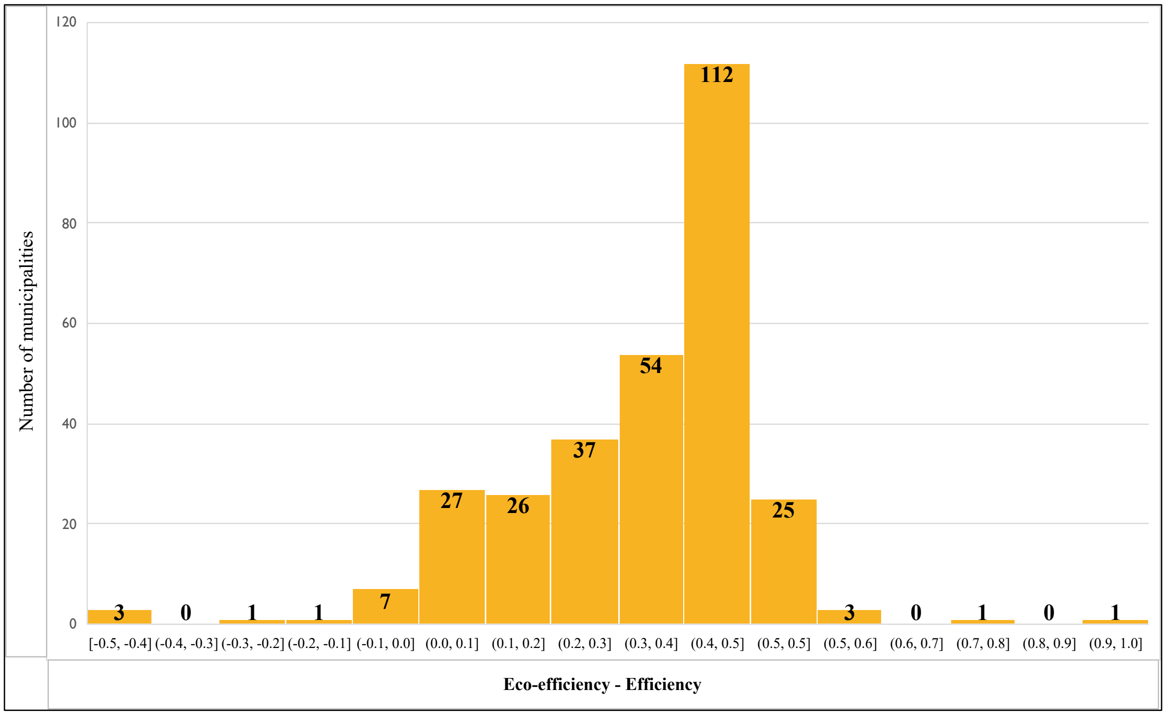

Figure 3-2: Histogram of difference between eco-efficiency and efficiency scores Chilean municipalities evaluated.

As Chile is a long and narrow country, efficiency and eco-efficiency scores were also reported geographically as it is illustrated on Figures 3-3 and 3-4. Both maps show the ranges of the performance (efficiency and eco-efficiency scores) of the Chilean municipalities in the provision of MSW services. Those municipalities whose efficiency (eco-efficiency) score was less than 0.5 are in red colour; those whose efficiency (eco-efficiency) score ranges between 0.50 and 0.75 are in orange colour; those whose efficiency (eco-efficiency) score ranges between 0.75 and 1.0 are in yellow color and finally, those municipalities efficient (eco-efficient), i.e., efficiency (eco-efficiency) score equal to 1.0, are in green color. Figure 3-3 shows that efficient municipalities in the provision of MSW services are distributed in different regions across the country. This indicates that the geographical factor is not so determinant in the efficiency of the municipalities in the provision of MSW services. It should also be noted that in the area of the Metropolitan Region of Santiago, the capital of Chile, lives a population of around 7,037 million (40% approx of the total population of the country), municipalities with the diversity of efficiency were found, which clearly shows the lack of collaboration between municipalities and absence of a standard regional policy.

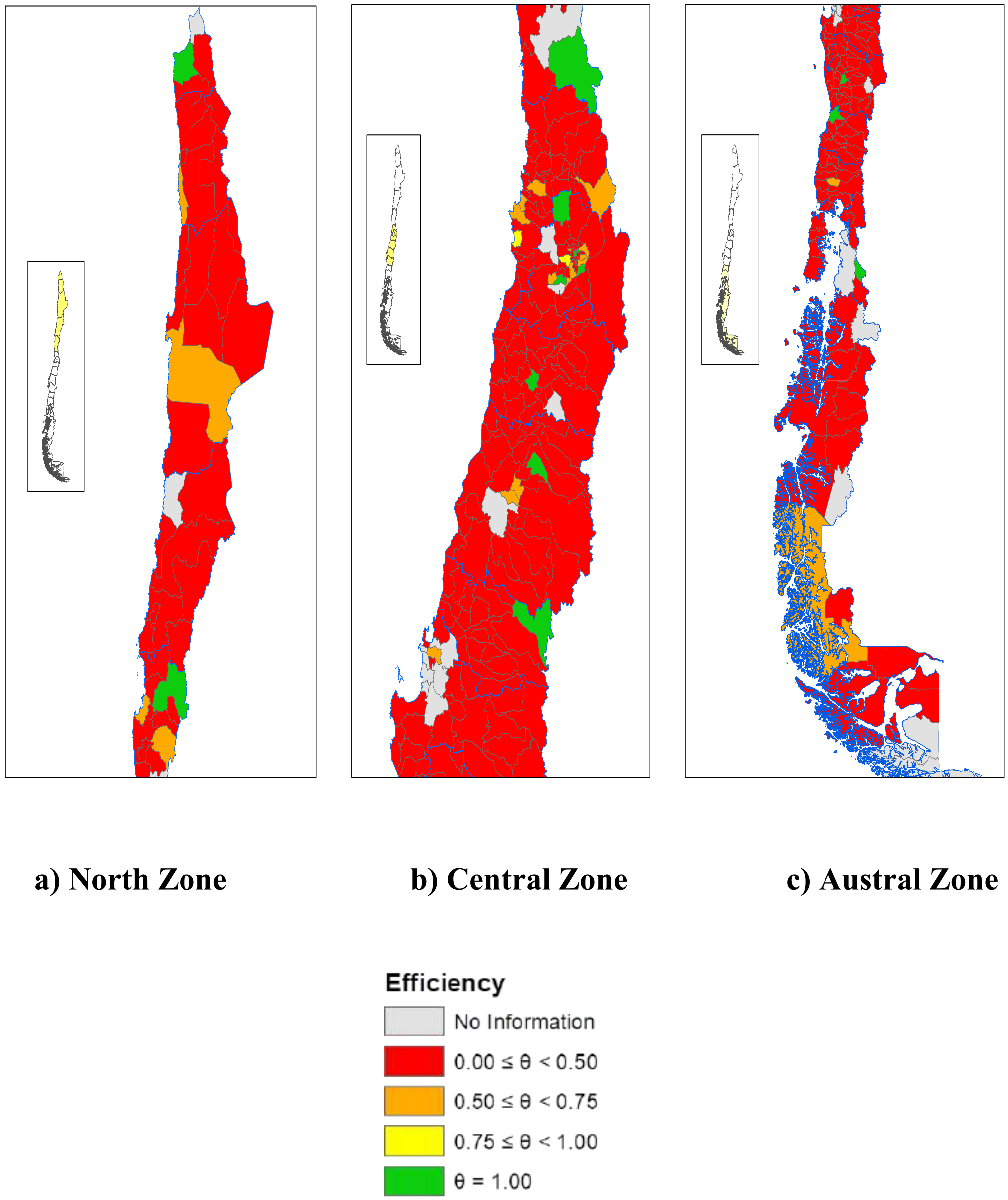

Figure 3-3: Efficiency scores for each Chilean municipality evaluated.

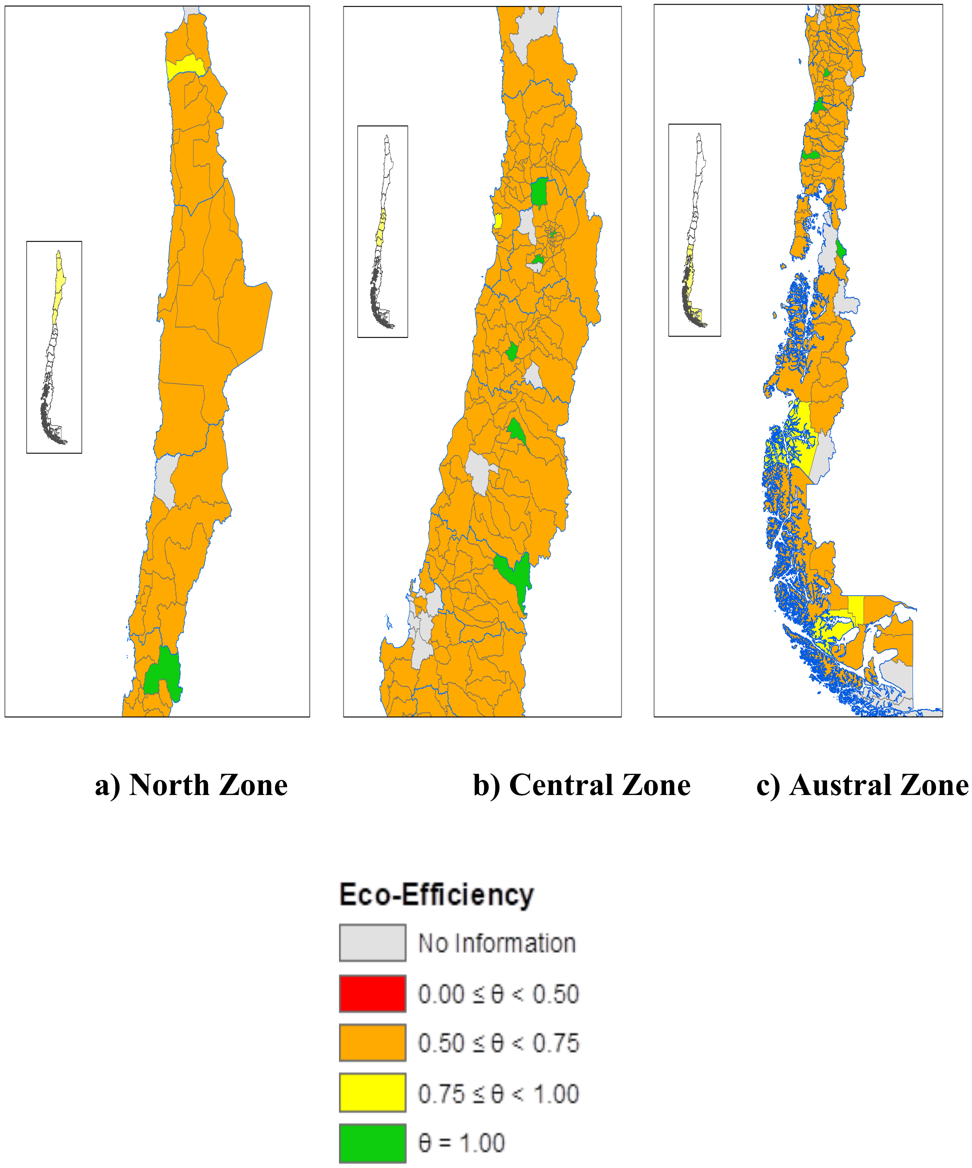

Figure 3-4: Eco-efficiency scores for each Chilean municipality evaluated.

Figure 3-4 shows that the municipalities that are eco-efficient are different from the ones that are identified as efficient (see Figure 3-3). It involves that some municipalities have focused on reducing the operational costs of MSW management whereas other municipalities have also make notable efforts to increase the amount of recycled waste. In this context, it should be noted that from the legal point of view, in Chile, since 2016, the Law 20.920 establishes the framework for waste management, the extended responsibility of the producer and promotion of recycling, which seeks to reduce the generation of waste, increase the recovery, reuse and recycling and protect health human and environmental. This law obliges producers to be responsible for the processing and valorization of the product, granting municipalities the power to establish agreements with management systems and with grassroots recyclers, the obligation to incorporate separation at source in their municipal ordinances, implement communication and awareness strategies, handle permit applications for storage facilities and promote environmental education. However, in the face of all political efforts, this has led to each municipality taking charge of its management, thus bringing differences in the quality of the service, little effectiveness in the MSW collection services, since this is carried out the house by home and not from a specific point. Besides, Chile is the second country that most sends garbage to landfills among the 34 countries that make up the Organization for Economic Cooperation and Development (OECD).

To better visualize efficiency and eco-efficiency scores, Figure 3-5 shows that most of the evaluated municipalities are in green colour which means they present larger eco-efficiency scores than efficiency ones. This may be mainly because municipalities have developed environmental management tools or incorporated "green practices" in their internal processes. Due to efficiency and eco-efficiency differences observed, this study also evaluated the external factors that may be affect them in the subsequently section.

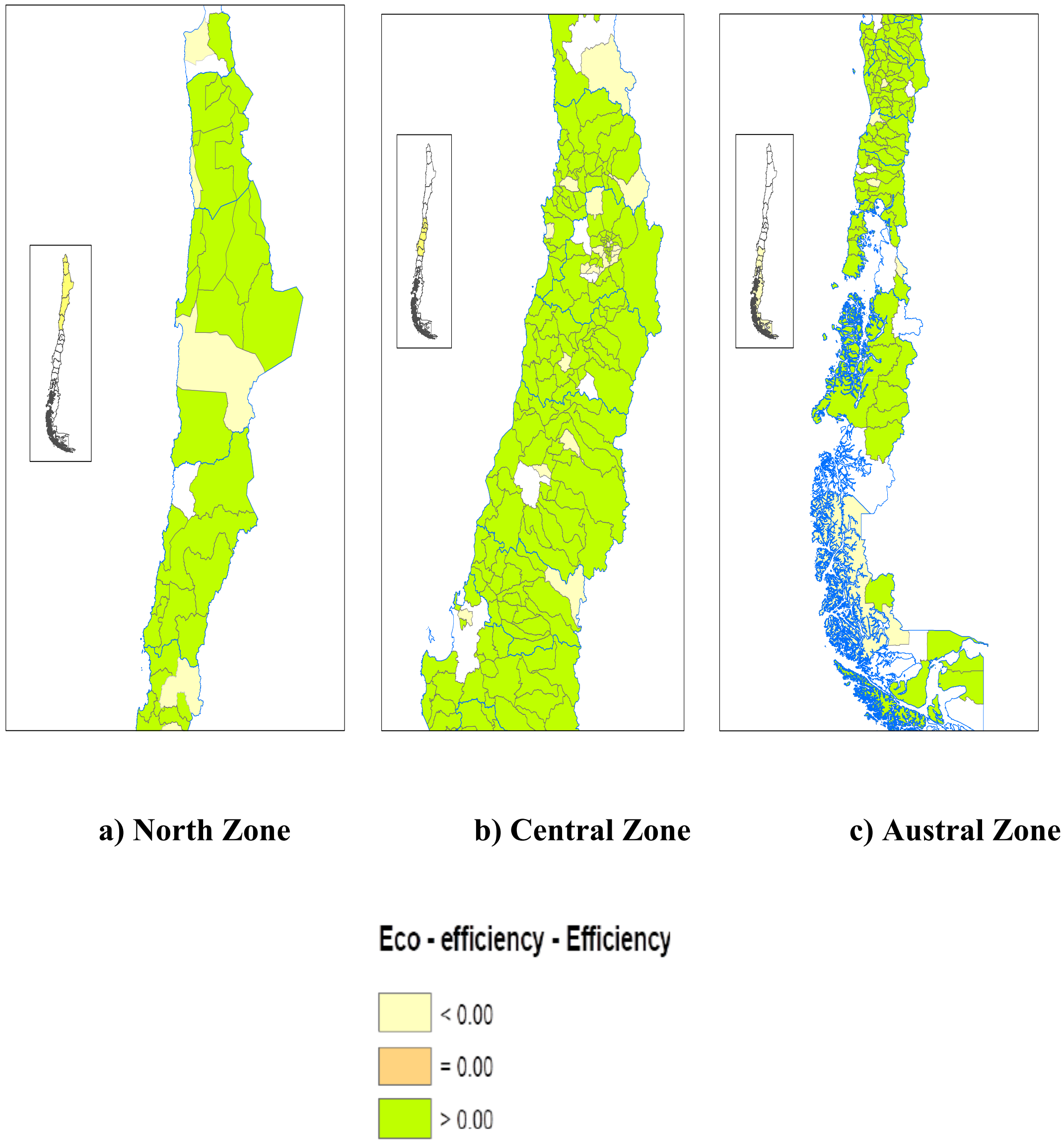

Figure 3-5: Differences in eco-efficiency and efficiency scores for the Chilean municipalities evaluated.

