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기후변화정책학 석사 학위논문

**Methane Emissions from  
Landfills of Municipal Solid  
Waste in Lima Province, Peru:  
Case Study of El Zapallal Landfill**

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# Chapter 1. Introduction

## 1.1 Background

In the world, waste generation rates are rising. In 2016, the world's cities generated 2.01 billion tons of solid waste, amounting to a footprint of 0.74 kilograms per person per day. With rapid population growth and urbanization, annual waste generation is expected to increase by 70% from 2016 to 3.40 billion tons in 2050 (The World Bank, 2022).

Compared to those in developed nations, residents in developing countries, especially the urban poor, are more severely impacted by unsustainably managed waste. Over 90% of waste is often disposed of in unregulated dumps or openly burned in low-income countries. These practices create serious health, safety, and environmental consequences. Poorly managed waste is a breeding ground for disease vectors, contributes to global climate change through methane generation, and can even promote urban violence (The World Bank, 2022).

Peru's economic growth has brought more significant amounts of solid waste due to increased consumption. However, despite higher economic income, there has been no timely investment in reducing waste generation or contamination of soils, rivers, and seas due to their poor disposal. Only during the five years 2014 - 2018, 35,305,971 tons of municipal solid waste were generated throughout the country, equivalent to 7,061,194 tons of municipal solid waste per year, 19,346 tons per day, and 806 tons per hour. 70% of this waste was generated in households (Ombudsman Office, 2019).

Likewise, municipal solid waste generation increased by 7% at the end of that period, from 6,904,950 tons (2014) to 7,374,821 tons (2018). In the same line, Lima, which has had around one-third of the national population for over one decade, increased 44.2% of the municipal solid waste generated in the country during the last five years (2014-2018). It is shown in figure 2 (Ombudsman Office, 2019).

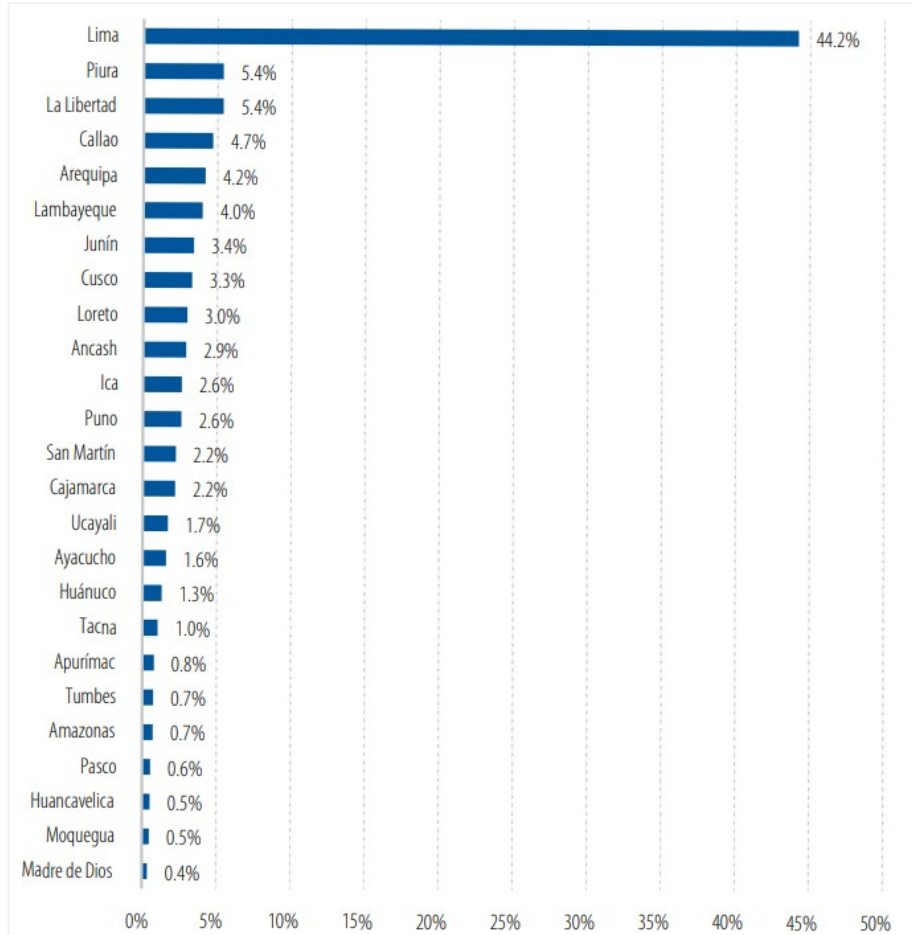
Currently, Peru has 1704 degraded areas by municipal solid waste and 955 areas degraded by non-municipal solid waste from construction and demolition, where the waste produced is dumped in dumpsites (Agency for Environmental Assessment and Enforcement – OEFA, 2022).

In 2019, there were 47 landfills, representing a deficit in landfills for waste generated in the country since Peru should have 256 landfills to cover the demand. (Ombudsman Office, 2019, pag. 153). In 2022, according to the OEFA (2022), 83 infrastructures of final disposition are in the National Inventory of Solid Waste



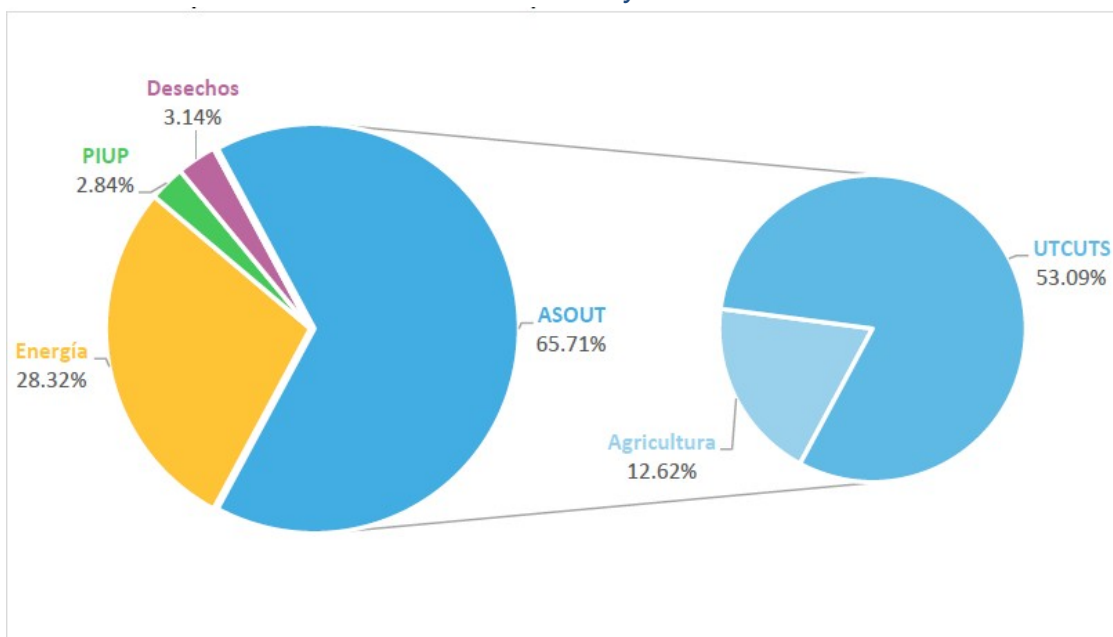
generates GHG emissions, with 3.14% (6,437.67 Gg CO<sub>2</sub>eq) of the net emissions. It is shown in figure 3.