3.3.2 Factors affecting differences between efficiency and eco-efficiency sores

Previous studies by the authors (Sarra et al., 2017), (Pérez-Gómez et al., 2018) and (Romano and Molinos-Senante, 2020) investigated external factors affecting the eco-efficiency of municipalities in the provision of MSW services. Taken into account the main objective of this study, i.e., evaluating the impact of separative collection and recycling on the performance of

MSW service providers, we focused on assessing the impact of exogenous variables on the difference of efficiency and eco-efficiency scores measured as relative difference (Eq. 3-8). Results of the Kruskal-Wallis tests conducted are shown in Table 3-4.
Regarding the variable number of inhabitants, Table 3-4 shows that for populations between 3,100 and 10,900 inhabitants, the differences between efficiency and eco-efficiency scores are the highest. In contrast, for larger municipalities, the differences both indices are not so relevant. Results from the Kruskal-Wallis test revealed that population served has a statistically significant impact on the difference between efficiency and eco-efficiency scores of MSW services provided by Chilean municipalities. This finding means that as the size of the population increases (in terms of population served) differences in the economic and joint economic and environmental performance are not so relevant.

Focusing on the size of the municipality, expressed in km^2, the p-value of the Kruskal-Wallis test (> 0.05) did not allowed us to reject the null hypothesis which involves that this variable does not have a statistically significant impact on efficiency and eco-efficiency differences. It involves that the size of the municipality does not impact on the differences between efficiency and eco-efficiency scores. However, Table 3-4 shows that the largest municipalities have a greater difference between the efficiency and eco-efficiency indices, which may be due to the difficulty in establishing green points to collect recyclable wastes.

The third variable evaluated was the population density. The null hypothesis is that this variable does not impact on efficiency and eco-efficiency differences. However, the results of the Kruskal-Wallis test illustrated that the null hypothesis should be rejected since the p-value is < 0.050, which means that population density significantly affects difference between efficiency and eco-efficiency scores. Population density plays an important role as an exogenous variable. The results obtained in this work are congruent with recent studies carried out by (Sarra et al., 2020), where they concluded that this external variable negatively affects efficiency, which may be mainly due to the complex intra-municipal organization, regulation and control from service. Even more so in this case where each municipality carries out its management of waste collection services.

Regarding tourism, Table 3-4 shows the differences between efficiency and eco-efficiency scores are statistically significant (p-value = 0.002) which indicates that this exogenous variable impacts on waste management at the municipal level. In particular, larger differences among both metrics (efficiency and eco-efficiency) were reported for municipalities with a moderate tourism. By contrast, the municipalities with the largest tourism index lower differences between efficiency and eco-efficiency scores. Previous studies such as those carried out by (Guerrini et al., 2017) and (Romano and Molinos-Senante, 2020) concluded that tourism might impact on MSW management because the excess of waste generation in high tourism seasons is not collected or managed efficiently.

Finally, the last factor evaluated in this study was the amount of waste generated per capita. The p-value results of the Kruskal-Wallis test (<0.05) reveal that this exogenous factor does significantly affects the efficiency and eco-efficiency differences in the management of MSW. Table 4 also shows that larger differences are observed for those municipalities whose citizens produce small amount of waste (less than 405 Kg per inhabitant and year) which facilitates the recycling of MSW.

Table 3-4: Number of municipalities per group, average relative difference between efficiency and eco-efficiency scores and p-value for each environmental variable.

	Number of Municipalities	*Average Relative Difference (%)*	*p-value of Kruskal-Wallis*
Population Served (Inhabitant)			
< 3,100	35	1,079	0.000
3,100-10,900	95	11,994	
10,901-13,500	26	402	
> 13,500	142	116	
Municipal size (Km²)			
< 248	79	186	0.448
240-420	36	346	
420-600	40	383	
> 600	143	8,124	
Population Density (Inhabitant/Km²)			
< 4	24	1,096	0.002
4 - 48	154	7,534	
48 - 11,000	108	159	
> 11,000	12	40	
Tourism Ranking			
< 0.10	67	661	0.002
0.10-0.59	155	7,419	
0.59-0.87	40	164	
> 0.87	36	93	
Kg waste generated/ Nº of inhabitants (Kg waste generated / inhabitant*year)			
< 405	44	25,897	0.000
405 - 510	72	231	
510 - 1210	161	268	
> 1210	21	232	

3.4. Conclusions

The importance of MSW management is explained by the fact that it is an essential service that is directly related to the environment and public health; therefore, it must be approached in an interdisciplinary way. This study analyzed the impact of selective collection and recycling of MSW on the waste management performance of municipalities by evaluating and comparing the efficiency and eco-efficiency scores for an empirical sample of 298 municipalities in Chile.

The results from the empirical application illustrate that the selective collection and recycling of MSW had an impact on the performance of municipalities from a statistical point of view. Both metrics (efficiency and eco-efficiency) employed in this study demonstrated the low performance of Chilean municipalities in the provision of MSW services. The percentage of inefficient municipalities was determined to be 95.30% and 96.64%, according to the efficiency and eco-efficiency scores, respectively. These results reveal that the municipalities must improve their management significantly. Moreover, this study shows that efficient and eco-efficient municipalities are not the same; for example, some of them focus on economic issues, whereas others are managed according to both economic and environmental issues. From a geographical point of view, the findings indicate the lack of cooperation in the management of MSW among nearby municipalities, which present very divergent efficiency and eco-efficiency scores. Thus, a regional policy needs to be implemented in order to improve the management of MSW services in Chile. Finally, some exogenous variables, such as the population served, population density, tourism and waste generated per capita, were shown to have a significant impact on the differences between the efficiency and eco-efficiency scores. This information is very relevant for policy makers who aim to improve not just efficiency but also eco-efficiency in the provision of MSW services.

From a political perspective, the results of this study are very relevant to supporting and adopting specific actions by policy makers. Firstly, the few municipalities identified as eco-efficient should be considered as examples for the other municipalities and therefore, the actions and policies implemented by eco-efficient municipalities should be monitored, collected and disseminated to the rest of Chilean municipalities to improve their eco-efficiency. Another strategy for improving the eco-efficiency of municipalities in the provision of MSW would be the promotion of environmental education at the local level, in schools and non-profit institutions. Additionally, the generation of alliances with the private sector for funding installations and specific measures for MSW recycling would help improve the eco-efficiency of municipalities.

CHAPTER 4

4. ASSESSING ECO-PRODUCTIVITY CHANGE IN CHILEAN MUNICIPAL SOLID WASTE SERVICES

4.1. Introduction

Recently, significant changes have transpired in the management of municipal solid waste (MSW), mainly due to demographic evolution and the economic growth of countries, which have a direct impact on the environment, public health, and municipal welfare (Guerrini et al., 2017; Romano et al., 2020). The significant increase in the generation of MSW has become one of the most severe problems in today's world. As a result, the United Nations has recognized the importance of improving MSW management through Goals 11 and 12 of the Sustainable Development Goals (United Nations, 2015; Di Foggia and Beccarello, 2018; Llanquileo-Melgarejo et al., 2021; Lombardi et al., 2021). In this context, the circular economy defined "as a system where the values of products, materials and resources are kept in the economy for as long as possible, thus minimizing the generation of waste" (European Commission 2015; European Commission, 2018a, 2018b), national has been identified as an example of efficiently promoting improvements in MSW management.

Because MSW management significantly impacts the environment, public health, and municipal well-being, the efficiency achieved in the provision of this service is extremely relevant (Simoes and Marques, 2012; Agovino et al., 2016; Guerrini et al., 2017; Magrini et al., 2021; Amaral et al., 2022). Efficiency is defined as the relationship between the products produced and inputs used by the units analyzed (in this case, solid waste service providers). Efficiency assessment is a relative measure because it compares the performance of the evaluated units (Korhonen and Luptacik, 2004). Most studies that evaluated the efficiency of municipalities in the provision of MSW services employ economic variables as inputs and waste generated as outputs and sought to assess the economic efficiency of municipalities (Rogge and De Jaeger, 2013; Perez-Lopez et al., 2016; Halkos and Petrou, 2019; Romano et al., 2020; Fan et al., 2015). However, because of the increase in environmental concerns, the concept of eco-efficiency was proposed, where the prefix ´eco` represents environmental and economic performance (Gómez et al., 2018). Eco-efficiency is defined as the production of more goods (products) and services with fewer resources (inputs) and less environmental impact (Beltrán-Esteve et al., 2017). Given the relevance of the circular economy and the recycling of MSW, studies that aim to evaluate the eco-efficiency of waste service providers have been increasing (Díaz-Villavicencio et al., 2017; Sarra et al., 2017, 2019, 2020; Guerrini et al., 2017; Expósito and Velasco, 2018; Romano et al., 2019; Romano and Molinos-Senante, 2020; Llanquileo-Melgarejo and Molinos-Senante, 2021; Llanquileo-Melgarejo et al., 2021; Delgado-Antequera et al., 2021; Lo Storto, 2021).

Of note, eco-efficiency provides a static evaluation of the performance of the units analyzed. Accordingly, eco-efficiency evaluates the performance of units at a given timepoint without considering the potential changes within them over time (Kortelainen, 2007; Pérez-López et al., 2021). 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 setting (Yang et al., 2018; Lo Storto, 2021). The ability to assess changes in eco-productivity over time not only allows one to compare the economic and environmental performances among units (Al-Refaie et al., 2016), but also enables on to determine whether they have improved or worsened over a given period of time. 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 municipalities in the provision of MSW services.

Therefore, to overcome this gap in the literature, the main objective of this study was to evaluate the performance over time (i.e., eco-productivity change) of a representative sample of Chilean municipalities (91%) that provide MSW services focusing on recycling activities[6]. Chile is an interesting example because, unlike European countries, waste management policies to promote sustainability and circular economy are relatively new in most Latin American countries. The second objective of this study was to explore the impact of external factors that could affect the

[6] Circular Economy involves reusing, repairing, renovating and recycling all types of waste: unsorted and selective waste. In this context, this study focused on the eco-efficiency of municipalities related to recycling of solid waste.

eco-productivity change of municipalities in the provision of MSW services. Currently, the literature is inconclusive about the impact of external factors on the performance of waste service providers (García-Sánchez, 2008; Benito-López et al., 2011; Boetti et al., 2012; Romano and Molinos-Senante, 2020; Llanquileo- Melgarejo and Molinos-Senante, 2021; Llanquileo-Melgarejo et al., 2021; Delgado-Antequera et al., 2021; Lo Storto., 2021). Therefore, an in-depth analysis of the relevant factors and their change over time should be conducted.

4.2. Material and Methods

From a methodological viewpoint, our analysis was divided into two steps. First, the change in eco-productivity of Chilean municipalities in the provision of MSW services was evaluated using the Malmquist-Luenberger Productivity Index (MLPI) (Chung et al., 1997). It should be noted that there are different indicators and indices to evaluate dynamic performance of units such as the Malmquist Productivity Index and the Luenberger Productivity Indicator. However, their estimation is based on inputs and desirable outputs (Molinos-Senante and Sala-Garrido, 2015). Considering that we are interested in evaluating the eco-productivity change of municipalities taken into account both unsorted waste and recycled waste, the MLPI was selected. MLPI is a radial data envelopment analysis (DEA) approach that provides an eco-productivity change score for each of the analyzed municipality based on recyclable waste, unsorted waste, and costs as desirable outputs and undesirable outputs and inputs, respectively. Second, the influence of exogenous factors on Chilean municipalities' eco-productivity change was determined using a non-parametric hypothesis method, such as the Kruskal-Wallis test.

4.2.1 Eco-productivity change estimation: MLPI

The assessment of the eco-productivity change of municipalities in the provision of MSW services was based on the MLPI estimation presented by (Chung et al., 1997). This approach uses a directional distance function that has the following merits: i) it seeks to increase the desirable outputs while decreasing the undesirable outputs; ii) it prevents the computational problems associated with the calculation of output efficiency as a solution to nonlinear programming problems; and iii) it avoids the occurrence of ill-defined solutions when the mixed-period distance function is computed (Chen et al., 2007).

The notation to estimate eco-productivity change of the municipalities is as follows:

$x \in N_+^N$: Vector of inputs

$y \in N_+^M$: Vector of desirable outputs

$b \in N_+^l$: Vector of undesirable outputs

t : Time. First year of study

$t+1$: Time. Last year of study

The directional distance function, including undesirable outputs, is defined as:

$$\overrightarrow{D_o}(x, y, b; g) = \quad sup\,\{\beta : (y, b) + \beta g \in P(x)\} \tag{4.1}$$

where g is the vector of the directions in which the outputs are scaled. $g = (g^y, -g^b)$ represents $g^y \in R_+^M$ and $g^b \in R_+^l$. In this case, $g = (1, -1)$, which involves an increase in the desirable outputs and a decrease in the undesirable outputs.

Considering $t = 1, \dots, T$ time periods, the MLPI is defined as:

$$MLPI_t^{t+1} = \left[\frac{\left(1+\underline{D}_0^t(x^t, y^t,\ b^t; g^t)\right)}{\left(1+\underline{D}_0^t(x^{t+1}, y^{t+1},\ b^{t+1}; g^{t+1})\right)} * \frac{\left(1+\underline{D}_0^{t+1}(x^t, y^t,\ b^t; g^t)\right)}{\left(1+\underline{D}_0^{t+1}(x^{t+1}, y^{t+1},\ b^{t+1}; g^{t+1})\right)} \right]^{\frac{1}{2}} \tag{4.2}$$

The MLPI may be disintegrated into two components: the efficiency change (MLECH) and the technical change (MLTCH). The main advantage of such decomposition is the identification of drivers that contribute the most to the eco-productivity change (positive or negative) of each municipality. The first term, MLECH, represents the component of efficiency change, a movement toward the frontier of best practices (Kumar, 2006). This component is related to the ability of the units to be managed according to the best operating practices. Therefore, the change in efficiency is known as the catch-up index (Maziotis et al., 2017). In contrast, the MLTECH component measures the change in the efficient frontier between two periods (Arabi et al., 2014). The measurement of these components is essential for effective long-term strategic planning.

MLPI is decomposed into MLECH and MLTCH as follows (Ananda, 2018):

$$MLECH_t^{t+1} = [\frac{(1+D_0^t(x^t,y^t,\ b^t;g^t)}{(1+D_0^t(x^{t+1},y^{t+1},\ b^{t+1};g^{t+1})} * \frac{(1+D_0^{t+1}(x^t,y^t,\ b^t;g^t)}{(1+D_0^{t+1}(x^{t+1},y^{t+1},\ b^{t+1};g^{t+1})}]^{1/2} \quad (4.3)$$

$$MLTCH_t^{t+1} = [\frac{(1+D_0^{t+1}(x^t,y^t,\ b^t;g^t)}{(1+D_0^t(x^t,y^t,\ b^t;g^t)} * \frac{(1+D_0^{t+1}(x^{t+1},y^{t+1},\ b^{t+1};g^{t+1})}{(1+D_0^{t+1}(x^{t+1},y^{t+1},\ b^{t+1};g^{t+1})}]^{1/2} \quad (4.4)$$

A municipality has improved its eco-productivity in the provision of MSW services if MLPI >1; however, worsening of the eco-productivity is indicated by an MLPI <1. An MLPI =1 indicates that the productivity is unchanged. For the components of the MLPI (i.e., MLECH and MLTCH), the same interpretation applies (Maziotis et al., 2017).

Based on the definition of the MLPI (Eq. 4.2), four linear programming problems must be solved for each unit (municipality) to compute this index (4.5 – 4.8):

$$\begin{aligned}
&\overline{D}_0^t(x_{k'}^t, y_{k'}^t, b_{k'}^t; g_{k'}^t) = Max\ \beta \\
&s.t.: \\
&\textstyle\sum_{k=1}^K \lambda_k^t y_{km}^t \geq (1+\beta) y_{k'm}^t \qquad m = 1,2,\dots,M \\
&\textstyle\sum_{k=1}^K \lambda_k^t b_{ki}^t = (1-\beta) b_{k'i}^t \qquad i = 1,2,\dots,I \\
&\textstyle\sum_{k=1}^K \lambda_k^t x_{kn}^t \leq x_{k'n}^t \qquad n = 1,2,\dots,N \\
&\lambda_k^t \geq 0 \qquad k = 1,2,\dots,K
\end{aligned} \quad (4.5)$$

$$\begin{aligned}
&\overline{D}_0^{t+1}\left(x_{k'}^{t+1}, y_{k'}^{t+1}, b_{k'}^{t+1}; g_{k'}^t\right) = Max\ \beta \\
&s.t.: \\
&\textstyle\sum_{k=1}^K \lambda_k^{t+1} y_{km}^{t+1} \geq (1+\beta) y_{k'm}^{t+1} \qquad m = 1,2,\dots,M \\
&\textstyle\sum_{k=1}^K \lambda_k^{t+1} b_{ki}^{t+1} = (1-\beta) b_{k'i}^{t+1} \qquad i = 1,2,\dots,I \\
&\textstyle\sum_{k=1}^K \lambda_k^{t+1} x_{kn}^{t+1} \leq x_{k'n}^{t+1} \qquad n = 1,2,\dots,N \\
&\lambda_k^{t+1} \geq 0 \qquad k = 1,2,\dots,K
\end{aligned} \quad (4.6)$$

$$\overline{D}_0^{t+1}(x_{k'}^t, y_{k'}^t, b_{k'}^t; g_{k'}^t) = Max\,\beta$$
$$s.t.:$$
$$\sum_{k=1}^{K} \lambda_k^{t+1} y_{km}^{t+1} \geq (1+\beta) y_{k'm}^t \quad m = 1, 2, \ldots, M$$
$$\sum_{k=1}^{K} \lambda_k^{t+1} b_{ki}^{t+1} = (1-\beta) b_{k'i}^t \quad i = 1, 2, \ldots, I \tag{4.7}$$
$$\sum_{k=1}^{K} \lambda_k^{t+1} x_{kn}^{t+1} \leq x_{k'n}^t \quad n = 1, 2, \ldots, N$$
$$\lambda_k^{t+1} \geq 0 \quad k = 1, 2, \ldots, K$$

$$\overline{D}_0^{t}\left(x_{k'}^{t+1}, y_{k'}^{t+1}, b_{k'}^{t+1}; g_{k'}^t\right) = Max\,\beta$$
$$s.t.:$$
$$\sum_{k=1}^{K} \lambda_k^{t} y_{km}^{t} \geq (1+\beta) y_{k'm}^{t+1} \quad m = 1, 2, \ldots, M$$
$$\sum_{k=1}^{K} \lambda_k^{t} b_{ki}^{t} = (1-\beta) b_{k'i}^{t+1} \quad i = 1, 2, \ldots, I \tag{4.8}$$
$$\sum_{k=1}^{K} \lambda_k^{t} x_{kn}^{t} \leq x_{k'n}^{t+1} \quad n = 1, 2, \ldots, N$$
$$\lambda_k^{t} \geq 0 \quad k = 1, 2, \ldots, K$$

where M is the number of desirable outputs generated, I is the number of undesirable outputs produced, N is the number of inputs used, K is the number of units evaluated and λ_k is a set of intensity variables.

4.2.2 Factors affecting eco-productivity change

To identify the factors or exogenous variables that affect eco-productivity change, previous studies (Fernández-Aracil et al., 2018) have used parametric methodologies, such as econometric models in which the dependent variable is the performance index (eco-efficiency score) and the independent variables are the external factors evaluated (Simões and Marques 2011). However, this approach has problems related to multicollinearity (Marques and Simões, 2009). Therefore, a non-parametric methodology was applied in this study. The evaluated municipalities were grouped according to factors that were suspected to affect their eco-productivity change, and statistically significant differences in the distribution of eco-productivity scores were analyzed. Further, a non-parametric Kruskal-Wallis test was applied (see Eq. 4.9). According to the null hypothesis, the K samples are derived from the same population. The null hypothesis was rejected at a significance level of 95% when the p-value was less than or equal to 0.05.

The Kruskal Wallis test is given by (Theodorsson-Norheim, 1986):

$$T = 12/[N\ (N+1)] \sum_{i=1}^{k} \frac{Ri^2}{Ni} - 3(N+1) \tag{4.9}$$

where N is the total number of observations; Ri is the rank for an individual sample; K is the number of groups and Ni is the number of observations in group i.

4.2.3 Sample description and data

The sample used for this empirical application corresponds to 313 of the 345 Chilean municipalities. For the remaining Chilean municipalities there were not data available. Thus, the assessment involved 91% of the Chilean municipalities, and considers the 2015-2019 period. In 2016, Law 20,920 was adopted in Chile. The law establishes a framework for waste management, extended producer responsibility, and recycling promotion, with goals of reducing waste generation, increasing recovery, reuse, and recycling; and protecting human and environmental health. This law obliges producers to assume responsibility for the processing and valuation of a product from a life cycle perspective. However, the executive orders needed for its implementation were approved in mid-2020. There were some policies, procedures and activities to promote MSW recycling which were implemented before 2020. Nevertheless, as highlighted by (Valenzuela-Levi, 2021), the separate collection and recycling rates of MSW in Chile are poor. In most of the Chilean municipalities, the collection of MSW is door-to-door. For this reason, informal recyclers in Chile do not have the same central role that can be observed in other Latin American Countries (Valenzuela-Levi, 2020). In most of the municipalities, their impact on household waste recycled is most likely non-significant (Valenzuela-Levi, 2019). Whereas municipalities are responsible for waste collection and treatment (including final disposal) both services are usually outsourced (Valenzuela-Levi, 2021). According to the

Chilean National System of Waste Declaration (SINADER in Spanish), in 2015, 42 out of 313 municipalities (13.4%) recycle at least one type of solid waste. By contrast, in 2019 this figure increases up to 66, i.e., 21.1% of the municipalities evaluated recycle one type of MSW. Nevertheless, the percentage of municipalities recycling all types of MSW is very limited being only 2.9% in 2015 and 8.7% in 2019. It evidences that the partial implementation of the law has impacted positively in the management of solid waste. Nevertheless, the percentage of municipalities recycling in Chile is still being very low. Moreover, according to the hierarchy of waste management, the Chilean policy makers should be focus on preventing the generation of solid waste since according to OECD statistics the generation of solid waste per capita in Chile has increased from 400.5 kg/year in 2015 to 436.6 kg/year in 2018 (last available year).

The input considered in this study was based on that of previous studies (Marques and Simoes 2009; Simões et al., 2010; Expósito and Velasco, 2018; Romano et al., 2019; Llanquileo-Melgarejo et al., 2021; Llanquileo-Melgarejo and Molinos-Senante, 2021) and represents the total annual cost of the provision of MSW services. It is defined as the expenditure made by each municipality in the provision of MSW, waste collection, waste treatment, staff and maintenance costs of the devices for waste collection and treatment. It is expressed in Chilean pesos/year. This variable was collected from the National Municipal Information System (SINIM) for the years 2015-2019. Regarding undesirable outputs, unsorted waste (tons/year) was considered following previously described methodological approach (Sarra et al., 2017; Expósito and Velasco 2018; Llanquileo-Melgarejo and Molinos-Senante 2021). For desirable outputs, recyclable wastes (tons/year) were considered, such as: (i) paper and paperboard, (ii) glass, (iii) plastics, (iv) organic waste, and (v) other inorganic waste. Data regarding recyclable and unsorted waste were collected from the National System of Waste Declaration. Although recycled wastes are considered as desirable outputs, it should be noted that according to the waste management hierarchy the top priority is given to waste prevention, followed by re-use, recycling, recovery and finally disposal. Because our study focused on MSW already produced, unsorted waste which is disposed in landfills is considered undesirable output whereas recycled wastes are desirable outputs. Because of the large number of units analyzed in this study (313 municipalities), the average values and standard deviations of the sample outliers were determined (Wilson, 1993); this step was essential to evaluate the municipalities' performance using non-parametric methods, such as DEA, which is a deterministic method. Outliers can affect the eco-productivity change results because they act as pairs of other units (Ananda, 2019). However, no outliers were identified in the empirical analysis.

Based on past research, to select exogenous variables that might affect eco-productivity change scores, three criteria were considered: (i) the main characteristics of the MSW sector in Chile, (ii) the available statistical data, and (iii) environmental variables considered previously in the literature (Sarra et al., 2017; Calabrò and Komilis, 2019; Romano and Molinos-Senante, 2020; Llanquileo-Melgarejo et al., 2021). Thus, the following environmental variables were evaluated: (i) the population served, defined as the number of inhabitants of the municipality; (ii) the size of the urban area of the municipality, expressed in km^2, (iii) population density, which is expressed as the number of inhabitants per km^2 of the urban area of the municipality; and (iv) the tourism index ranking, proposed by the Division of Studies and Territory of the Subsecretariat of Tourism (Llanquileo-Melgarejo et al., 2021). It is a synthetic index whose objective is measuring the level of tourism at local level based on 15 variables such as the number of overnight stays, accommodation services, non-resident population, tourist attractions, etc.

The variables employed to estimate eco-productivity change scores of the sample of Chilean municipalities and the exogenous variables that might affect eco-productivity are presented in Table 4-1.

Table 4-1: Descriptive statistics of the variables used for 2015 and 2019.

		2015		**2019**	
Variable	***Unit of measure***	***Average***	***Standard Deviation***	***Average***	***Standard Deviation***
Costs	CLP/year	897,051	1,552,862	1,252,928	2,068,017
Paper and paperboard	Tons/year	99	987	455	3,863
Glass	Tons/year	36	180	107	310
Plastics	Tons/year	9	83	53	677
Organic waste	Tons/year	283	1,525	546	4,698
Other inorganic waste	Tons/year	345	2,427	1,109	7,875
Unsorted waste	Tons/year	22,071	39,253	50,248	473,831

Table 4-1 shows the average and standard deviation of the variables used to evaluate the eco-efficiency of Chilean municipalities in the provision of MSW services. Operational costs were found to increase by 1.4-fold from 2015 to 2019. This increase is reflected in the desirable outputs, that is, in the recycled waste. For example, the amount of paper and paperboard recycled increased by 4.5-fold, the amount of glass recycled tripled, and plastic recycling increased by six-fold from 2015 to 2019. This increase in recycling highlights the efforts made by local entities to improve the management of MSW in recent years. Nevertheless, the amount of unsorted waste also increased from 2015 to 2019, the production of which doubled.

4.3. Results and Discussion

MLPI scores were calculated using MAX-DEA software. The average values of MLPI and its components, MLECH and MLTCH, for the 313 Chilean municipalities are shown in Table 4-2 and Figure 4-1. The average MLPI was larger than one for all years, with the exception of 2017/18. The average MLPI for the 2015/2019 period was 1.07, which indicates that Chilean municipalities improved their eco-productivity throughout the years. Nevertheless, the wide range of MLPI estimated, that is, the difference between the minimum and maximum MLPI scores, should be noted. Such finding indicates that Chilean municipalities had marked differences in terms of dynamic eco-efficiency, thereby highlight room for improvement for several municipalities.

On average, MLECH contributed negatively to eco-productivity change during the first two years evaluated. In contrast, the efficiency change component increased between 2017/18 and 2018/19, with average scores of 1.048 and 1.055, respectively. Such finding indicates that during the first two years, the performance of the Chilean municipalities moved away from the efficient production frontier and approached this frontier during the last two years.

This change might be explained by improvements in the daily operations of waste service providers and the increase in volume of recycled waste owing to the implementation of local initiatives, such as composting centers for organic matter recycling. This result is consistent with that of previous studies (Llanquileo-Melgarejo and Molinos-Senante, 2021), which found improvements in eco-efficiency for a sample of Chilean municipalities. According to Table 4-2 and Figure 4-1, MLTCH was the main driver of eco-productivity change in Chilean municipalities as it presented the same evolution pattern as MLPI. Thus, during three of the four periods evaluated (2015/17 and 2018/19), the average MLTCH was larger than one, indicating that there was a positive shift in the efficient production frontier. This improvement in MLTCH was more accentuated during 2018/19 owing to the implementation of various measures derived from the Chilean Law for promoting waste recycling, which includes educational campaigns for promoting the separation of MSW, an essential step for their recycling.

Table 4-2: Summary of the eco-productivity results for each component for the years 2015-2019, considering undesirable products.

MLPI

Years	*2015/16*	*2016/17*	*2017/18*	*2018/19*
Average	1.025	1.025	0.991	1.242
St. Dev.	0.251	0.350	0.234	0.779
Minimum	0.043	0.028	0.080	0.050
Maximum	3.561	5.446	3.821	5.924

MLECH

Years	*2015/16*	*2016/17*	*2017/18*	*2018/19*
Average	0.999	0.993	1.048	1.055
St. Dev.	0.153	0.141	0.217	0.221
Minimum	0.503	0.500	0.500	0.501
Maximum	1.999	2.000	2.000	1.998

MLTCH

Years	*2015/16*	*2016/17*	*2017/18*	*2018/19*
Average	1.030	1.027	0.949	1.137
St. Dev.	0.186	0.255	0.149	0.457
Minimum	0.043	0.056	0.159	0.050
Maximum	2.193	4.600	1.916	4.174

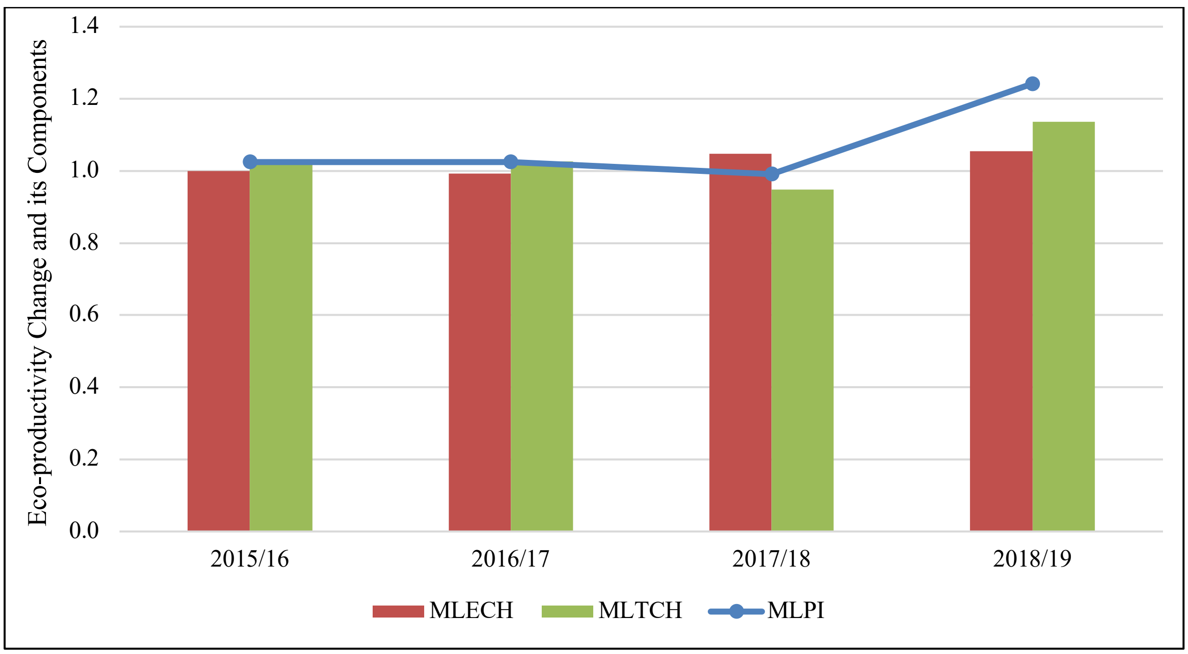

Figure 4-1: Average eco-productivity change and its components for Chilean municipalities evaluated.