Figure 2: Peru: Generation of municipal solid waste at the national level, 2014 – 2018



Source: Ombudsman Office, 2019

Figure 3: Percentage distribution of net emissions by sectors in the 2016 National GHG Inventory



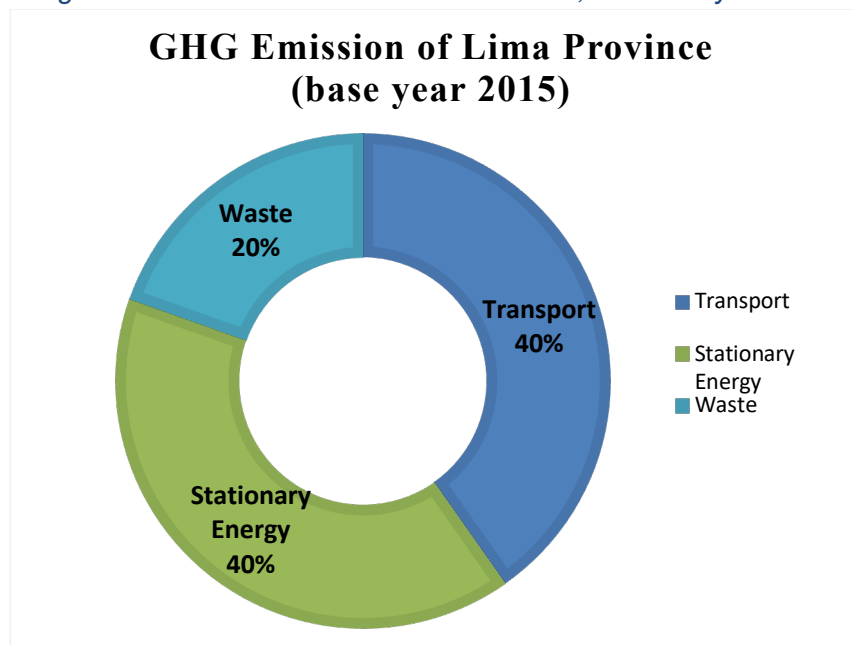
Source: Ministry of Environment, 2021

Likewise, Peru has updated its Nationally Determined Contributions (NDC) (2021-2030). This document considers measures of adaptation and mitigation that the country wants to reach for the year 2030 to reduce its vulnerability to the effects of climate change and reduce its green gases emissions (GEI) by 40%. Among the measures, the NDC considers 62 measures of mitigation, focusing on the sectors of i) stationary energy, ii) mobile energy, iii) industrial processes, iv) agriculture, v) Land Use, Land Use Change, and Forestry (LULUCF), and vi) waste sector. (Ministry of Environment, 2021).

Regarding the mitigation measures in the waste sector, it considers a) construction of sanitary landfills with semi-aerobic technology, b) the construction of sanitary landfills with capture and centralized burning of biogas, c) segregation of organic solid waste for material recovery in composting plants, and others similar actions for the reduction of GHG from the waste. (Ministry of Environment, 2018).

On the other hand, according to the Local Plan of Climate Change of Lima Province (2021), the main source of GHG emissions in Lima Province is the transport sector, with 6,355,530 t CO<sub>2</sub>eq (40%). It is followed by stationary energy with 6,340,795 tons CO<sub>2</sub>eq (40%) and the waste sector with 3,093,113 tons CO<sub>2</sub>eq (20%). The total emissions give an amount of 15,789,438 tons CO<sub>2</sub>eq.

Figure 4: GHG Emission of Lima Province, the base year 2015



Source: Prepared by the author based on the Local Plan of Climate Change of Lima Province, 2021

## 1.2 Objectives

### A. Main Objective

To determine the methane emissions of Municipal Solid Waste from El Zapallal Landfill in Metropolitan Lima-Peru, and the potential mitigation strategies.

### B. Specific Objectives

In order to fulfill the aforementioned overall objective, we have broken it down into three sub-objectives allowing us to keep the focus of this research:

- To predict the amount of Municipal Solid Waste (MSW) landfilled in El Zapallal Landfill of Lima Province, Peru.
- To estimate methane emissions (CH<sub>4</sub>) until 2050 from El Zapallal Landfill of Lima Province.
- To determine the potential mitigation strategy to reduce the methane gas emissions from landfills.



### **1.3 Research Question**

- How much will the Municipal Solid Waste (MSW) be landfilled in El Zapallal Landfill of Lima Province, Peru, in the period of 2021 to 2039?
- What will the future Methane (CH<sub>4</sub>) Emission forecast until 2050 from the MSW El Zapallal landfill in Lima Province, Peru?
- What mitigation strategy can be applied based on current and future methane (CH<sub>4</sub>) emissions from the Solid Waste Disposal Sites (SWDS)?

### **1.4 Significance of the Study**

This research aims to determine the methane emissions from one of the landfills of Municipal Solid Waste located in Lima Province, the capital of Peru, and the potential mitigation strategies to reduce the greenhouse gases (GHG) produced by this solid waste disposal site. Likewise, the other intended outcome is to predict the amount of Municipal Solid Waste (MSW) landfilled in the El Zapallal landfill until the projected closing year based on the future population and GDP. The information obtained in the study will contribute to identifying mitigation strategy options to reduce methane emissions from MSW disposal sites. The obtained information will further help Lima City find solutions to environmental issues and sustainable waste management in the future. Therefore, this research will be fundamental for policymakers to understand the source of emissions, apply strategies to reduce GHGs, and track progress. Moreover, the estimation of Methane in this representative landfill of Lima City will be a baseline for future inventories. Lastly, it will also be used to propose the establishment of waste processing facilities as landfill methane collectors to generate recovered energy to supply the self-support operation of the landfill.

### **1.5 Expected Outcomes**

This research is expected to include an inventory of methane emissions from 1990 to 2020, as well as projections until 2050, using the IPCC's FOD model for the El Zapallal landfill in Lima Province. Furthermore, the theoretical findings of this research will serve as the basis for other future studies in this field of study aligned with the model used and the circumstances of the area under investigation.

## Chapter 2. Literature Review

### 2.1 Overview of previous research related to emissions from landfills

Sereenendorj (2022) researched the methane emissions from the Landfill of Municipal Solid Waste in Ulaanbaatar city, Mongolia, to quantify methane emissions from Municipal Solid Waste (MSW) for three different landfills in Ulaanbaatar City, Mongolia. It sought to predict methane emissions until 2030 and determine the strategies to manage the methane gas emissions from landfills. In the development of this study, the author used the IPCC 2006 guideline, specifically the First Order Decay (FOD) model, to calculate CH<sub>4</sub> emissions from the Solid Waste Disposal Sites (SWDS). As part of the results, waste generation in Ulaanbaatar city SWDS used waste data that had entered the landfill over 12 years, and its prediction uses the geometry method. The amount of waste generated in the landfills from the 2009-2020 data increased in quantity, and Methane emissions increased from 2009-2020. The prediction results of methane emissions (CH<sub>4</sub>) are based on population and waste generation. Based on the solid waste generation forecast, methane emissions (CH<sub>4</sub>) prediction in 2030 reached around 40 Gg under scenario 1. This emission will remain almost stable at approximately 12 Gg in the same years under scenario 2.

Samadov (2022) conducted the research called *Energy Potential of Methane Collected from Landfills of Municipal Solid Waste in Azerbaijan (Sumqayıt case study)* to find the amount of Methane from MSW, energy generation potential of Methane, and the cost of using Methane from MSW for electricity production in Sumqayıt city landfill for between 2021 and 2040. The author used the IPCC tier 2 method to calculate the methane CH<sub>4</sub> from MSW. This methodology required quality country-specific activity data (AD) and historical waste disposal data from 2005 to 2020. On the other hand, the energy potential of Methane from municipal waste in Sumqayıt city was estimated based on primary and secondary data. The amount of disposal waste in the landfill and the composition of the waste, as well as the population, were considered primary data (from 2005 to 2020) but also predicted the future population from 2021 to 2030 through the linear growth model. The secondary data was related to IPCC 2006 guidelines, such as methane correction factor, oxidation factor, etc. One of the findings was the amount of CH<sub>4</sub> from 2021 to 2040 rose over the years; after the starting years (2021) reached 252-ton CH<sub>4</sub> and peaked in 2031. After the closing year of the landfill with 4185,96 tons of CH<sub>4</sub>. After 2031 the amount of Methane reduces gradually until the end of 2040. In 2040 the amount of CH<sub>4</sub> will be 2524,03 tons. The total amount of Methane for 2021-2040 will be 67694,28 tons.

On the other hand, the electricity generation potential of the Methane from MSW was calculated using the LFG-COST web model. Methane's highest electricity generation capacity was in the "Standard reciprocating engine-generator set" and "CHP- Standard reciprocating engine-generator set" projects with 1925502 kW. The lowest capacity was in the "Small Engine Generator Set" with 1189169kW electricity.

Cai et al. (2018) researched the CH<sub>4</sub> mitigation potential from China landfills and related environmental co-benefits. In this study, the authors estimated and projected the emissions from China's CH<sub>4</sub> emissions from 1955 existing (old) and 495 planned (new) landfills, through the First Order Decay (FOD) model, with a 2012 baseline year and 2030 projected target year. Likewise, Nine key CH<sub>4</sub> mitigation measures were proposed for the CH<sub>4</sub> mitigation assessment from landfills. Approximately 0.66 million metric tons (Mt) of CH<sub>4</sub> and 1.14 Mt of CH<sub>4</sub> were released from new and existing landfills under a 2030 business-as-usual (BAU) scenario, which is 23.5% lower than a U.S. Environmental Protection Agency estimation.

At the same time, it was estimated that 0.60 and 0.97 Mt of CH<sub>4</sub> could be reduced under new policies (NP) and low-carbon (LC) policy scenarios, respectively. The authors referred that the combined bio cover and landfill gas collection and the flaring system is the most promising mitigation measure, while mechanical biological treatment and mineral landfill also contribute substantially to CH<sub>4</sub> reduction.

Xiaoli et al. (2016) conducted research called *Methane emissions as energy reservoir: Context, scope, causes, and mitigation strategies*, to make known the Methane (CH<sub>4</sub>) as a bridge fuel between the present fossil (carbon) economy and desired renewables and its influence in the global energy mix well beyond 2035. The authors also mentioned that CH<sub>4</sub> is the second most abundant greenhouse gas (GHG), accounting for 14.3% of global anthropogenic GHG emissions. Five key anthropogenic sources: agriculture, coal, landfills, oil and gas operations, and wastewater, accounted for 68 percent of all CH<sub>4</sub> emissions. Landfills are ranked as the third-highest anthropogenic CH<sub>4</sub> emission source, behind agriculture and coal mines. (2015).

CH<sub>4</sub> has the potential as an energy source production and pathways for conversion into renewable gaseous fuel for use as compressed natural gas (CNG) and clean liquids. The authors did a review where they mentioned that it could be used as either a drop-in replacement (gasoline, diesel, jet fuel hydrocarbons) or advanced oxygenated fuels such as methanol, a clean diesel substitute.

Yedla & Sindhu (2016) researched the Assessment of alternative disposal methods to reduce greenhouse gas emissions from municipal solid waste in India to estimate

the GHG control potential associated. With alternative waste disposal methods suited to conditions in India and the relative costs to control GHG emissions. Among the alternative solid waste disposal methods were considered the most common methods adopted and accepted for disposal of waste in India i) Aerobic composting (windrow composting), ii) Vermi-composting, iii) Anaerobic digestion, and iv) Purpose Built Landfill System (PBLF), which is a semi-engineered landfill system with gas recovery and leachate collection system targeting at methane harvest.

According to the authors, the purpose-built landfill system has shown promise in controlling greenhouse gas and saving land. However, these studies show that aerobic composting offers the optimal method to regulate greenhouse gas emissions and reduce costs, mainly by requiring less land than other methods.

Stanisavljević et al. (2012) researched the estimation of methane emission from landfills in Serbia and potential mitigation strategies. They identified and characterized waste disposal sites. One of the main findings was that only 50 landfills in Serbia contained more than 100,000 m<sup>3</sup> of waste, producing approximately 60,000 tons of CH<sub>4</sub> emissions in 2010. Likewise, the researchers evaluated different measures [*soil cover*, compost cover, and landfill gas (LFG) systems] for mitigating greenhouse gas emissions from Serbian landfills. It indicated that enhanced microbial CH<sub>4</sub> oxidation (using a compost cover) and installing LFG systems could generate net revenues as saved CH<sub>4</sub> emissions are creditable for the European Greenhouse Gas Emissions Trading Scheme. Between 4 and 7 million tons of CO<sub>2</sub> equivalent, emissions could be avoided within 20 years by mitigating CH<sub>4</sub> emissions from Serbian landfills.

Matthews & Themelis (2007) researched the Potential for Reducing Global Methane Emissions from Landfills, 2000-2030. This study investigated the potential for future mitigation of methane emissions from landfills. The authors developed reference projections of waste generation, recycling, and landfill gas capture, together with four waste in Waste-to-Energy (WtE) scenarios ranging from very conservative to aggressive. These scenarios show global 2030 CH<sub>4</sub> emissions, including recycling reductions, ranging from 86 Tg (most conservative) to 27 Tg (most aggressive). WtE appears to provide the best option for limiting future waste-related emissions.

Kumar et al. (2004) conducted the Estimation method for national methane emission from solid waste landfills to estimate the realistic values of methane emission from municipal solid waste (MSW) in Indian landfills by carrying out extensive investigations from the field and available national statistics. The authors mentioned that in India, most of the solid wastes are disposed of by landfilling in low-lying areas located in and around the urban centers resulting in the generation of large quantities of biogas containing a sizeable proportion of Methane. The

estimation of methane gas is directed to estimate the Landfill Gas (LFG) for its extraction and utilization as a renewable energy source. The authors also said that after a review of the literature on the methodology for estimating methane emissions, the default methodology was used in the estimation following the IPCC guidelines 1996. However, as the default methodology assumes that all potential Methane is emitted in the year of waste deposition, a triangular model for biogas from landfills was proposed, and the results were compared. Therefore, according to the authors, the methodology proposed for methane emissions from landfills based on a triangular model is more realistic and can very well be used in estimation on a global basis. The LFG could be better estimated using the first-order decay (FOD) in two phases. In the first phase, the generation rate keeps increasing until the peak is reached; after that, it keeps declining until the material is stabilized. Methane emissions from MSW landfills for the year 1980– 1999 were estimated, which could be used in computing national inventories of methane emissions.

## **2.2 Acts / Policies Focus on the Reduction of Greenhouse Emissions from the Waste Sector in Peru**

### **2.2.1 Catalog of Mitigation Measures Part of the Nationally Determined Contributions (NDC) 2021 – 2030**

Peru was the first Hispanic American to ratify the Paris Agreement in 2016; hence, in 2020, the Nationally Determined Contribution (NDC), submitted previously in 2015, was updated for 2021 to 2030.

The Ministry of the Environment, through a cross-sectorial initiative involving 13 government portfolios, has developed the "Catalog of Mitigation Measures." This document contains actions to mitigate the country's greenhouse gas (GHG) emissions as part of the Nationally Determined Contributions (NDC). NDC is the Peruvian response to climate change that seeks to reach for the year 2030, the reduction of vulnerability and the effects of climate change, as well as reduce its green gases emissions (GEI) by 40%.

Among the mitigation measures, the "Catalogue of Mitigation Measures" of the NDC considers 62 measures of mitigation, focusing on the sectors of i) stationary energy, ii) mobile energy, iii) industrial processes, iv) agriculture, v) Land Use, Land Use Change and Forestry (LULUCF), and vi) waste sector. (Ministry of Environment, 2021).

Regarding the mitigation measures in the waste sector, it considers the following measures:

- a) Construction of sanitary landfills with semi-aerobic technology,
- b) Construction of sanitary landfills with capture and centralized burning of biogas,
- c) Segregation of organic solid waste for material recovery in composting plants, and other similar actions for the reduction of GHG from the waste. (Ministry of Environment, 2018).

## 2.2.2 Local Plan of Climate Change (LPCC) of Lima Province 2021 – 2030

The Local Plan of Climate Change of Lima Province 2021 – 2030 was enacted in June of 2021 through the Municipal Ordinance N° 2353-2021.

As part of the diagnostic of the Local Plan of Climate Change of Lima Province, it refers that the main source of GHG emissions in Lima Province is the transport sector, with 6,355,530 t CO<sub>2</sub>eq (40%). It is followed by stationary energy with 6,340,795 t CO<sub>2</sub>eq (40%) and the waste sector with 3,093,113 t CO<sub>2</sub>eq (20%). In total, it gives a global amount of 15,789,438 t CO<sub>2</sub>eq.

Whereby as part of the mitigation measure for reducing these emissions, specifically in the waste sector, the Local Plan of Climate Change of Lima Province establishes some measures described below, intending to reduce *greenhouse gas emissions in the Province of Lima by 30% compared to the trend scenario*. Likewise, these measures seek to *minimize generation, maximize selective collection and modernize infrastructure to recover organic and inorganic waste*.