The histograms in Figures 4-2, 4-3, and 4-4 illustrate the percentage of Chilean municipalities whose MLPI, MLECH, and MLTCH increased, remained constant, or decreased over time. As mentioned in Section 4.2.1, if MLPI (and its drivers) is larger than 1, eco-productivity increases over time; if lower than 1, eco-productivity decreases over time; and if equal to 1, eco-productivity remains constant. Although the average MLPI was larger than one from 2015 to 2019, the percentage of municipalities that suffered a retardation in eco-productivity increased over time as depicted in Figure 4-2. Thus, in 2015/16, eco-productivity change was negative for 38.0% of the Chilean municipalities evaluated, but increased to 44.4% in 2018/19, reaching a maximum value in 2017/18, where 47.9% of Chilean municipalities evaluated (150 of 313) regressed in eco-productivity change scores. This finding indicates that several Chilean municipalities lack introduced measures or successfully adopted policies to improve their eco-efficiency over time. Such finding also reveals that differences in the performance of municipalities in the provision of MSW services have been accentuated, thereby supporting the conclusions of (Araya-Cordova et al., 2021) who demonstrated that the probability of the adoption of recycling programs in Chilean municipalities has improved over time but is not enough to induce a substantial change toward a more sustainable MSW management model.

As depicted in Figure 4-3, after 2016, the year in which the Law for Promoting Recycling in Chile was adopted, the percentage of municipalities whose efficiency change improved was noticeable. Thus, during the last period evaluated (2018/19), 209 of the 313 municipalities approached the efficient frontier while 19.2% of municipalities moved away from the efficient frontier. This finding indicates that the programs and measures for promoting MSW recycling do not reach all of Chile, and additional efforts are needed to improve MSW management. Figure 4-4 shows the evolution of the other component of the MLPI, MLTCH.

During the first period considered (2015/16), a significant percentage of municipalities (45%) did not experience any change in MLTCH; this is because there was no specific and articulated policy for MSW recycling during this period. This situation was even worse in the following years, where the percentage of municipalities whose frontier shift was positive decreased. In the last period (2018/19), the trend seemed to have changed, with 39% of the municipalities improving technical change. Such finding supports the conclusion of (Cetrulo et al., 2018) who reported that the presence of a legal context for MSW does not guarantee good management. Institutional, political, and cultural issues, especially in middle-income countries such as Chile, are also relevant for improving recycling rates.

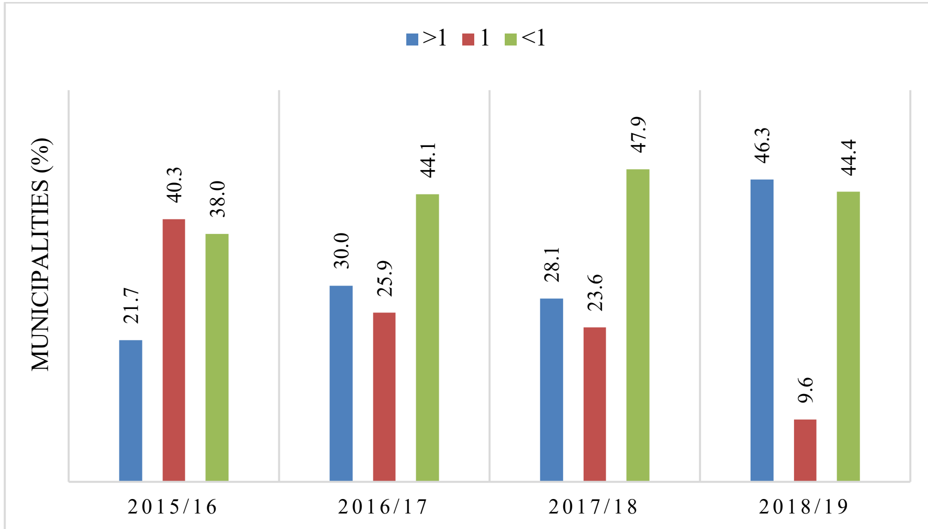

Figure 4-2: Histogram with groups of Chilean municipalities according to Malmquist Luenberger Productivity Index scores.

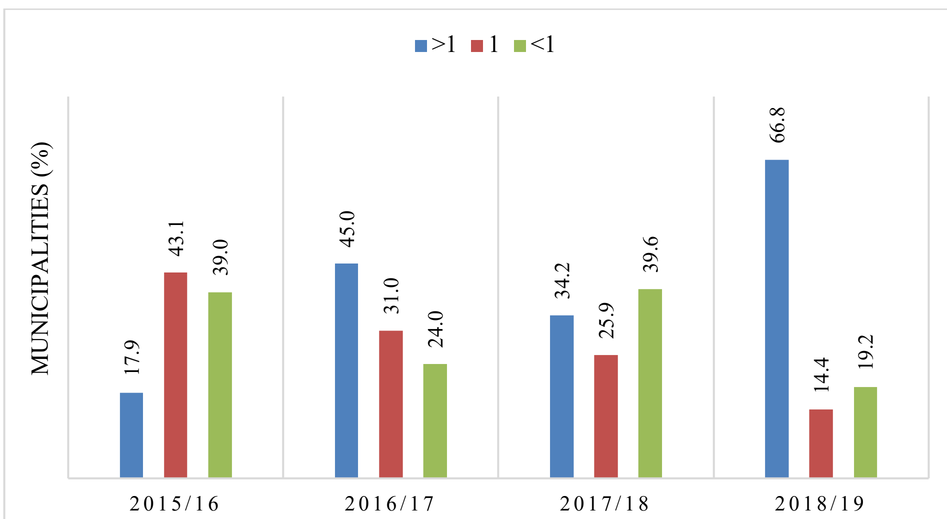

Figure 4-3: Histogram with groups of Chilean municipalities according to efficiency change scores.

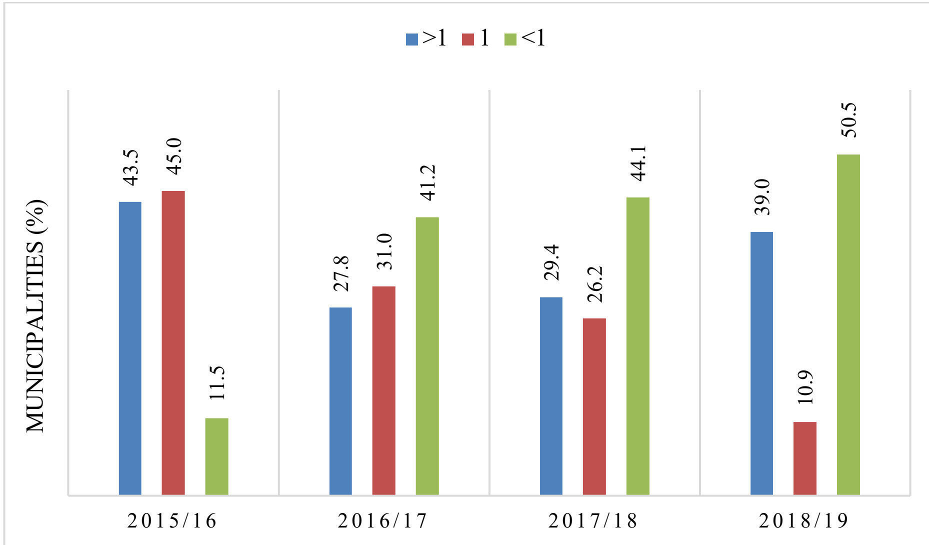

Figure 4-4: Histogram with groups of Chilean municipalities according to technical change scores.

Figures 4-5a and 4-5b show the MLPI scores for the periods 2015/16 and 2018/19, respectively, ultimately highlighting the potential influence of geographical conditions on eco-productivity change in Chilean municipalities. Interestingly, during the first period (2015/16), no pattern was observed in terms of eco-productivity change. Thus, municipalities improving and worsening their eco-productivity are distributed throughout Chile. In fact, neighboring municipalities presented opposing MLPI scores; this is because in Chile, local entities are responsible for MSW management. Therefore, potential economies of scale are not considered for reducing operational costs of MSW collection or treatment (Llanquileo-Melgarejo and Molinos-Senante, 2021). Although a markedly better situation was not observed in 2018/19, municipalities located in the northern area of the country did not experience a retardation in eco-productivity. In contrast, several municipalities in the middle and southern regions of the country suffered a retardation in eco-productivity. Nevertheless, for 2015/16 and 2018/19, Figures 5-5a and 5-b illustrate that eco-productivity remained constant for many Chilean municipalities. Despite the economic, environmental, and health relevance of moving toward a sustainable MSW management, these municipalities have not effectively introduced measures to improve collection or treatment of MSW from a sustainable or circular economy perspective.

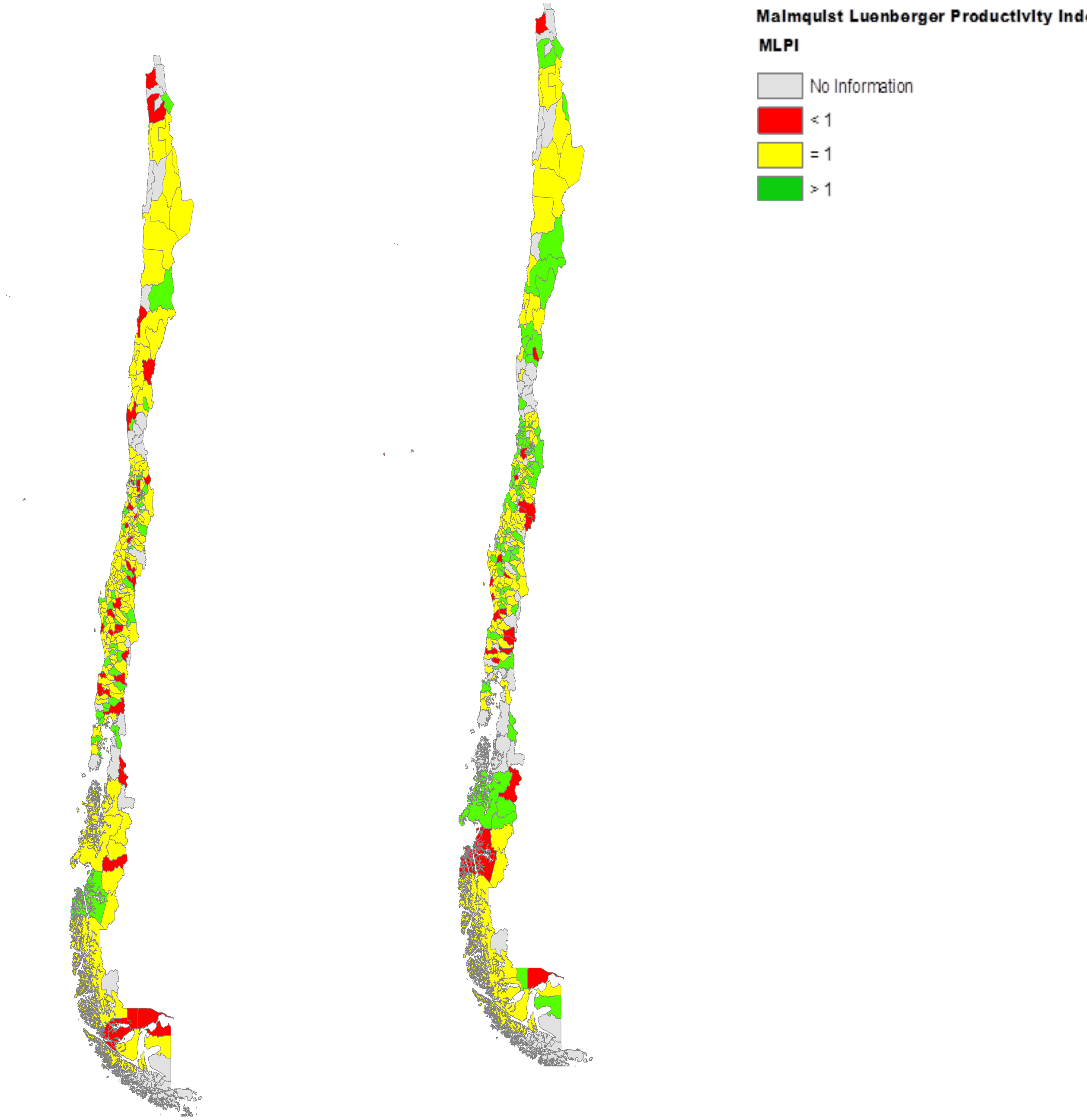

Figure 4-5a **Figure 4-5b**

Figures 4-5a and 4-5b: Malmquist-Luenberger Productivity Index for Chilean municipalities for 2015/16 (Figure 4-5a) and 2018/19 (Figure 4-5b).

The graphical distribution of the drivers of the MLPI is shown in Figures 4-6a, 4-6b, 4-7a, and 4-7b. On one hand, Figure 4-6a shows yellow as the predominant color, which means that most of the Chilean municipalities did not have a change in their efficiency from 2015 to 2016. In contrast, Figure 4-6b shows that most of the municipalities improved their eco-efficiency from 2018 to 2019, as green is the predominant color. The geographical distribution of MLECH scores also revealed that most of the Chilean municipalities located in the central area of Chile, which concentrates a relevant percentage of the Chilean population, improved its eco-efficiency in the last period evaluated. This finding is relevant from a policy perspective because it indicates that the Law for promoting recycling and its associated measures allows municipalities to improve MSW management in terms of eco-efficiency. Unlike MLETCH, a better performance in terms of technical change was reported for 2015/16 (Figure 4-7a) than for 2018/19 (Figure 4-7b). Figure 4-7a illustrates that most of the Chilean municipalities evaluated in the austral area of the country presented a positive shift in the efficient production frontier from 2015 to 2016. In contrast, as shown in Figure 4-7b, the opposite behavior is observed. Several municipalities located in the central area of the country also experienced a negative performance in terms of technical change during this period. This finding reveals that the policies and measures adopted in Chile for improving MSW management are, in many cases, superficial, dependent on municipalities and have not produced the structural changes required for a true and depth transformation and improvement in the management of MSW toward a circular economy.