*Table 1: Mitigation Measures to reduce GHG in the Waste Sector, identified by the Local Plan of Climate Change of Lima Province*

<b>Comprehensive Solid Waste Management Strategy</b>	
<b>Measures identified by the LPCC of Lima Province</b>	<ul style="list-style-type: none"> <li>• <b>Preparation of the Comprehensive Solid Waste Management Plan - PIGARS in the Province of Lima and future updates</b></li> </ul> <p>This action proposes implementing the city's Comprehensive Solid Waste Management Plan - PIGARS, which defines the measures to be taken for efficient solid waste management on a metropolitan scale.</p> <ul style="list-style-type: none"> <li>• <b>Improvement and expansion of the public cleaning service of the Cercado de Lima and modernization of solid waste infrastructure of the Metropolitan Municipality of Lima</b></li> </ul> <p>Improve and expand the collection of solid waste in the Historic Center of Lima, including the implementation of electric vehicles for its transfer. Likewise, the implementation of a Municipal Solid Waste Treatment and Recovery Plant in an available area of the property where the "El Zapallal" sanitary landfill is located, including the progressive construction of</p>

	infrastructures for the material and energy recovery of municipal organic solid waste, as well as the implementation of other technologies.
<b>Prioritized Actions for the Solid Waste Strategy</b>	
<b>Action 1</b>	<b>Improvement and expansion of the public cleaning service in the Cercado de Lima and modernization of the waste infrastructure solids of the Metropolitan Municipality of Lima</b>
	<p>This action includes assisting in modernizing solid waste infrastructure at the Lima Province level. It consists of some measurements such as:</p> <ul style="list-style-type: none"> <li>• To implement a Municipal Solid Waste Treatment and Recovery Plant in an area of the property where the "El Zapallal" landfill is located.</li> <li>• Progressively implement methane capture infrastructures and material and energy recovery of municipal organic solid waste.</li> </ul>
Stakeholders involved	<ul style="list-style-type: none"> <li>• Metropolitan Municipality of Lima</li> <li>• District Municipalities</li> <li>• Ministry of Environmental</li> </ul>
<b>Action 2</b>	<b>Recycling program "Recycle Lima"</b>
	<p>Establishment of 3 measures to strengthen the segregation program at the source:</p> <ul style="list-style-type: none"> <li>• Recovery of organic waste from food markets and homes to produce organic fertilizers through composting, vermiculture and others.</li> <li>• Recovery of inorganic waste segregated at the source is collected by formalized waste pickers before door-to-door awareness by a team of environmental promoters.</li> <li>• The formalization of waste pickers carried out after training on the comprehensive management of solid waste, business management, personal skills, and personal protection equipment.</li> </ul>
Responsible actors and strategic partners	<ul style="list-style-type: none"> <li>• Metropolitan Municipality of Lima</li> <li>• Ministry of Housing and Construction</li> <li>• Construction sector unions</li> <li>• Green Building Council District Municipalities</li> </ul>
Actors benefited	The population of Lima Province

Source: Elaborated based on the Local Plan of Climate Change of Lima Province  
2021 – 2030

## 2.3 Legislation Related to Waste Management in Peru

### 2.3.1 Comprehensive Waste Management Law Solids, Decree of Law N° 1278

In December 2016 saw the approval of the Comprehensive Waste Management Law Solids - Decree of Law N° 1278. This law establishes rights, obligations, attributions, and responsibilities for the recovery of components, treatment, or recovery of soils, among other options that avoid their final disposal. Likewise, the mentioned law applies to the activities, processes, and operations of the management and handling of solid waste, from generation to final disposal, including the different sources of generation of said waste, in the economic, social, and community sectors.

*Table 2: Articles from the Comprehensive Waste Management Law Solids of Peru (Decree of Law N° 1278) related to the research*

<b>Comprehensive Waste Management Law Solids (CWMLS) - Decree of Law N° 1278</b>	
Article 24.1, items a), c),	The District Municipalities, in terms of solid waste management, are competent to:  a) Ensure an adequate provision of the cleaning service, collection, and transport of waste in its jurisdiction, and must guarantee the adequate final disposal of the same.  c) Regulate, in their jurisdiction, the management of solid waste services under its jurisdiction, under the provisions issued by the provincial municipalities.
Article 24.1, item d) of the CWMLS	Regarding solid waste management, the District Municipalities are competent to promote and progressively implement segregation programs at the source and the selective collection of solid waste throughout its jurisdiction, facilitating waste recovery and ensuring a technically adequate final disposal.
Article 51 of the CWMLS	Municipalities must prioritize organic waste from the maintenance of green areas and municipal markets, as well as, if feasible, organic waste from households.
Article 69, item b) of the CWMLS	Municipalities, sectors, and MINAM must promote, through actions aimed at raising awareness and training, that the population reaches a high degree of awareness, education, and environmental culture in the country that allows it to get actively involved in the minimization, segregation at source and proper management of the solid waste it generates.

Source: Elaborated by the Author



### 2.3.2 Regulation of the Comprehensive Waste Management Law Solids - Supreme Decree N° 014-2017-MINAM

Regarding the Regulation of the Comprehensive Waste Management Law Solids, it was enacted through Supreme Decree N° 014-2017-MINAM in December 2017. This Regulation is intended to ensure constant maximization of efficiency in the use of materials and to regulate the management and handling of solid waste. It includes the minimization of the generation of solid waste at the source, the material, and energy recovery of solid waste, its adequate final disposal, and the sustainability of public cleaning services.

Between the articles of the Comprehensive Waste Management Law Solids (CWMLS), it mentions the following items:

*Table 3: Articles from the Regulation of the Comprehensive Waste Management Law Solids of Peru (Decree N° 014-2017-MINAM ) related to the research*

<b>Regulation of the Comprehensive Waste Management Law Solids - Decree N° 014-2017-MINAM</b>	
Article 11 of the Regulation of the CWMLS	The Solid Waste Segregation at Source and Selective Collection Program is a technical instrument <i>developed by the municipalities</i> whereby strategies are formulated for source segregation and the design of a selective collection of solid waste generated in their jurisdiction, considering an approach that includes the participation of organizations of formalized waste pickers.
Article 19 of the Regulation of the CWMLS	Municipalities must regulate the process of segregating municipal solid waste at the source in their jurisdiction within the framework of the Program for Segregation at the Source and Selective Collection of Solid Waste
Article 114 of the Regulation of the CWMLS	In the case of Sanitary landfill facilities, it mentions:  In the case of sanitary landfills that handle more than 200 tons of solid waste per day, centralized gas capture and burning must be progressively implemented in order to reduce greenhouse gas emissions. If they are less than 200 tons per day, capture and conventional burning of gases or another measure to mitigate greenhouse gases must be implemented. Similarly, they may include energy recovery activities through the use of biomass for power generation.

Source: Elaborated by the Author

## **2.4 Legislation Related to Climate Change in Peru**

### **2.4.1 Framework Law on Climate Change (FLCC) - Law N° 30754**

On April 17, 2018, Peru enacted the Framework Law on Climate Change N° 30754, reaffirming its commitment to sustainable growth for present and future generations. Subsequently, on December 31, 2019, Supreme Decree N° 013-2019-MINAM approved the Regulation of this law.

Article 8 of the FLCC refers that regional and local governments, within the framework of their powers and functions, are responsible for the following:

Article 8.1: Execute national public policies on climate change and design, monitor, evaluate and redesign regional strategies on climate change.

Article 8.2: Incorporate climate change mitigation and adaptation measures in its Territorial Plan, Regional and Local Concerted Development Plan, Institutional Strategic Plan, Institutional Operational Plan, Budget Programs, and investment instruments. Among other responsibilities.

Likewise, in article N° 16 of the FLCC, about climate change mitigation measures, it mentions:

Article 16: The State, at all levels of government, in an articulated and participatory manner, designs and implements programs, projects, and activities aimed at reducing greenhouse gas emissions, such as carbon sequestration and the increase of sinks; prioritizing the protection, conservation, and sustainable management of forests, afforestation, and reforestation; the control of the use and change of land use; sustainable transport; solid waste management, among others.

## **Chapter 3. Methodology**

### **3.1 Data Collection and Analysis**

The theoretical framework of this research is prepared based on references from the previous study, research articles, domestic and international information, and reports.

Moreover, this study collects three kinds of secondary data, Population, Gross Domestic Product (GDP), and Municipal Solid Waste (MSW) generation data of Metropolitan Lima in the last twenty-five years (1996 to 2020) provided by the Municipality of Lima. Data processing, analysis, and discussion of methane emission estimation based on (1) waste generation and waste characteristics in the municipal solid waste landfill (El Zapallal landfill), (2) the Population of Metropolitan Lima, and the population of the districts attended by the El Zapallal landfill, and the (3) GDP per capita, will be done using the methodology of IPCC Waste Model 2006.

### **3.2 Study Area: El Zapallal Landfill of Lima Province**

This study is conducted in a semi-aerobic managed landfill, El Zapallal Landfill, located in Metropolitan Lima (Lima Province), the capital of Peru, with a population of more than 10 million people.

According to United Nations (2019), Metropolitan Lima is also considered a megacity due to its number of inhabitants, it represents almost 30% of the population of Peru (33 million 396 thousand 698 people) concentrated in that area. (National Institute of Statistics and Informatics, 2022).

El Zapallal landfill is one of the two landfill sites in Lima province, where the MSW generated by the province of Lima is sent. Currently, It collects 20.4% of the total MSW produced in Lima (National Institute of Statistics and Informatics, 2021), as is shown in figure 8.

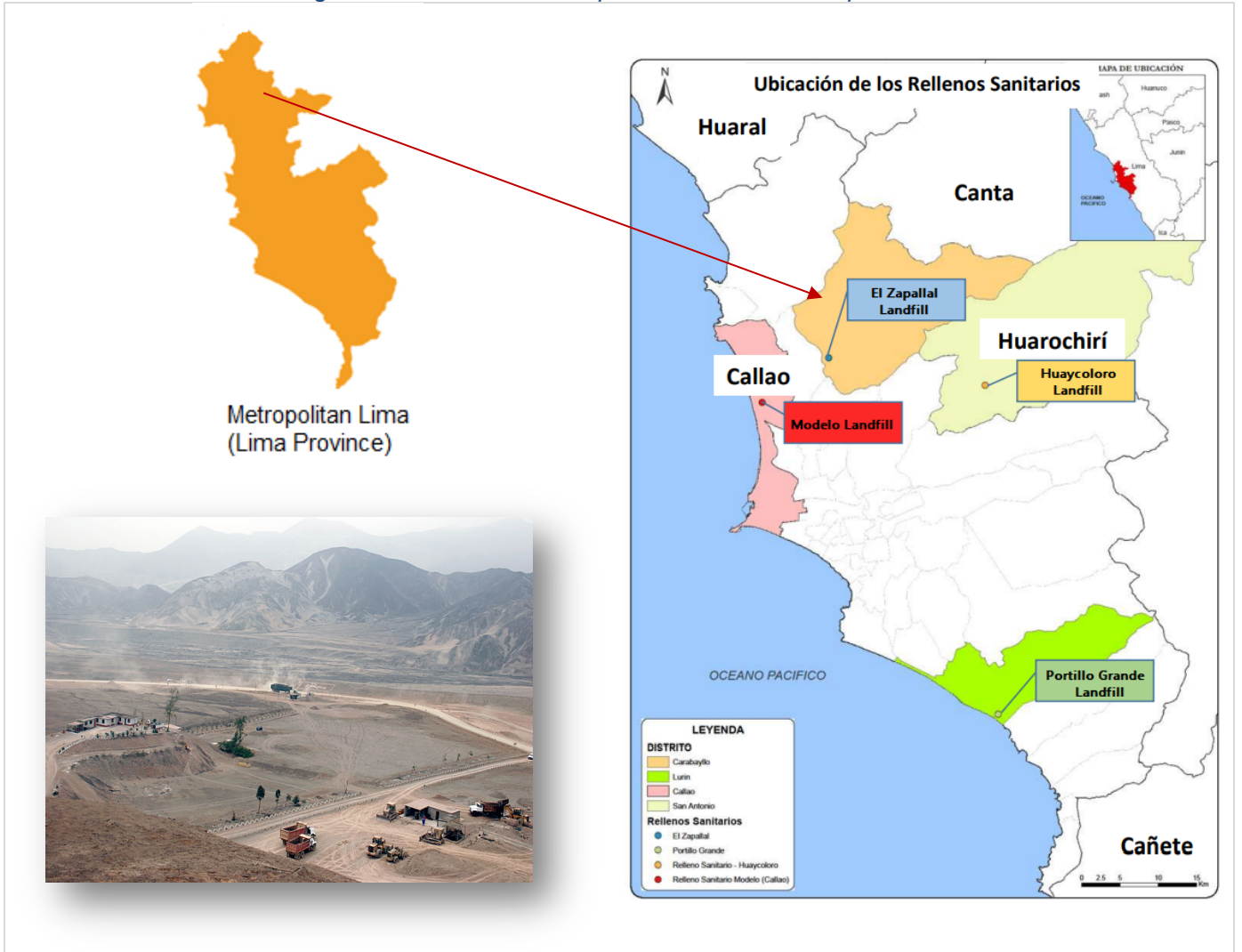
*Figure 5: Location of Metropolitan Lima*



Source:

<https://www.istockphoto.com/kr/collaboration/boards/RKMkZCOSMEGGGZ3zjniDow>

Figure 6: Location of El Zapallal Landfill in Lima province

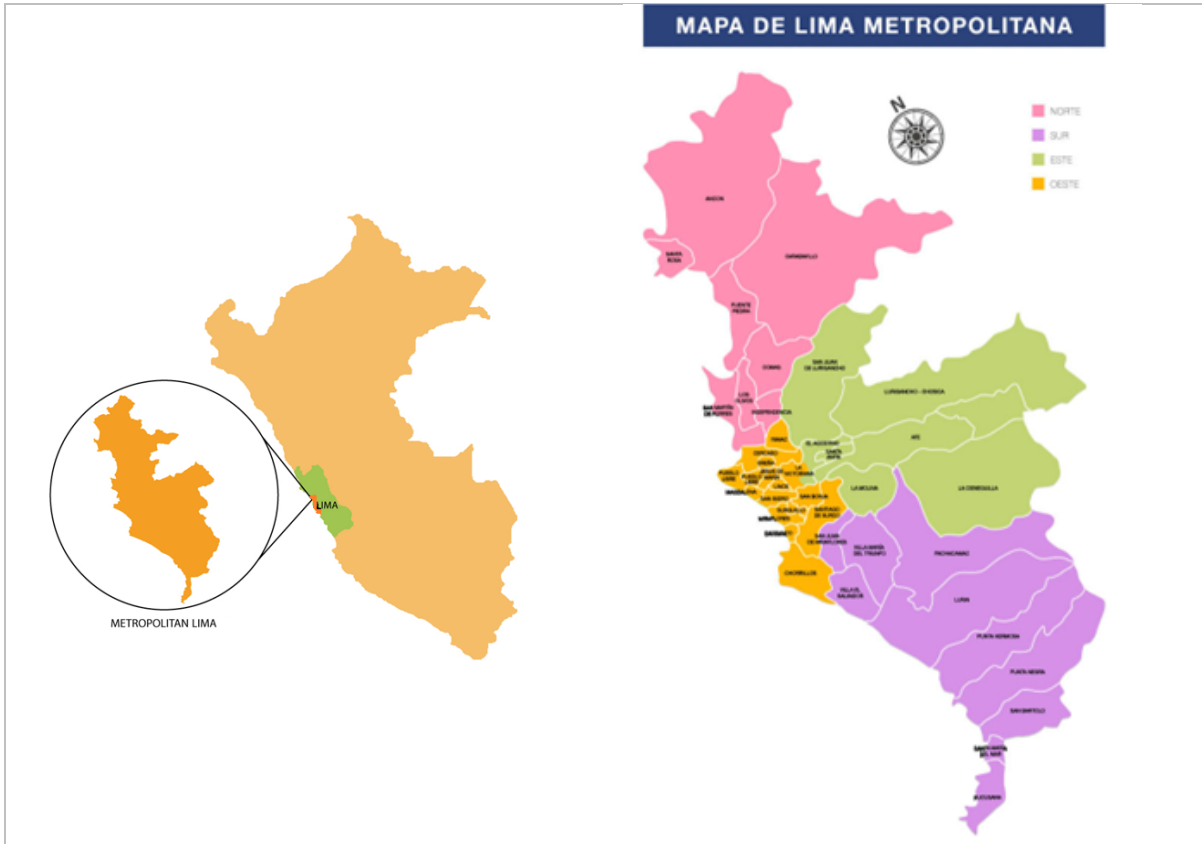


Source: Municipality of Lima (2014)

Lima province has 43 districts, and each district is in charge of the management of waste, as the recollection, and the disposition of the waste in the surrounding landfills.