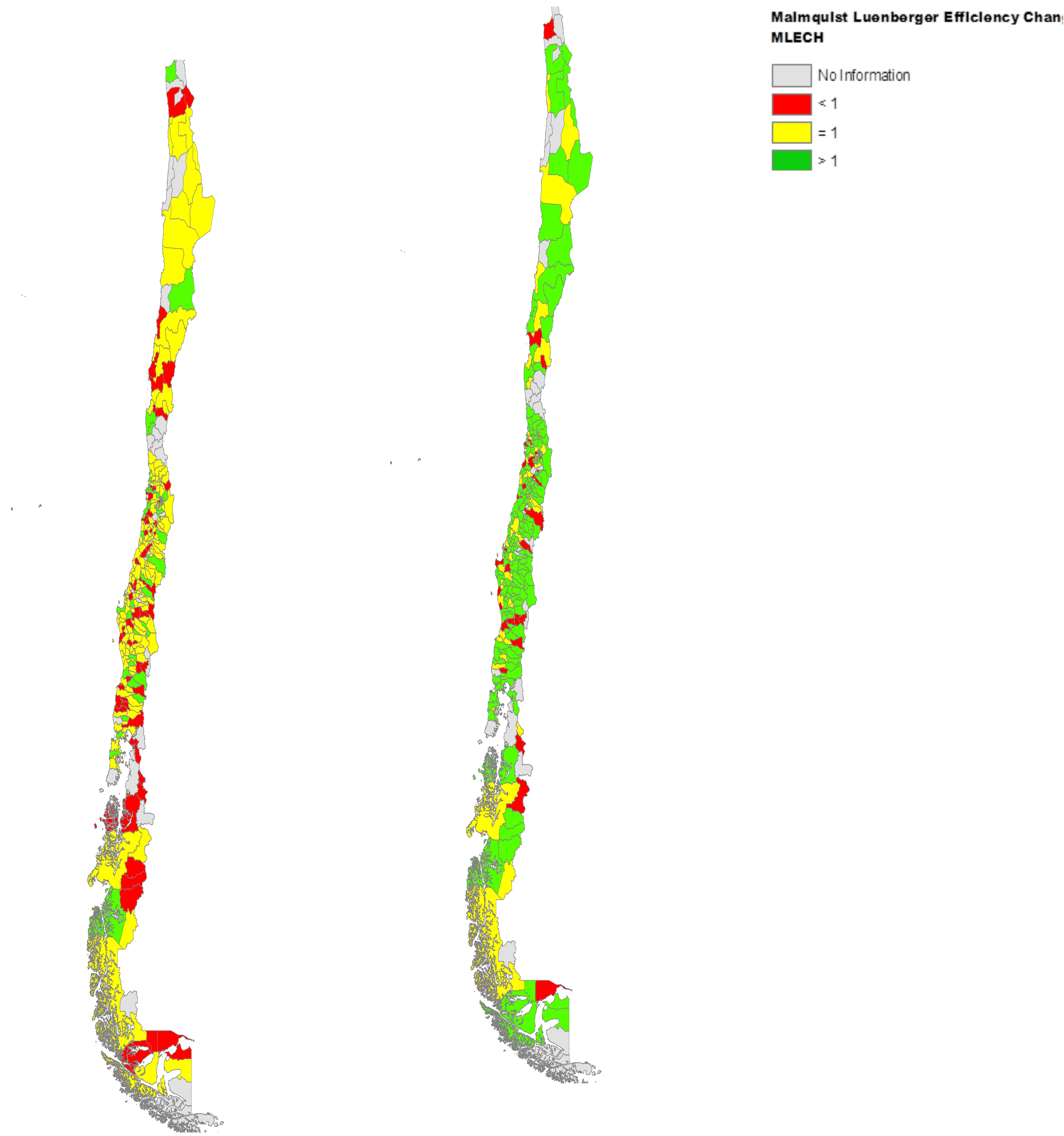

Figure 4-6a **Figure 4-6b**

Figures 4-6a and 4-6b: Malmquist-Luenberger Efficiency Change for Chilean municipalities for 2015/16 (Figure 4-6a) and 2018/19 (Figure 4-6b).

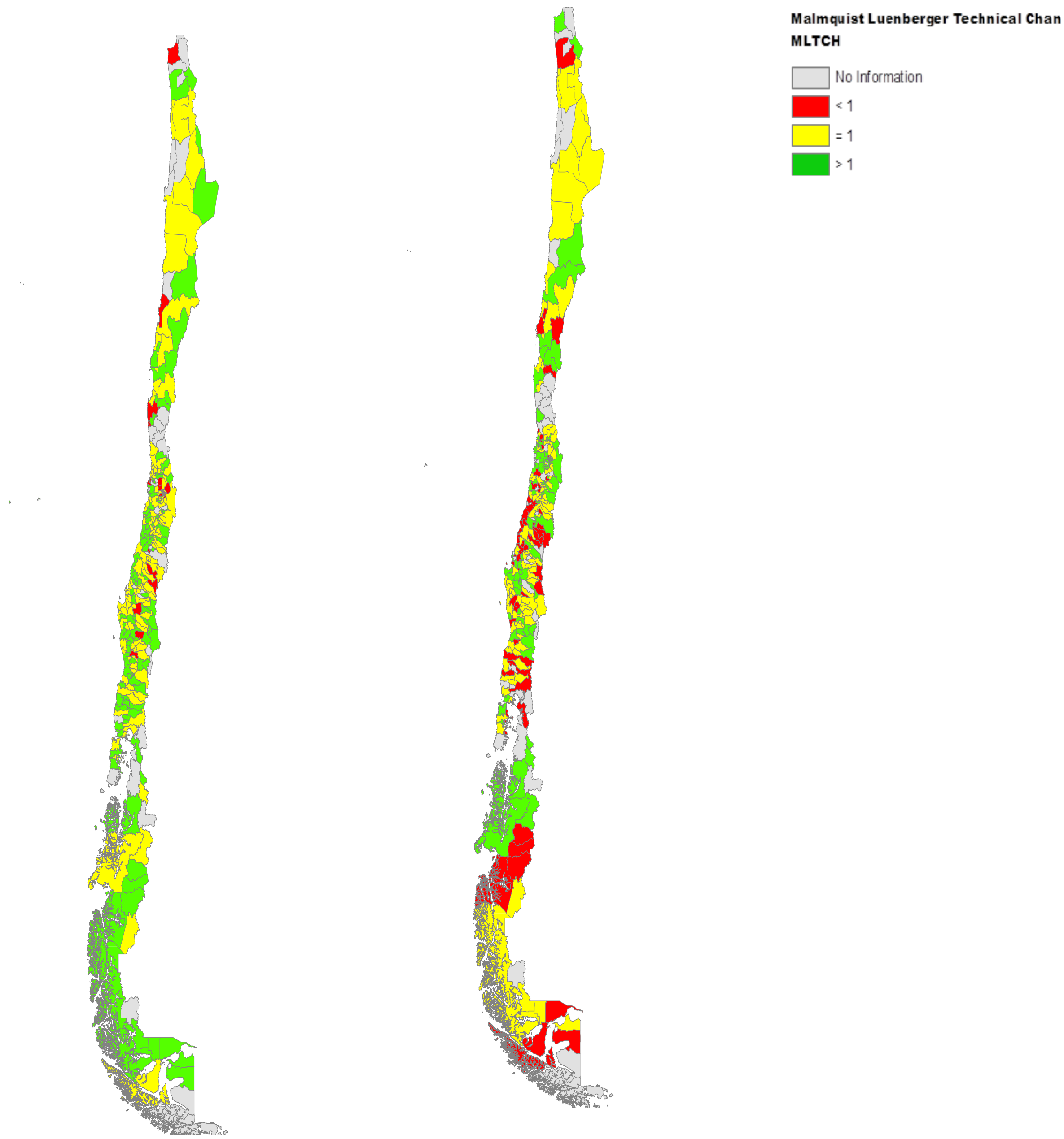

Figure 4-7a

Figure 4-7b

Figures 4-7a and 4-7b: Malmquist-Luenberger Technical Change for Chilean municipalities for 2015/16 (Figure 4-7a) and 2018/19 (Figure 4-7b).

Based on the assessment of the potential impact of some exogenous variables on the eco-productivity change and its drivers of municipalities, Table 4-3 shows the average MLPI, MLECH, and MLTCH scores from 2015 to 2019 and the p-value of the Kruskal-Wallis tests.

For all variables evaluated, the p-value was less than 0.05. Such finding indicates that the null hypotheses were rejected for the four variables considered and the eco-productivity change and its components for the different groups were statistically different at the significance level of 0.05. In other words, these exogenous variables influence the performance of waste management services, considering the time period studied. These results are consistent with those of previous studies conducted by (Llanquileo-Melgarejo et al., 2021; Llanquileo-Melgarejo and Molinos-Senante, 2021; Valenzuela-Levi, 2021), who concluded that several exogenous variables impact the performance of the Chilean municipalities' management. Nevertheless, the analysis conducted by these researchers was static rather than dynamic, as performed in this study.

As shown in Table 4-3, the largest municipalities whose population is larger than 100,000 are those with the most improvement in eco-productivity. The p-value of the Kruskal-Wallis test was lower than 0.05, which means that differences among the three groups of municipalities according to population size were statistically significant. These differences in eco-productivity change estimations are mainly attributable to technical change components, as MLTCH scores were statistically significantly different among the three groups of municipalities. However, the null hypothesis cannot be rejected for MLECH drivers. Because this is the first study to evaluate the eco-productivity change of solid waste service providers, we cannot directly compare these results with previous findings. Nevertheless, previous studies (Carvalho and Marques, 2014; Perez-Lopez et al., 2018; Romano and Molinos-Senante 2020, Delgado-Antequera et al., 2021; Llanquileo-Melgarejo and Molinos-Senante, 2021) concluded that the variable population served is a determinant of the performance of MSW services. However, (Guerrini et al., 2017) and (Expósito and Velasco, 2018) did not find any statistical influence of population on the efficiency of municipalities in the provision of MSW services.

The literature is inconclusive about the impact of population density on the performance of solid waste providers (De Jaeger et al., 2011; Vishwakama et al., 2012; Expósito and Velasco, 2018; Delgado-Antequera et al., 2021). However, the results shown in Table 5-3 indicate that urban areas that are more densely occupied are those with the largest MLPI (i.e., those whose eco-productivity improved the most). In particular, for the sample of Chilean local entities evaluated, the average MLPI for the municipalities whose density is larger than 100 inhabitants/km^2 was

1.539, which implies that in five years, eco-productivity improved by 59.3%. The Kruskal-Wallis test led us to reject the hypothesis of equality of means for both drivers of MLPI, that is, MLECH and MLTCH, with 95% significance, based on the population density of the Chilean municipalities analyzed.

The size of the municipalities evaluated in this study ranged from 7 km^2 to 30,718 km^2, with an average of 1,024 km^2 and 436 km^2, respectively. Considering these values, municipalities were grouped into three categories: i) less than 300 km^2, ii) between 300 and 1000 km^2, and iii) larger than 1000 km^2. As shown in Table 3, the smallest municipalities are municipalities with the most improvement in eco-productivity, with statistically significant differences found for the MLPI according to the Kruskal-Wallis test. This finding does not fully align with the conclusions of (Sarra et al., 2017; Fidelis and Colmenero, 2018; Delgado-Antequera et al., 2021), who illustrated that as the size of the municipalities increases, their efficiency in MSW services improves. Of note, the collection system of MSW in Chile is door-to-door, and as the size of the municipalities increases, vehicles embark on longer journeys. Differences among the three groups of municipalities were also statistically significant for MLTCH but not for MLECH.

Finally, the potential impact of tourism on the eco-productivity change of municipalities in the provision of MSW services was evaluated. The Kruskal-Wallis test results shown in Table 3 reveal that from a statistical point of view, tourism had no influence on the dynamic eco-efficiency, that is, eco-productivity change of Chilean municipalities. The same results apply for both drivers of the MLPI (i.e., MLECH and MLTCH). These results diverge from past findings (García-Sanchez, 2008; Guerrini et al., 2017; Llanquileo-Melgarejo and Molinos-Senante, 2021) where tourism activity was concluded to impact the performance of municipalities in the provision of MSW services. Hence, future research might be conducted with alternative indices to measure tourism intensity for studies integrating solid waste generated by restaurants and hotels in different regions of the country.

The results of this study revealed the existence of large differences in eco-productivity change among municipalities. It evidences that the national law to promote recycling is not enough for all municipalities. In particular, municipalities with low income will present difficulties to adopt the law and therefore, regional laws and policies will be required. Moreover, it has been illustrated that Chilean municipalities present economies of scale in the provision of MSW and therefore, as in other countries, consortiums among neighboring municipalities should be adopted to improve dynamic eco-efficiency in the provision of MSW services.

Table 4-3: Number of municipalities per group, average MLPI, MLECH y MLTCH scores from 2015 to 2019 and p-value for each external variable.

	Number of Municipalities	*MLPI*		*MLECH*		*MTCH*	
		Average	*p-value*	*Average*	*p-value*	*Average*	*p-value*
Population Served (Inhabitant)							
< 10,000	69	1.102		1.086		1.005	
10,000 - 100,0(	184	1.157	< 0.001	1.034	0.325	1.089	0.002
> 100,000	60	1.683		1.087		1.456	
Population Density (inhabitant /km^2)							
< 20	109	1.068		1.053		1.010	
20 – 100	110	1.171	< 0.001	1.038	0.002	1.088	0.001
> 100	94	1.539		1.080		1.355	
Municipal Size (km^2)							
< 300	98	1.499		1.074		1.327	
300 - 1000	111	1.117	< 0.001	1.047	0.251	1.044	0.004
> 1,000	104	1.145		1.047		1.069	
Tourism Index							
< 0.01	122	1.232		1.076		1.102	
0.01 - 0.02	71	1.209	0.201	1.027	0.215	1.154	0.125
> 0.02	120	1.282		1.052		1.173	

4.4. Conclusions

Improving the management of MSW in a circular economy is essential to meet the Sustainable Development Goals. Evaluating the eco-efficiency for MSW services provides relevant information because it identifies municipalities with the best economic and environmental performance. However, eco-efficiency is a static assessment that does not integrate the temporal dimension. To overcome a relevant gap in the literature, this study evaluated for the first time the eco-productivity change (i.e., temporal dynamics of eco-efficiency) of a sample of Chilean municipalities in the provision of MSW services from 2015 to 2019.

On average, Chilean municipalities slightly improved their eco-productivity from 2015 to 2019. Notable differences were reported among municipalities without any geographical patterns. This is because in Chile, local entities are responsible for the management of MSW, and there are no collaboration or cooperation strategies among municipalities. Technical change drivers had better results in the 2015/16 period than the 2018/19 period, which highlights the need to implement further strategies to improve MSW collection and recycling. In this context, several neighboring municipalities present opposite eco-productivity change values, which indicates that the lack of cooperation among municipalities hinders the recycling of MSW, especially in the poorest municipalities. A second stage of analysis revealed that three exogenous variables – population served, population density, and municipality size – significantly influenced eco-productivity change. In contrast, tourism activity was not found to significantly impact the eco-productivity change of Chilean municipalities.

From a policy perspective, the results of this study revealed that in countries such as Chile, where laws and policies for promoting sustainable management of MSW are incipient, cultural and social factors play a relevant role in improving recycling rates. As a large divergence in MLPI scores was found among Chilean municipalities, policymakers should develop and implement policies at the metropolitan or regional scale to take advantage of the potential economies of scale in the collection and treatment of MSW. Additionally, alternative collection systems to the current door-to-door approach could be implemented to reduce the operational costs of MSW collection. Thus, educational campaigns should be carried out to encourage the population to carry out separative collection, which is essential for improving recycling rates.

CHAPTER 5

5. THE IMPACT OF RECYCLING ON THE PRODUCTIVITY OF MUNICIPAL SOLID WASTE: A COMPARISON OF THE MALMQUIST AND MALMQUIST-LUENBERGER PRODUCTIVITY INDEXES

5.1 Introduction

The alarming and escalating rise in the generation of MSW has emerged as a significant global concern, primarily attributed to its detrimental impacts on the environment and public health (Guerrini et al., 2017; Ashish Soni et al., 2022). Recognizing the gravity of this issue, the United Nations has acknowledged and emphasized the significance of enhancing MSW management through Goals 11 and 12 of the Sustainable Development Goals (Di Foggia and Beccarello, 2018; Al-Dailami et al., 2022).

In December 2019, the European Green Pact was introduced as a roadmap to modernize the European economy, enhancing its efficiency and competitiveness in resource utilization (The European Green Deal, 2019; Romano et al., 2020). As part of the European Green Pact (adopted in 2020), the new Action Plan for the circular economy was approved, encompassing measures to encourage businesses, public administrations, and consumers to adopt a sustainable model. Consequently, European countries have made progress in implementing the circular economy. There exists a notable disparity in other regions, such as Latin America and the Caribbean, regarding the adoption of the circular economy (Mihai et al., 2022). This highlights the significance of contributing to this study, specifically focusing on waste management in Latin American countries.