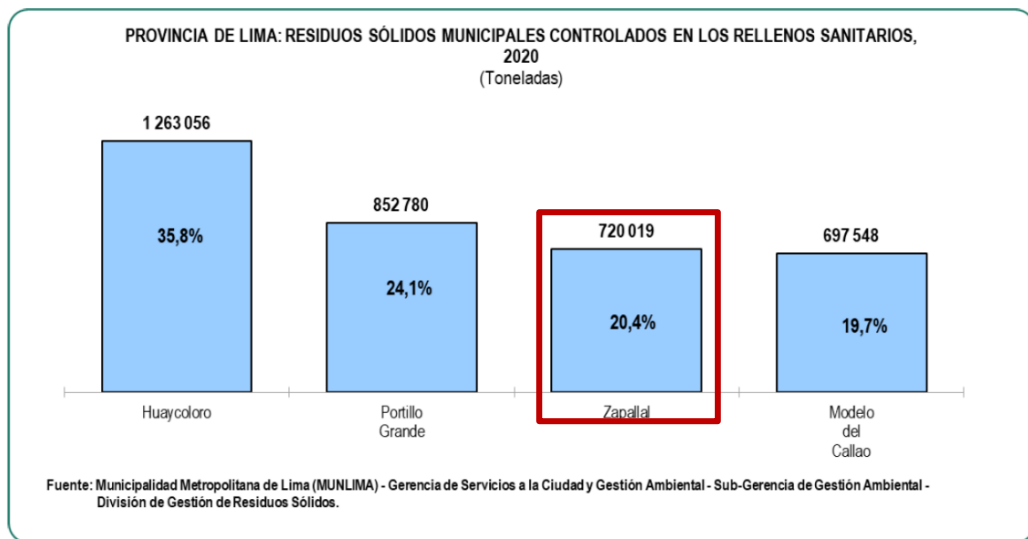
These districts of Lima province, due to the lack of landfills, dispose of their municipal solid waste in four (04) landfills. Two (02) of them are located in their own jurisdiction (in the south and north), which are under the administration of the Municipality of Lima; another is in the Constitutional Province of Callao, and the other is located in the province of Huarochiri (Municipality of Lima, 2021), as is showed in figure 6, and detailed in Table 4.

Figure 7: Map of Metropolitan Lima with its 43 districts



Source: Adapted by the author from <https://www.mapadelima.com/mapa-de-districtos-de-lima/>

Figure 8: Landfills used by the districts of Metropolitan Lima (Lima Province) to dispose of their MSW



Source: National Institute of Statistics and Informatics [INEI], 2021

Table 4: Landfills in which the districts of Metropolitan Lima dispose of their MSW

Name of the facility	Category	Other Province (out of Lima province)	Lima Province (Metropolitan Lima)	Attended Districts (*)
1 El Zapallal	Landfill & sites for hazardous	-	X District: Carabayllo	8 Seven districts from Lima Province & 1 district from Canta Province District of Lima Province: Barranco, Breña, Carabayllo, Magdalena del Mar, Puente Piedra, Rimac, San Juan de Miraflores; District of Canta Province: Santa Rosa de Quives.
2 Portillo Grande	Landfill & sites for hazardous	-	X District: Lurín	11 Ten districts from Lima Province & district of Huarochirí Province District of Lima Province: Lima Cercado, Chorrillos, Pucusana, Punta Hermosa, Punta Negra, San Bartolo, San Borja, Santa María del Mar, Villa El Salvador, Villa María del Triunfo; District of Huarochirí Province: Santo Domingo de Olleros
3 Huaycoloro	Landfill & sites for hazardous	X	-	22 Among districts of Lima Province & of

4	Petramas S.A.C. (El Modelo)	Landfill	Province: Huarochirí X Constitutional Province: Callao	-	17	Huarochirí Province Districts of Lima Province & districts of Callao Province
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Source: Prepared by the author based on the Ministry of Environment (2021)

(\*) The Ministry of Environment (2021), in its *List of landfills 2021 mentioned that there are cases, especially in Lima Province, in which one district can be attended by more than one landfill.*

### 3.3 Features and Parameters of El Zapallal Landfill

The following table presents some features of the El Zapallal landfill, as well as some parameters of this to use in the methodology to estimate CH<sub>4</sub> emissions.

[Table 5: Description of El Zapallal landfill assessed in the current study](#)

Landfill	El Zapallal
Location	District of Carabayllo, North of Lima province
Climatic Characteristics	Hyper-arid coast <sup>1</sup>
Average temperature	18.7 °C <sup>2</sup>
Average annual precipitation (mm)	16 mm <sup>3</sup>
Altitude (masl)	365 masl
Daily capacity (tons)	2800 tons/day (2019) <sup>4</sup> 326.5 hectares (ha), actual.
Area	Before: 338.89 ha. [According to MML (2014), PIGARS]
Type of Landfill	Mechanized Landfill, Semi-aerobic managed landfill
Start Operation	1990 [According to the MML(2014), MML(2022)]
Lifespan	2039(*)

<sup>1</sup> (Ziegler-Rodriguez et al., 2019)

<sup>2</sup> (Ziegler-Rodriguez et al., 2019)

<sup>3</sup> (Ziegler-Rodriguez et al., 2019)

<sup>4</sup> (Equipo de residuos sólidos ETRS - FIA UNI, 2021) & (MML, 2022)



Owner	Municipality of Lima
Administrated by	Innova Ambiental, since 1996 (private enterprise)
Leachate collection system	Through longitudinal and transverse drains
Leachate treatment system	Recirculation
Biogas collection system	Through vertical drains and burner installation (Chimneys)
Biogas treatment system	Gas burning gas burning (Combustion)

Source: Elaborated by the Author

(\*) In the *Integral Plan of Waste Management in Lima Province [PIGARS] 2015-2025* of the Municipality of Lima (2014), they mentioned that lifespan of the Zapallal landfill was 25 years further, whereby the lifespan is considered until 2039.

Table 6: Values employed for the case study El Zapallal landfill. The values in parentheses represent the upper and lower ranges of these parameters

Parameter	Value
<i>DOC (Degradable organic carbon)</i>	
DOC – Food waste	0.15 (0.08 – 0.20)
DOC – Paper waste	0.4 (0.36 – 0.45)
DOCf (Fraction of DOC dissimilated)	0.5
MCF (Methane Correction Factor)	0.5 [ <i>Managed - semi-aerobic</i> ]
F (Fraction of methane)	0.5
<i>k (Methane generation rate constant)</i>	<i>Dry temperate</i>
k – Food waste	0.06 (0.05 - 0.08)
k – Paper waste	0.04 (0.03 - 0.05)
OX (Oxidation factor)	0 [ <i>Managed</i> ]
R (Methane recovery)	0

Source: Elaborated by the Author based on data from IPCC

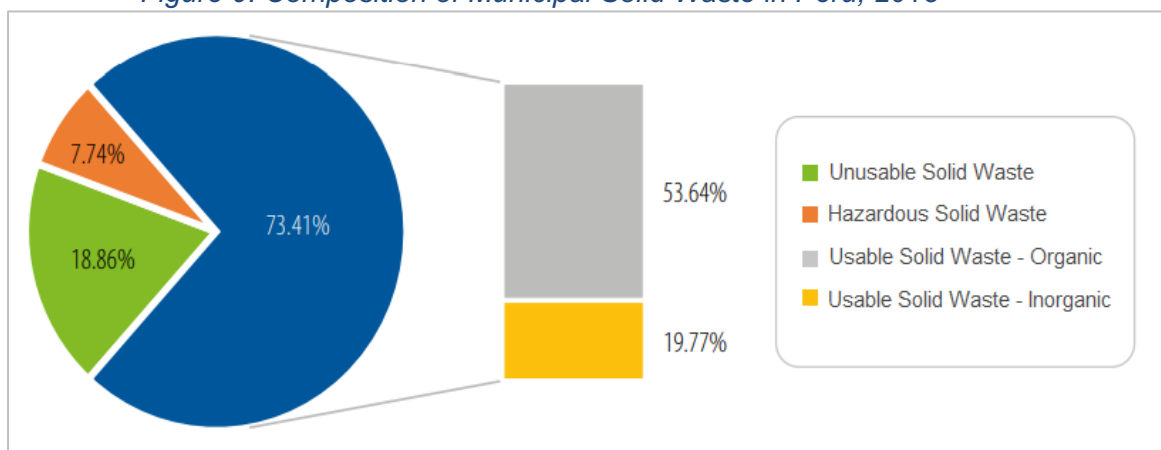
### 3.4 Waste Composition in El Zapallal Landfill

According to the Ombudsman Office (2019), based on the information provided by the Ministry of Environment, mentioned that in the year 2018, the municipal solid

waste composition generated in Peru was distributed as follows: **53.64% of organic solid waste** (3,800,712.15 tons), 19.77% of inorganic solid waste (1,400,585.3 ton), 18.86% of unusable solid waste (1,336,020.45 ton), and 7.74% of hazardous solid waste (548,328.55 ton).

Likewise, this institution indicated that 53.64% of the organic waste generated in 2018 originates mainly from domiciliary. These residues generate some of the Greenhouse Gases (GHG), which cause global warming. Therefore, it was important that citizens, companies, and all those who generate this type of waste implement, for example, composting in their homes and/or in their facilities. Similarly, it was required that the municipalities promote this and other harvesting techniques.

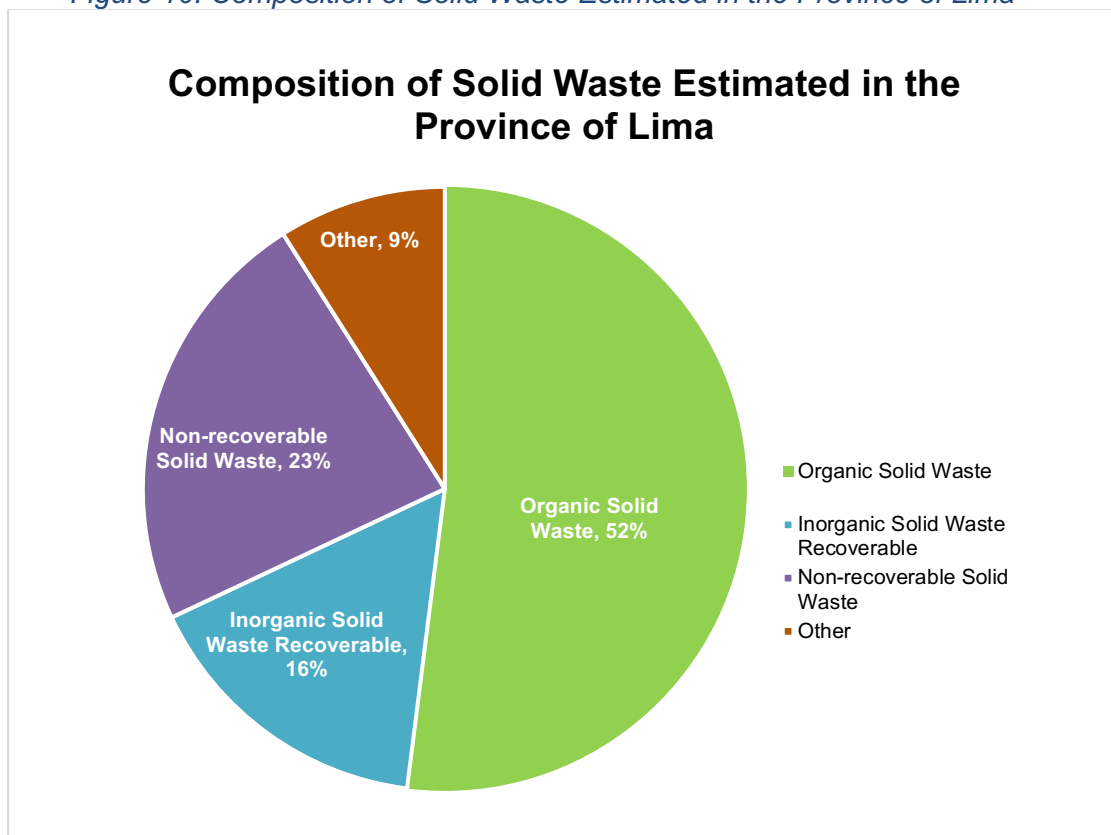
*Figure 9: Composition of Municipal Solid Waste in Peru, 2018*



Source: Ombudsman Office, 2019

Related to the composition of municipal solid waste in Lima Province, in the year 2019, it is estimated that **52% is organic solid waste**, 16% is inorganic solid waste recoverable, and 23% is non-recoverable solid waste. (Municipality of Lima, 2021)

Figure 10: Composition of Solid Waste Estimated in the Province of Lima



Source: Municipality of Lima, 2021

Respect the characterization of the waste deposited in the El Zapallal landfill, it was obtained from the analysis of the Consulting for the development of a baseline to support the definition of prioritized measures in the CAP: Greenhouse Gas Reduction Analysis (2020) carried out by the Metropolitan Municipality of Lima and the organization C40 Cities.

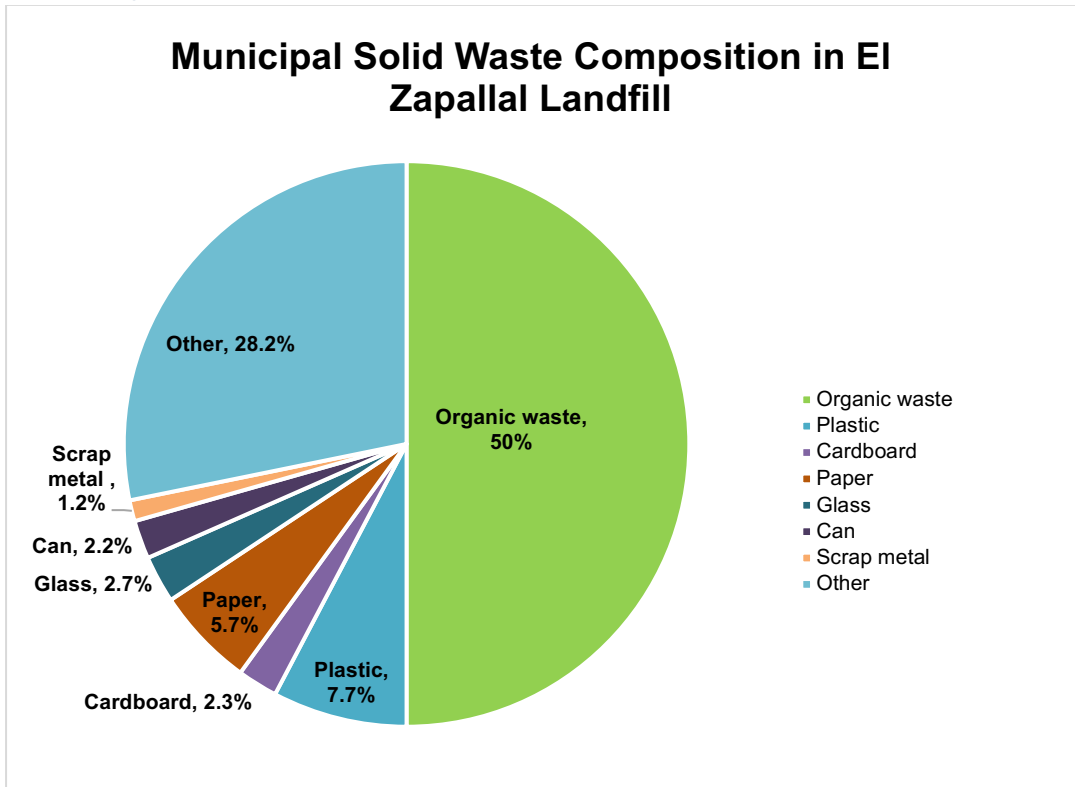
Therefore, in this study, an average of the percentage of waste deposited was calculated according to its typology, considering the data of the districts served by the El Zapallal landfill. Based on the characterization reports of the waste deposited in the landfill under study, compiled by the National Institute of Statistics and Informatics (INEI in Spanish). Published in their Yearbooks of Environmental Statistics. Obtaining the following values of municipal solid waste composition in the El Zapallal landfill:

Table 7: Municipal Solid Waste Composition in El Zapallal Landfill

<b>Organic waste</b>	<b>Plastic</b>	<b>Cardboard</b>	<b>Paper</b>	<b>Glass</b>	<b>Can</b>	<b>Scrap metal</b>	<b>Other</b>	<b>Total</b>
50%	7.7%	2.3%	5.7%	2.7%	2.2%	1.2%	28.2%	100%

Source: Municipality of Lima, 2022

Figure 11: Municipal Solid Waste Composition in El Zapallal Landfill



Source: Elaborated by the Author, based on the information of the Municipality of Lima (2022)

### 3.5 Estimation Method for Solid Waste Generation Rates (SWGR)

According to the literature review on solid waste management, a city's population and economic growth directly affect how much waste is produced there. In the case of this study, known information on landfill garbage at the El Zapallal landfill for specific and scattered years was merged with SWGR values from several scientific sources used in our literature review. This gave us a starting point from which we could apply prediction techniques to fill in the years that were lacking. The SWGR is correlated with the population and its income (GDP). The Incremental Increase Method was helpful for forecasting the population up to 2050 according to the following mathematical expression:

*Equation 1: Incremental Increase Method Equation*

$$P_n = P_o + nI + n \left( \frac{n+1}{2} \right) Y$$

Where:

$P_n$  = Future population  
 $P_o$  = Present population  
 $I$  = Average increment per decade  
 $Y$  = Incremental increase  
 $n$  = no. of decades.

Regarding the GDP per capita, we used the data available from the World Bank for the country of the period from 1990 to 2020 to project future years until 2050 by the method of extrapolation following an exponential model by means of Microsoft Excel.