Literature highlights the relevance of the efficiency assessment of MSW management in the transition towards a circular economy and the fulfilment of its objectives (Agovino et al., 2019; Llanquileo-Melgarejo and Molinos-Senante, 2021). Evaluating the performance in the provision of MSW services allows municipalities to determine the most cost-effective strategies for handling solid waste. It provided valuable data for policy development and decision-making. Municipalities can use this information to formulate effective waste management policies, set goals and targets, allocate resources, and track progress towards sustainability objectives (Romano et al., 2021; Llanquileo-Melgarejo et al., 2021).

Some studies have evaluated the efficiency of units (countries, regions, and municipalities) in providing MSW services (Song et al., 2012; Gastaldi et al., 2020; Struk and Boda, 2022). Most research on this topic has used economic variables as inputs and waste collected as outputs to assess the performance of units and economic efficiency (Halkos and Petrou, 2019; Romano et al., 2020). Considering the relevance of moving towards a circular economy, the concept of eco-efficiency is being used incipiently to evaluate the performance of municipalities in the provision of MSW services (Expósito and Velasco, 2018; Romano et al., 2019). Eco-efficiency is defined as the production of more goods (products) and services with fewer resources (inputs) and less environmental impact (Beltrán-Esteve et al., 2017). The prefix ”eco” represents environmental and economic issues; the eco-efficiency assessment provides relevant information from an economic and environmental perspective (Lo Storto, 2021).

Eco-efficiency provides information about the performance of the units analysed for a specific time, i.e., it is a static evaluation that cannot account for changes in performance over time (Gómez et al., 2018). This assessment might be extended using methods and models that allow evaluating the performance of units over time, i.e., evaluating the eco-productivity change of units (Mahlberg et al., 2011). The assessment of eco-productivity change involves extending the notion of eco-efficiency to a temporal setting. Assessing changes in eco-productivity allows one to compute the eco-efficiency of a unit for any given period and helps to compare the eco-efficiency among units. Obtaining information about the temporal dynamics of eco-efficiency, i.e., eco-productivity change, is essential to support decision-making and enhance the circular economy (Romano et al., 2021).

Despite the crucial implications of assessing the change in eco-productivity for significant public decisions, to our knowledge, only (Romano et al., 2021) and (Lo Storto, 2021) have conducted evaluations on the eco-productivity change in a sample of large cities regarding solid waste services. On one hand, (Romano et al., 2021) focused on comparing the eco-productivity change among municipalities with publicly, privately, and mixed-owned entrusted waste utilities, utilizing the Metafrontier Malmquist-Luenberger productivity index. On the other hand, (Lo

Storto , 2021) applied the Global Malmquist Productivity Index to assess the eco-productivity change in the provision of MSW services in a sample of Italian municipalities from 2010 to 2017. In the context of a circular economy, it is imperative to evaluate the impact of changes in MSW recycling rates on the performance of municipalities. In other words, it is essential to compare the metrics of productivity change (which do not integrate environmental variables) and eco-productivity change (which differentiates between recycled waste and unsorted waste) in the provision of MSW services by municipalities.

Against this background, the main objective is to evaluate the impact of MSW recycling on the dynamic performance of municipalities in the provision of MSW services by estimating and comparing their productivity and eco-productivity change. Both metrics of dynamic performance can be decomposed into technical change and efficiency change, which is why the approach in this study allowed us to identify the main drivers of both productivity and eco-productivity change. This information is essential for designing specific policies to enhance MSW recycling and improve the performance of municipalities.

The significance of this study to the existing body of literature can be summarized as follows:

This paper stands out as one of the limited number of studies that examine the dynamics of performance in MSW management. As far as our knowledge extends, this study is the first to compare estimations of productivity and eco-productivity. It introduces a novel approach by examining the impact of recycling rates on the productivity of MSW management. Previous research on this subject has predominantly focused on developed countries, where circular economy concepts and MSW recycling policies are well-established. In contrast, our case study centers on Chile, a middle-income country with emerging regulations to promote MSW recycling. Consequently, the insights gained from our research in Chile could offer valuable lessons for other developing nations.

5.2. Material and methods

This analysis was divided into two steps: First, the productivity change in the provision of MSW services in Chilean municipalities was evaluated through the Malmquist Productivity Index (MPI) (Caves et al., 1982). In the second step, environmental variables were included in the assessment by estimating the eco-productivity change using the Malmquist-Luenberger Productivity Index (MLPI) (Chung et al., 1997).

5.2.1 Productivity Change estimation: Malmquist Productivity Index (MPI)

First, a set of production possibilities that describes feasible relationships between inputs and outputs is presented. Assuming there are $k = 1, \dots, K$ municipalities during $t = 1, \dots, T$ periods, the production technology for municipalities producing M desirable outputs, $y \in R_{+}^{M}$, by using N inputs, $X \in R_{+}^{N}$, is represented by the possibility set T, which is as follows:

$$T(x) = \{(x, y): x\ can\ produce\ y\} \tag{5.1}$$

The output distance function is defined as follows:

$$D_0\ (x, y) = min\ \left\{q\ :\ x, \frac{y}{q} \in T\right\} \tag{5.2}$$

The productivity change for each unit (municipality) is estimated based on the MPI, which is defined as follows (Caves et al., 1982):

$$MPI\ \left(y_t, x_{t,}\ y_{t+1,} x_{t+1}\right) = \sqrt{\frac{D_0^t(y_{t+1,}\ x_{t+1}) * D_0^{t+1}(y_{t+1,}\ x_{t+1})}{D_0^t(y_{t,}\ x_t) * D_0^{t+1}(y_{t,}\ x_t)}} \tag{5.3}$$

Productivity change is decomposed into efficiency change ($MECH$) and technical change ($MTCH$) as follows:

$$MPI\left(y_t, x_t, y_{t+1}, x_{t+1}\right) = \frac{D_0^t(y_{t+1}, x_{t+1})}{D_0^t(y_t, x_t)} \sqrt{\frac{D_0^t(y_{t+1}, x_{t+1}) * D_0^{t+1}(y_{t+1}, x_{t+1})}{D_0^t(y_t, x_t) * D_0^{t+1}(y_t, x_t)}} = MECH * MTCH$$

(5.4)

The advantage of this decomposition is that the drivers that contribute the most to each municipality's productivity change (positive or negative) are identified. Efficiency change component informs about the movement of units (municipalities) towards the best practice frontier (Kumar, 2006). This component is related to the ability of units to be managed by the best operating practices. On the other hand, the technical change component measures the change in the efficient frontier between the two periods (Kumar, 2006). The measurement of these components is essential for strategic and effective long-term planning.

A municipality has improved its productivity over time if MPI > 1; whereas it has suffered retardation in productivity if MPI < 1. An MPI = 1 means that the productivity is constant over time. For the components of the MPI, i.e., MECH and MLTCH, the same interpretation applies.

The MPI can be calculated using a non-parametric methodology, such as the data envelopment analysis (DEA). The following models should be solved for each unit evaluated to compute productivity indicators:

$\overline{D}_0^t(x_{k'}^t, y_{k'}^t)$, $\overline{D}_0^t\left(x_{k'}^{t+1}, y_{k'}^{t+1}\right)$, $\overline{D}_0^{t+1}\left(x_{k'}^{t+1}, y_{k'}^{t+1}\right)$ and $\overline{D}_0^{t+1}(x_{k'}^t, y_{k'}^t)$:

$$\overline{D}_0^t(x_{k'}^t, y_{k'}^t) = Max\ \beta \tag{5.5}$$

$s.t.$:

$\sum_{k=1}^{K} \lambda_k^t y_{km}^t \geq (\beta) y_{k'm}^t, \qquad m = 1, 2, \dots, M$

$\sum_{k=1}^{K} \lambda_k^t x_{kn}^t \leq x_{k'n}^t, \qquad n = 1, 2, \dots, N$

$\lambda_k^t \geq 0, \qquad k = 1, 2, \dots, K$

$$\overline{D}_0^t\left(x_{k'}^{t+1}, y_{k'}^{t+1}\right) = Max\ \beta \tag{5.6}$$

$s.t.$:

$\sum_{k=1}^{K} \lambda_k^t y_{km}^t \geq (\beta) y_{k'm}^{t+1}, \qquad m = 1, 2, \dots, M$

$\sum_{k=1}^{K} \lambda_k^t x_{kn}^t \leq x_{k'n}^{t+1}, \qquad n = 1, 2, \dots, N$

$\lambda_k^t \geq 0, \qquad k = 1, 2, \dots, K$

$$\overline{D}_0^{t+1}\left(x_{k'}^{t+1}, y_{k'}^{t+1}\right) = Max\ \beta \tag{5.7}$$

$s.t.$:

$\sum_{k=1}^{K} \lambda_k^{t+1} y_{km}^{t+1} \geq (\beta) y_{k'm}^{t+1}, \quad m = 1, 2, \dots, M$

$\sum_{k=1}^{K} \lambda_k^{t+1} x_{kn}^{t+1} \leq x_{k'n}^{t+1}, \qquad n = 1, 2, \dots, N$

$\lambda_k^{t+1} \geq 0, \qquad k = 1, 2, \dots, K$

$$\overline{D}_0^{t+1}(x_{k'}^{t}, y_{k'}^{t}) = Max\ \beta \tag{5.8}$$

$s.t.$:

$\sum_{k=1}^{K} \lambda_k^{t+1} y_{km}^{t+1} \geq (\beta) y_{k'm}^{t}, \quad m = 1, 2, \dots, M$

$\sum_{k=1}^{K} \lambda_k^{t+1} x_{kn}^{t+1} \leq x_{k'n}^{t}, \qquad n = 1, 2, \dots, N$

$\lambda_k^{t+1} \geq 0, \qquad k = 1, 2, \dots, K$

where M is the number of outputs generated, N is the number of inputs used, K is the number of units evaluated and λ_k is a set of intensity variables.

5.2.2 Eco-productivity Change estimation: Malmquist-Luenberger Productivity Index (MLPI)

The evaluation of the eco-productivity change of the evaluated units was based on the estimation of the MLPI by (Chung et al., 1997). This approach used the directional distance function, which does the following: i) seeks to increase the desirable outputs while decreasing the undesirable outputs and ii) avoids computational problems associated with the calculation of the output efficiency as a solution to non-linear programming problems.

The notation used to estimate the change in the eco-productivity of the municipalities is similar to that described in Section 2.1 for the MPI. The main difference is that in the MLPI methodological approach, the vector of outputs is decomposed into desirable outputs, $y \in \Re_+^S$ (recycled waste), and undesirable outputs, $b \in \Re_+^H$, (unsorted waste).

The directional distance function, including undesirable outputs, is defined as:

$$\overrightarrow{D_o}(x, y, b; g) = sup\,\{\beta: (y, b) + \beta g \in P(x)\} \tag{5.9}$$

where g is the vector of directions in which outputs are scaled, with $g = (g^y, -g^b)$ being $g^y \in R_+^M$ and $g^b \in R_+^I$. In this case, $g = (1, -1)$ assumes that the desired outputs are increased and undesirable outputs are decreased.

Considering $t = 1, \dots, T$ periods, the MLPI is defined as follows:

$$MLPI_t^{t+1} = \left[\frac{\left(1+\underline{D}_0^t(x^t, y^t, b^t; g^t)\right)}{\left(1+\underline{D}_0^t(x^{t+1}, y^{t+1}, b^{t+1}; g^{t+1})\right)} * \frac{\left(1+\underline{D}_0^{t+1}(x^t, y^t, b^t; g^t)\right)}{\left(1+\underline{D}_0^{t+1}(x^{t+1}, y^{t+1}, b^{t+1}; g^{t+1})\right)}\right]^{\frac{1}{2}} \tag{5.10}$$

The MLPI can be decomposed into two variables: the efficiency change (MLECH) and the technical change (MLTCH) (Ananda, 2018):

$$MLECH_t^{t+1} = [\frac{(1+D_0^t(x^t, y^t,\ b^t;\ g^t)}{(1+D_0^t(x^{t+1} + y^{t+1} +\ b^{t+1};\ g^{t+1})} * \frac{(1+D_0^{t+1}(x^t, y^t,\ b^t;\ g^t)}{(1+D_0^{t+1}(x^{t+1}, y^{t+1},\ b^{t+1};\ g^{t+1})}]^{1/2.} \tag{5.11}$$

$$MLTCH_t^{t+1} = [\frac{(1+D_0^{t+1}(x^t, y^t,\ b^t;\ g^t)}{(1+D_0^t(x^t, y^t,\ b^t;\ g^t)} * \frac{(1+D_0^{t+1}(x^{t+1}, y^{t+1},\ b^{t+1};\ g^{t+1})}{(1+D_0^{t+1}(x^{t+1}, y^{t+1},\ b^{t+1};\ g^{t+1})}]^{1/2.} \tag{5.12}$$

A municipality has improved its eco-productivity in the provision of MSW services if MLPI > 1, whereas an MLPI < 1 means worsening of the eco-productivity; an MLPI = 1 means that the productivity is unchanged. For the components of the MLPI, i.e., MLECH and MLTCH, the same interpretation applies (Maziotis et al., 2017).

Based on the definition of the MLPI (Eq. 5.10), four linear-programming problems must be solved for each unit (municipality) to compute the MLPI. The problems are shown in Eqs. (5.13—5.16).

$$\overline{D}_0^t(x_{k'}^t, y_{k'}^t, b_{k'}^t; g_{k'}^t) = Max\ \beta \tag{5.13}$$

$s.t.$:

$$\textstyle\sum_{k=1}^{K} \lambda_k^t y_{km}^t \geq (1+\beta) y_{k'm}^t, \qquad m = 1, 2, \dots, M$$

$\sum_{k=1}^{K} \lambda_k^t b_{ki}^t = (1-\beta) b_{k'i}^t , \qquad i = 1, 2, \dots, I$

$\sum_{k=1}^{K} \lambda_k^t x_{kn}^t \leq x_{k'n}^t , \qquad n = 1, 2, \dots, N$

$\lambda_k^t \geq 0, \qquad k = 1, 2, \dots, K$

$$\bar{D}_0^{t+1}\left(x_{k'}^{t+1}, y_{k'}^{t+1}, b_{k'}^{t+1}; g_{k'}^t\right) = Max\ \beta \tag{5.14}$$

$s.t.$:

$\sum_{k=1}^{K} \lambda_k^{t+1} y_{km}^{t+1} \geq (1+\beta) y_{k'm}^{t+1} , \quad m = 1, 2, \dots, M$

$\sum_{k=1}^{K} \lambda_k^{t+1} b_{ki}^{t+1} = (1-\beta) b_{k'i}^{t+1} , \quad i = 1, 2, \dots, I$

$\sum_{k=1}^{K} \lambda_k^{t+1} x_{kn}^{t+1} \leq x_{k'n}^{t+1} , \qquad n = 1, 2, \dots, N$

$\lambda_k^{t+1} \geq 0, \qquad k = 1, 2, \dots, K$

$$\bar{D}_0^{t+1}(x_{k'}^t, y_{k'}^t, b_{k'}^t; g_{k'}^t) = Max\ \beta \tag{5.15}$$

$s.t.$:

$\sum_{k=1}^{K} \lambda_k^{t+1} y_{km}^{t+1} \geq (1+\beta) y_{k'm}^{t} , \quad m = 1, 2, \dots, M$

$\sum_{k=1}^{K} \lambda_k^{t+1} b_{ki}^{t+1} = (1-\beta) b_{k'i}^{t} , \quad i = 1, 2, \dots, I$

$\sum_{k=1}^{K} \lambda_k^{t+1} x_{kn}^{t+1} \leq x_{k'n}^{t} , \qquad n = 1, 2, \dots, N$

$\lambda_k^{t+1} \geq 0, \qquad k = 1, 2, \dots, K$

$$\bar{D}_0^{t}\left(x_{k'}^{t+1}, y_{k'}^{t+1}, b_{k'}^{t+1}; g_{k'}^t\right) = Max\ \beta \tag{5.16}$$

$s.t.$:

$\sum_{k=1}^{K} \lambda_k^t y_{km}^t \geq (1+\beta) y_{k'm}^{t+1} , \qquad m = 1, 2, \dots, M$

$\sum_{k=1}^{K} \lambda_k^t b_{ki}^t = (1-\beta) b_{k'i}^{t+1} , \qquad i = 1, 2, \dots, I$

$\sum_{k=1}^{K} \lambda_k^t x_{kn}^t \leq x_{k'n}^{t+1} , \qquad n = 1, 2, \dots, N$

$\lambda_k^t \geq 0, \qquad k = 1, 2, \dots, K$

where M is the number of desirable generated outputs, I is the number of undesirable outputs produced, N is the number of used inputs, K is the number of evaluated units and λ_k is a set of intensity variables.

5.2.3 Case analysis

The empirical application in this study utilized a sample of 143 out of 345 Chilean municipalities (41.4%) during the period of 2015 to 2019. 22 out of the 143 analyzed municipalities can be categorized as small because its population is lower than 10,000 people. In recent years, Chile has implemented several policies aimed at enhancing the environmental management of MSW. For instance, the National Plan for Sustainable Consumption and Production 2017-2022 emphasizes the development, implementation, and strengthening of mechanisms to prevent waste generation and promote the valorization of waste across all sectors of the economy through financial and educational tools that incorporate concepts like eco-design and circular economy. Additionally, the National Waste Policy 2015-2025 has been instrumental in shaping waste management practices.

From an institutional standpoint, the Ministry of the Environment has established a Circular Economy Office, which focuses on research and innovation programs (such as Eco-design) and material recovery in collaboration with research centers, universities, and the Agency for Sustainability and Climate Change. Concerning the management of solid waste in Chile, Law 20,920 was approved in 2016. This legislation established a framework for waste management, extended producer responsibility, and the promotion of recycling. Its objectives include reducing waste generation, increasing recovery, reuse, and recycling, as well as safeguarding human and environmental health. The law requires producers to take responsibility for the processing and valorization of products throughout their lifecycle. The implementation of this law was initiated in mid-2020. As noted by (Valenzuela-Levi et al., 2021), the rates of separate collection and recycling of MSW in Chile still remain relatively low.

The evaluation of the productivity and eco-productivity change is based on the previous research (Marques and Simões, 2009; Simões et al., 2010). The input is the total annual cost of the provision of MSW services. It is defined as the expenditure by each municipality in the provision of MSW services, including cleaning services, waste collection and waste treatment or disposal.

The total annual cost is expressed in Chilean pesos per year[7]. This variable was collected from the National Municipal Information System (SINIM) for 2015—2019.

Regarding outputs, in the case of productivity change, only the volume of generated MSW was integrated into the model and expressed in metric tons per year. By contrast, to evaluate eco-productivity change, both undesirable and desirable outputs were integrated into the assessment. Per the existing studies on the eco-efficiency of MSW management (Sarra et al., 2017; Llanquileo-Melgarejo and Molinos-Senante, 2021), unsorted waste (tons/year) was considered undesirable output. Additionally, a set of recyclable wastes (tons/year) was considered as desirable output: (i) paper and paperboard, (ii) glass, (iii) plastic, (iv) organic waste and (v) other inorganic waste. Data about recyclable and unsorted waste were collected from the National System of Waste Declaration (SINADER in Spanish).

Due to many units analysed in this study (143 municipalities during 2015‒2019), atypical values were detected based on the average values and the standard deviation of the sample (Wilson, 1993). The detection of outliers is essential to evaluate the performance of municipalities using non-parametric methods such as the DEA since it is a deterministic method. Therefore, outliers can affect productivity and eco-productivity results since they act as pairs of other units (Ananda, 2019). Table 5-1 presents the average of the variables used to assess the productivity and eco-productivity change in terms of the provision of MSW services among 143 Chilean municipalities.

[7] On 9th February, the conversion rate was 1€ ≅ 942 CLP and 1 US$ ≅ 824 CLP

Table 5-1: Descriptive statistics of the variables used for 2015 and 2019 for 143 Chilean municipalities.

Variables	*Unit of measure*	2015		2019	
		Average	*Standard Deviation*	*Average*	*Standard Deviation*
Total anual costs	CLP/year	1,039,630	1,636,145	1,527,504	2,299,943
Paper and paperboard	Tons/year	182	1,412	533	3,853
Glass	Tons/year	75	260	204	411
Plastics	Tons/year	18	122	25	77
Organic waste	Tons/year	817	6,542	328	1,470
Other inorganic waste	Tons/year	712	3,528	1,243	6,304
Unsorted waste	Tons/year	26,205	39,928	31,010	45,202

5.3. Results and discussion

This section reports the estimates of productivity change and eco-productivity change based on the MPI and MLPI metrics which were calculated using the MAX-DEA software. In other words, it shows the impact of changes in recycling rates over time on the performance of Chilean municipalities in the provision of MSW services.

Figure 5-1 shows the average values of MPI and MLPI for a sample of 143 Chilean municipalities. It is illustrated that the average MPI was larger than the MLPI for all years evaluated. It means that when environmental variables are included in the assessment, municipalities are penalized in terms of its performance. This result also suggests that recycling MSW has a negative influence of the economics of municipalities since average eco-productivity change was lower than average productivity change. In the case of Chile, were around 50% of the households do not pay for MSW services (CSP, 2020), this finding involves that municipalities have to do additional economic efforts for recycling MSW services. In this context, it is essential to implement policies to increase municipal revenue associated to MSW services by implementing alternative tariff schemes such as pay-as-you-throw or volume-based waste fee in application of the "polluter pays principle" (Drosi et al., 2020; Ukkonen and Sahimaa, 2021). Alternatively, for small municipalities which would present difficulties in the implementation of these tariff schemes, additional funds from regional and/or national entities should be received to increase MSW recycling rates.

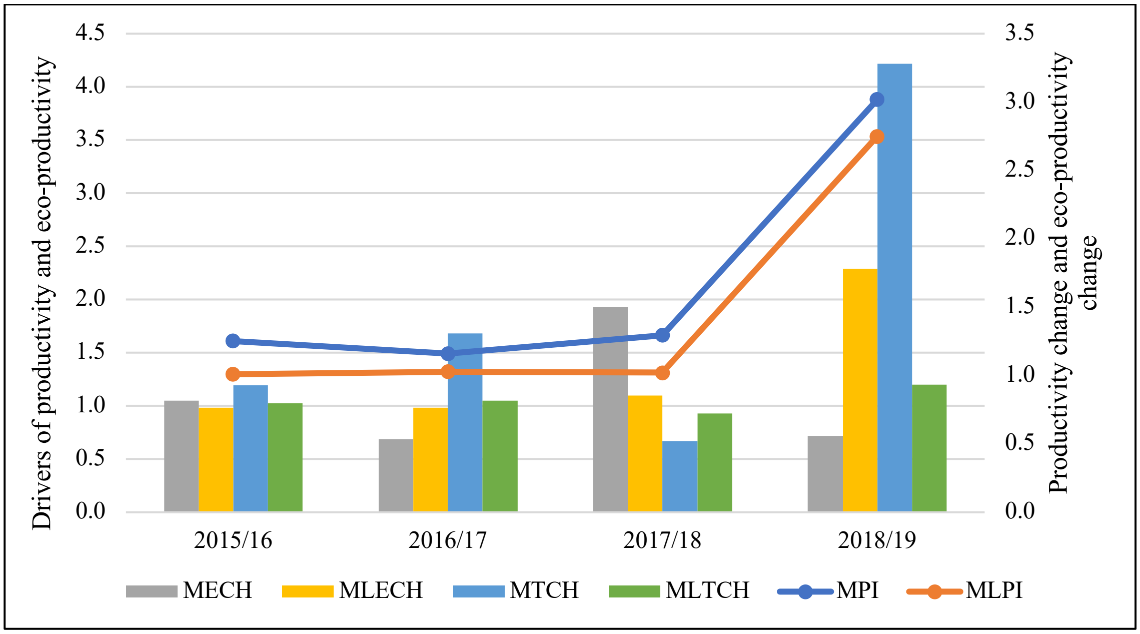

Figure 5-1: Average evolution of the productivity change (MPI) and eco-productivity change (MLPI) and its driver's efficiency change (MECH and MLECH) and technical change (MTCH and MLTCH) of the Chilean municipalities evaluated.

Figure 5-1 illustrates that both performance metrics, MPI and MLPI, are consistently higher than the index evaluated for all years. On average, Chilean municipalities have demonstrated improvement in their performance over the years from both an economic and environmental standpoint, reflecting the significant efforts made to enhance MSW management in recent times. This improvement is particularly notable in the most recent evaluated year (2018-2019), suggesting that two years after the implementation of the National Law for promoting MSW recycling (Law 20,920), Chilean municipalities have made strides in waste management, including recycling initiatives.

Further analysis of the results presented in Table 5-2 reveals substantial divergences among the evaluated municipalities. Specifically focusing on productivity change, there are significant variations between the minimum and maximum MPI scores for all the years examined. None of the evaluated Chilean municipalities have shown improvement in productivity over time. For instance, between 2018 and 2019, 29.4% of the municipalities (42 out of 143) did not witness any enhancement in their economic performance. The differences among municipalities become less significant when environmental variables are integrated into the assessment, i.e., when eco-productivity change is evaluated. Nevertheless, a noteworthy percentage of municipalities (32.9%) did not experience an improvement in their eco-productivity between 2018 and 2019, as well as in previous years. This indicates that certain municipalities need to reduce operational costs and/or increase their MSW recycling rates in order to match the efficiency levels of their peers.

Table 5-2: Main statistics of productivity change and eco-productivity change of Chilean municipalities evaluated.

	Malmquist Productivity Index				**Malmquist-Luenberger Productivity Index**			
	Average	***Minimum***	***Maximum***	***% Municipalities improved***	***Average***	***Minimum***	***Maximum***	***% Municipalities improved***
2015/16	1.254	0.296	7.423	55.9	1.010	0.341	1.925	33.6
2016/17	1.161	0.086	6.109	58.0	1.029	0.234	5.446	42.0
2017/18	1.295	0.109	8.109	53.1	1.021	0.050	3.821	45.5
2018/19	3.018	0.009	9.039	70.6	2.750	0.585	4.466	67.1

From a geographical perspective, it is interesting to analyze the difference between the aggregated MPI and MLPI (values for the 143 Chilean municipalities calculated between 2015 and 2019 (Figures 5-2a and 5-2b). The findings reveal that in 101 out of the 143 municipalities (70.6%), the aggregated values of MPI from 2015 to 2019 were higher than those for the MLPI metric. Over two-thirds of the analyzed Chilean municipalities demonstrated better dynamic performance from an economic standpoint compared to an environmental perspective. These results differ from the conclusions drawn by (Llanquileo-Melgarejo et al., 2021), who stated that most Chilean municipalities exhibit higher eco-efficiency scores than efficiency scores. It should be noted that their study focused solely on 2018 data. Thus, our study highlights the importance of incorporating the temporal dimension when evaluating the performance of municipalities in terms of the provision of MSW services. Figures 5-2a and 5-2b demonstrate that there was no discernible geographical pattern observed in the comparison of the MPI and MLPI metrics. This finding aligns with the results reported by (Llanquileo-Melgarejo et al. 2021), indicating that the geographical factor does not determine the performance of Chilean municipalities in terms of MSW service provision.

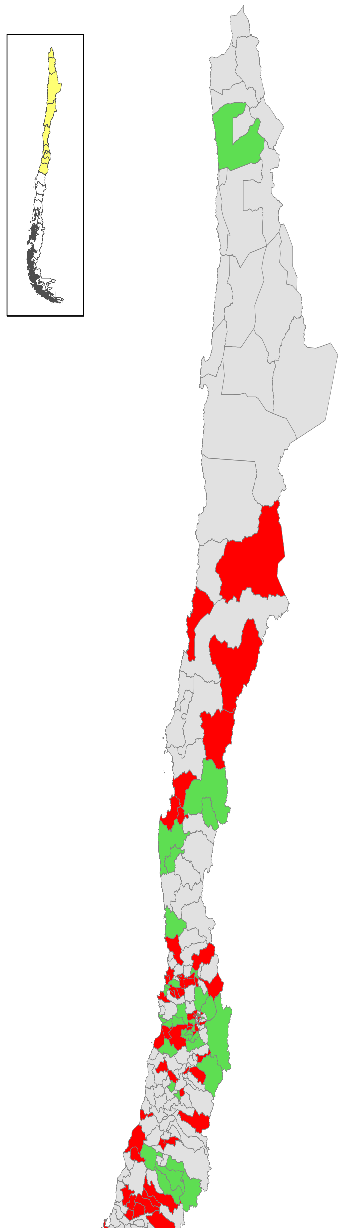

Figure 5-2a) North zone

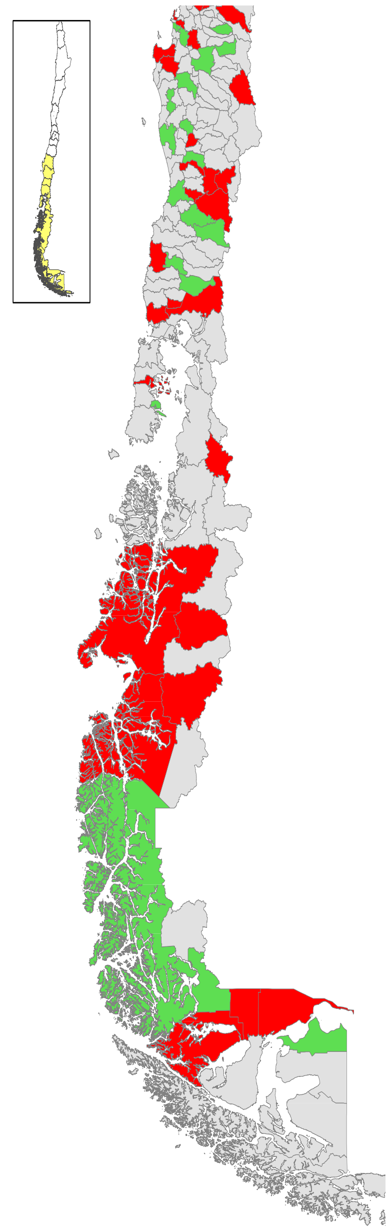

Figure 5-2b) South zone

Figures 5-2a and 5-2b: Difference between aggregated MPI and MLPI values for 2015/19 years for the Chilean municipalities evaluated.

Regarding the drivers of productivity and eco-productivity change estimations, the average values are depicted in Figure 5-1. In terms of economic dynamic performance metrics, specifically MPI, technological change (MTCH) was the primary factor contributing to the improvement in productivity change among Chilean municipalities, except for the period of

2017-2018 when it exceeded one. Throughout most of the evaluated years, there was a positive shift in the efficient frontier, particularly noticeable in the last evaluated year where MTCH improved by 4.215. Important to mention is the adoption of the Chilean Law 20,920 concerning waste management in 2016. Despite its gradual implementation over the years, it has led to significant changes in the primary waste management approaches in Chile. These changes are evident in the considerable positive shift observed in the estimated efficient frontier during the recent evaluated years.

This significant increase counterbalanced the considerable decrease in the efficiency change (MECH) driver, which experienced a decline of 29% during the 2018-2019 period. These results highlight notable variations among Chilean municipalities in terms of economic performance (MPI). While some municipalities showcased excellent performance, leading to a positive movement of the production frontier (MTCH > 1), many others did not improve their efficiency and remained further away from the efficient frontier, resulting in a negative efficiency change.

The trend observed in the environmental dynamic performance metric, MLPI, was slightly different (refer to Figure 5-1). The driver of efficiency change (MLECH) had a negative impact on the eco-productivity change of municipalities during the first two evaluated years (2015-2017). Following the implementation of Law 20,920, which promotes MSW recycling in Chilean municipalities, the average MLECH became positive. Between 2017 and 2019, the overall performance of municipalities improved, bringing them closer to the eco-efficient production frontier. Similarly, to MPI, the driver of technical change (MLTCH) was positive for all years except for 2017-2018. This suggests that, on average, the eco-efficiency frontier of municipalities, in terms of MSW service provision, has undergone a positive shift, indicating that municipalities are making improvements in their daily operations. The average values of the MLTCH component were closer to one, indicating that these improvements are gradual and likely related to the availability of funds for implementing policies to promote MSW recycling at the household level. This could be attributed to initiatives such as the Recycling Fund (FPR), one of the competitive funds established by the Chilean Ministry of the Environment. The FPR aims to support Extended Producer Responsibility under Law 20,920 by financing projects that prevent waste generation, promote reuse, recycling, and other types of recovery. These funds primarily target municipalities and associations.

Figures 5-3a and 5-3b illustrate the difference between the aggregated values of MECH and MLECH from 2015 to 2019 at the municipal level. It was observed that 61 out of 143 Chilean municipalities (42.7%) exhibited higher aggregate MECH values than MLECH for the 2015-2019 period. This indicates that the majority of evaluated Chilean municipalities (57.3%) have prioritized improving their environmental performance rather than focusing on economic aspects. Any observed regional trends could potentially be attributed to the low recycling rates in Chile (Valenzuela-Levi et al., 2021).

Similarly, Figures 5-4a and 5-4b present the difference between the aggregated values of MTCH and MLTCH from 2015 to 2019 as drivers of (eco)productivity change. In this case, the green color dominates the map, indicating that aggregate MTCH values were larger than MLTCH. Specifically, 139 out of 143 municipalities (97.2%) demonstrated higher scores in technological change when the assessment did not incorporate environmental variables. This implies that while municipalities have made efforts to adopt improved practices for enhancing MSW management from an environmental perspective, the most significant shift in the efficient frontier is driven by economic changes. It is worth noting that MSW management in Chile is funded through the municipal budget (SUBDERE, 2020) necessitating that the poorest municipalities concentrate on improving MSW management not only from an environmental standpoint but also from an economic standpoint.

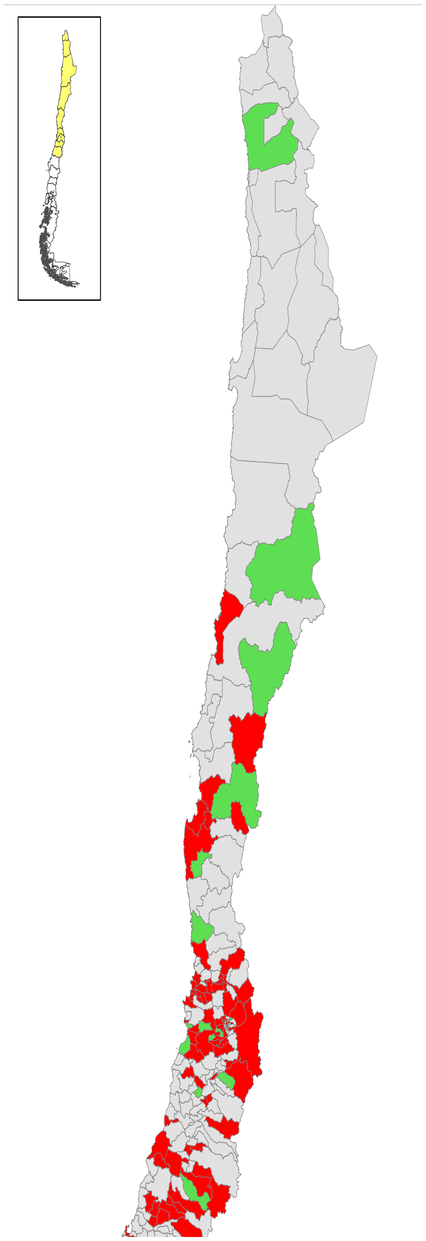

Figure 5-3a) North zone

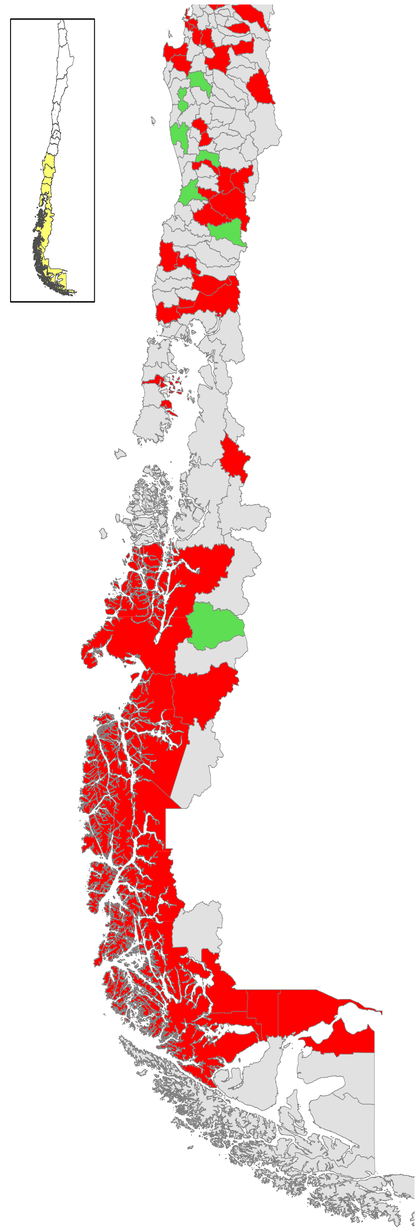

Figure 5-3b) South zone

Figures 5-3a and 5-3b: Difference between aggregated MECH and MLECH values for 2015/19 years for the Chilean municipalities evaluated.

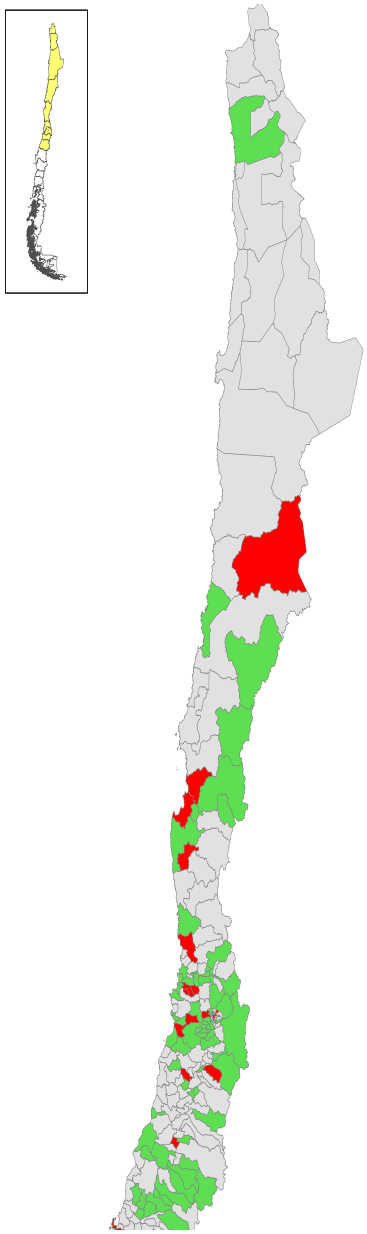

Figure 5-4a) North zone

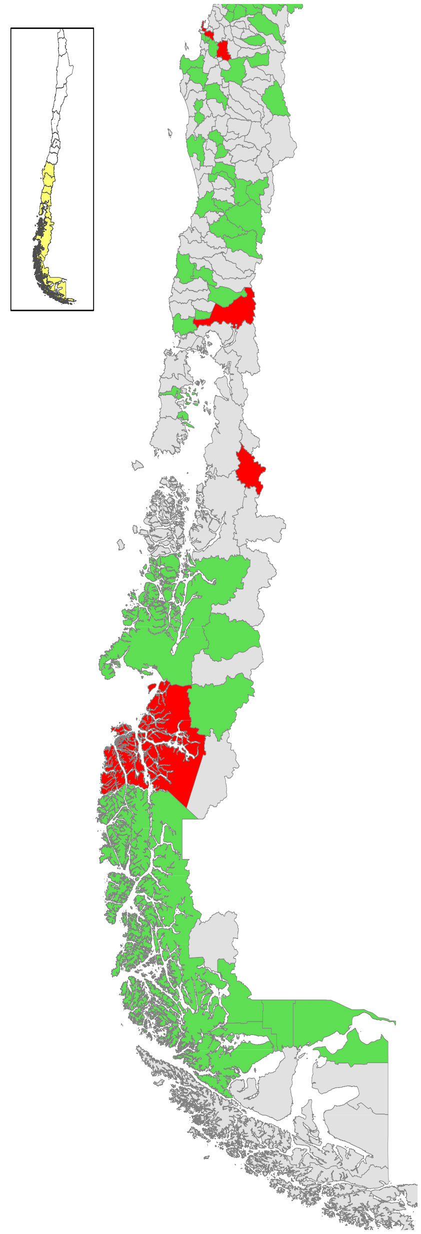

Figure 5-4b) South zone

Figures 5-4a and 5-4b: Difference between aggregated MTCH and MLTCH values for 2015/19 years for the Chilean municipalities evaluated.

The information provided in this study has implications for policymakers aiming to enhance productivity and eco-productivity in the provision of MSW services. Policymakers can use the findings to inform the development and implementation of targeted actions and policies to improve MSW management. One important aspect highlighted by the study is the identification of municipalities that have demonstrated eco-productive practices. These exemplary municipalities can serve as models for others to learn from and replicate their successful strategies. Policymakers can monitor and compile the actions and policies implemented by these eco-productive municipalities and disseminate this information to other municipalities, facilitating knowledge sharing and promoting best practices. Forging alliances with the private sector can be an effective strategy to finance the necessary infrastructure for improving MSW management. Collaboration with private entities can bring in resources and expertise, enabling municipalities to implement initiatives that enhance eco-productivity. Additionally, implementing specific measures for MSW recycling can significantly contribute to improving eco-productivity. Policymakers can introduce policies and incentives that encourage and support increased recycling rates, such as public awareness campaigns, infrastructure development, and extended producer responsibility programs.

5.4. Conclusions

In the context of a circular economy, the economic and environmental performance of municipalities must be improved in the provision of MSW services. Assessing productivity change and eco-productivity change in MSW management is essential for achieving cost-effective, environmentally sustainable, and socially responsible waste management practices. This study analysed the impact of MSW recycling on the performance of municipal waste management by evaluating and comparing the productivity change and eco-productivity scores of a sample of 143 Chilean municipalities between 2015 and 2019.

The empirical findings revealed that the recycling rates of MSW in Chile did not undergo significant changes over the evaluated years, as environmental policies promoting MSW recycling were still in their early stages. Correspondingly, the average productivity change estimations (MPI) were higher than the eco-productivity change estimations (MLPI) for all the years examined. This indicates that Chilean municipalities have placed more emphasis on improving their performance in MSW management from an economic perspective rather than an environmental one. Substantial variations were observed among municipalities, highlighting disparities in the available funds for implementing measures to promote MSW recycling. It also suggests a lack of collaboration in MSW management among neighboring municipalities. Therefore, to leverage potential economies of scale, the implementation of a regional policy is necessary to enhance the management of MSW services in Chile.

While this study makes a valuable contribution to the existing knowledge regarding the assessment of MSW services' performance, it also paves the way for further research in several areas. Firstly, the current assessment focuses on specific types of solid waste, excluding electronic waste, batteries, and used oil from consideration. Thus, future research could explore the performance of municipalities in providing MSW services for these waste types as well. Secondly, our study primarily examines the recycling of waste as desirable outputs, without delving into the recycling technologies employed or the sub-products generated. Therefore, an extension of our analysis would involve incorporating the evaluation of the stages undertaken by municipalities for MSW valorization. Lastly, conducting a second stage of analysis would help identify potential environmental factors that influence the dynamic performance of municipalities in MSW management.

CHAPTER 6.

6. GENERAL CONCLUSIONS AND PERSPECTIVES

From both environmental and public health perspectives, effective waste management throughout its lifecycle is crucial for mitigating adverse impacts on the environment, economy, and human well-being. This includes alleviating strain on natural resources and minimizing negative effects on the ecosystem. The reuse and recycling of waste materials are pivotal in addressing these challenges. Simultaneously, these practices contribute to reduced energy and water consumption needed for raw material extraction and processing, as well as diminished demand for waste disposal space. MSW recycling, in particular, seeks to transform materials within waste, such as paper, cardboard, glass, and plastic, into reusable resources for production processes. By doing so, it promotes a more sustainable use of resources and reduces the overall environmental burden.

With this perspective in mind, the foundational premise of this thesis was to assess the economic and environmental performance of Chilean municipalities in terms of MSW services over the period from 2015 to 2019. Specifically, the study aimed to investigate the influence of selective collection and MSW recycling on municipal performance. This was achieved by comparing efficiency and eco-efficiency indices, as well as examining changes in productivity and eco-productivity across municipalities during the years 2015 and 2019. Furthermore, the research aimed to identify external factors that impact the waste management performance of municipalities.

Based on the four research articles conducted in this dissertation, it can be concluded as follows:

The study reveals a prevailing trend of suboptimal performance among the majority of Chilean municipalities in the realms of both efficiency and eco-efficiency within waste management services. This outcome underscores the pressing need for substantial enhancements in waste management practices across the spectrum of municipalities. Furthermore, the research highlights a notable distinction in the efficiency scores attained by municipalities based on their primary focus, whether it is economic or environmental. This distinction reaffirms the validity of the first hypothesis of this dissertation. The hypothesis posited that the separate collection and recycling of MSW influence the performance of municipalities in delivering solid waste services. The empirical evidence presented in the study confirms this hypothesis, underlining that a shift towards more sustainable and environmentally conscious waste management practices does indeed impact the overall performance of municipalities in this domain.

When analyzing the changes in productivity over the years, it becomes evident that Chilean municipalities made modest improvements in their eco-productivity between 2015 and 2019. These advancements occurred without any discernible geographical patterns, implying that the changes were not limited to specific regions. However, an intriguing finding emerges when comparing the average productivity change estimations based on economic variables against those including environmental factors as well. The study indicates that Chilean municipalities have placed relatively greater emphasis on enhancing their performance in MSW management from an economic standpoint rather than an environmental one. This observation aligns with the notion that while economic considerations are often immediate and tangible, the environmental impact tends to be more complex to quantify and might have longer-term consequences. This trend prompts a reflection on the balance between economic priorities and environmental sustainability in waste management strategies within the Chilean municipalities studied.

The dissertation confirms the influence of various external factors beyond municipal management on the performance of Chilean municipalities. Factors such as population density, waste generation rates, tourism activity, and GDP per capita have been found to exert an impact on municipal performance, encompassing both economic and environmental dimensions. This finding underscores the complexity of waste management and the broader systemic influences that shape the outcomes of such endeavors. It signifies that waste management strategies need to be comprehensive, considering both economic and environmental aspects. The study underscores the importance of adopting holistic approaches that harmonize economic goals with environmental sustainability. By recognizing and addressing the external factors that affect municipal performance, waste management policies and practices can be formulated in a manner that optimizes both economic efficiency and environmental protection.

From a policy standpoint, the study underlines the necessity of transitioning from a localized approach to waste recycling towards a more regional or metropolitan level. The finding that municipalities with larger populations tend to exhibit greater eco-efficiency underscores the importance of adopting broader waste management policies that encompass multiple municipalities within a region. A notable challenge identified is the limited collaboration among neighboring municipalities. This highlights the potential benefits of developing regional policies that facilitate cooperation and coordination among municipalities to enhance waste management practices collectively.

The dissertation offers actionable recommendations for enhancing eco-efficiency in waste management. These include targeted environmental education initiatives at the local level, forming strategic partnerships with the private sector for financial support, and actively promoting recycling efforts. These strategies, aimed at improving waste management practices and eco-efficiency, can collectively contribute to more sustainable waste management outcomes across Chilean municipalities. Ultimately, these insights can guide policy-makers in formulating effective waste management strategies that align with both economic and environmental objectives.

CHAPTER 7.

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