*Equation 2: Exponential Extrapolation Model between GDP per capita and years*

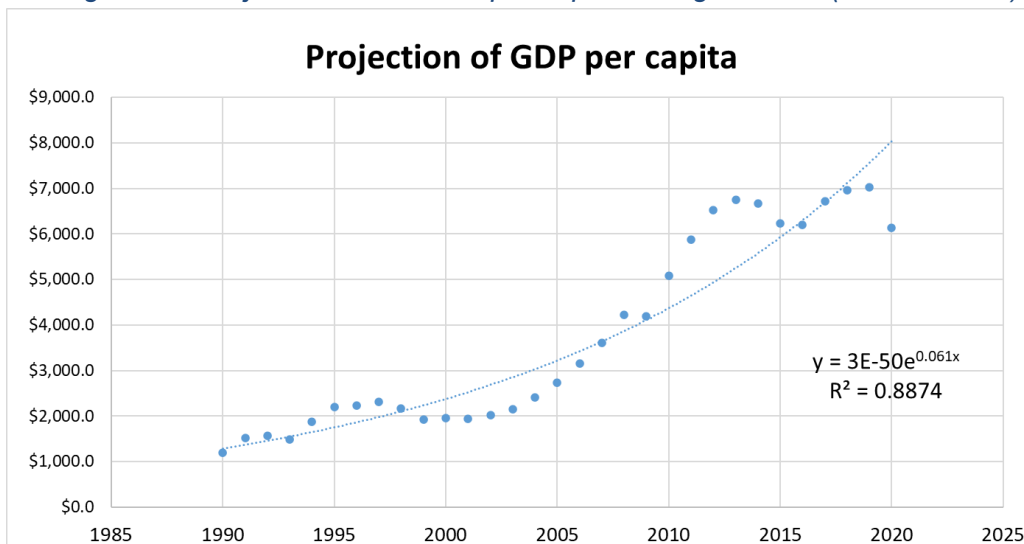
$$GDP = 3E - 50(e)^{0.061X}$$

Where:

$X$  = Year

$GDP$  = Gross Domestic Product per capita

*Figure 12: Projection of the GDP per capita during the time (1990 to 2020)*



Source: Prepared by the author

Since we already know the population and GDP projections for the following years (2021 to 2050), the projective series of the WGR will be obtained from the correlation of the multiple linear regression between SWGR known (1990 to 2020), population attended by the landfill, and GDP in the same period. Then we must determine what variable has more relation to define our model to estimate the WGR over the forward years.

### 3.5.1 Multiple Linear Regression (MLR)

According to Popli et al. (2021), the multi-linear regression approach is a methodology where the dependent variables are correlated to more than two independent variables to obtain a quantitative and qualitative relation between them.

*Equation 3: Mathematical Representation of the Multi-Linear Regression*

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + \dots + b_nX_n + \varepsilon$$

Where:

*Y: It signifies the dependent variable or to be forecasted or predicted variable*

*b<sub>0</sub>: It is the constant term*

*X<sub>1</sub>, X<sub>2</sub>, X<sub>3</sub>, X<sub>n</sub>: They are the independent variables*

*b<sub>1</sub>, b<sub>2</sub>, b<sub>3</sub>, b<sub>n</sub>: They are the regression coefficients of their respective independent variables, and,*

*ε: It is the residual error that is assumed to be independent and identically distributed with zero mean and constant variance.*

The value of the regression coefficients can be positive or negative, where the positive value signifies the direct relation and the negative value signifies the indirect relation of the independent variable with the dependent variable. The numerical value of the coefficients denotes the one-unit change of the value of the dependent variable with the respective independent variable.

### 3.6 Estimation Methodology for Methane Emissions from Landfill

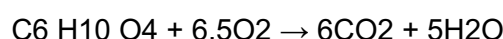
A significant amount of Methane is produced during the treatment and disposal of municipal, industrial, and other solid waste (CH<sub>4</sub>). The emission of carbon dioxide (CO<sub>2</sub>), volatile organic compounds other than Methane (VOCs), nitrous oxide (N<sub>2</sub>O), nitrogen oxides (NO<sub>x</sub>), and carbon monoxide in trace amounts occurs in solid waste disposal facilities (SWDF) (CO). The CH<sub>4</sub> produced in SWDS produces between 3 and 4% of the world's anthropogenic greenhouse gas emissions each year (IPCC, 2006). During the last ten years, there have been substantial changes in waste management in several developed countries. Policies for waste reduction, recycling, and reuse have been implemented to decrease waste generation, and the rapid adoption of alternative waste management methods to land-based solid waste disposal has decreased the environmental effects of waste management. of waste (Sreenendorj, 2021).

Thus, to estimate methane emissions from the El Zapallal landfill, the method provided in the IPCC 2006 guidelines will be used.

### 3.6.1 Degradation Process of Organic Wastes in Landfill

#### *Aerobic degradation*

The rapidly degradable organic chemicals near the landfill's outer surface, down to a depth of about 1 to 1.5 meters (Ehrig et al., 2011), are aerobically oxidized shortly after the deposition of MSW. Since the aerobic process produces heat and water as its byproducts, it is analogous to combustion in that it degrades organic matter by using oxygen from the atmosphere (Themelis & Ulloa, 2007). Themelis and Kim's studies suggest that the aerobic composting reaction can be described as follows:



In most cases, the aerobic process lasts only a few days or weeks; the landfilled materials are covered with newly deposited wastes, and the reaction continues anaerobically. Both aerobic and anaerobic reactions are biochemical in nature and necessitate the presence of various types of bacteria. (Sereenendorj, 2021).

#### *Anaerobic degradation*

Once the oxygen supply is complete, anaerobic digestion occurs, and this is the primary biological reaction in vertebrates. The reaction occurs in three stages, during which organic substances are converted into CH<sub>4</sub> and CO<sub>2</sub>, as well as small amounts of biomass and energy.

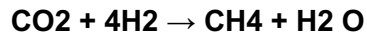
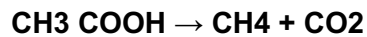
The following are the three steps in the anaerobic process (Ehrig et al., 2011; Themelis & Ulloa, 2007):

**1. Hydrolysis:** fermentative bacteria hydrolyze the complex organic matter (proteins, fats, carbohydrates, etc.) into simple soluble organic substances such as amino acids, glucose, etc.

**2. Acetogenesis:** the end products of hydrolysis are converted by acid-forming bacteria to volatile fatty acids, CO<sub>2</sub>, and H<sub>2</sub>. Acetogenic bacteria convert volatile fatty acids to acetic acid, carbon dioxide, and hydrogen gas. Acetic acid, propionic acid, butyric acid, and ethanol are the most common acids generated. The following is an example of a typical reaction:



**3. Methanogenesis:** at this phase, Methane is produced by methanogenic bacteria when acids are broken down into Methane and carbon dioxide or when carbon dioxide is reduced with hydrogen. The following is an example of a typical reaction:



In the second and third phases, acetogenic bacteria and methanogenic bacteria are extremely sensitive, strictly anaerobic, and substrate-specific.

### 3.6.2 Landfill Gas Generation Process

The biological decomposition of organic waste, general solid waste, and other elements deposited in the landfill results in landfill gas. With peak LNG production for any given disposal cell happening within the first or second year of waste placement, landfill gas production typically starts within a year of waste placement and may continue up to 50 years following landfill closure. With each additional ton of waste deposited in the landfill, the overall LNG production rate rises.

Gas generation processes and gas transit processes, such as volatilization, primarily biological degradation, and eventually chemical reactions, control landfill gas emissions. Here, biological decomposition will be the main focus.

Methane and carbon dioxide are the main components of landfill gas, which is generated by biological decomposition in sanitary landfills. Anaerobic and aerobic decomposition are the causes of landfill gas formation. It's crucial to realize that both aerobic and anaerobic deterioration will take place simultaneously, though.

### 3.6.3 Choice of Method

The IPCC employs the First Order Decay (FOD) method to calculate CH<sub>4</sub> emissions from Solid Waste Disposal Sites (SWDS). This method assumes that the degradable organic component (DOC) in trash decays slowly over several decades, producing CH<sub>4</sub> and CO<sub>2</sub>. If all other variables remain constant, the rate of CH<sub>4</sub> formation is solely determined by the amount of carbon left in the waste. As a result, CH<sub>4</sub> emissions from trash deposited at a disposal site are highest in the first few years after deposition, then gradually decrease as the waste's degradable carbon is consumed by the microorganisms that cause decay.

To convert degradable materials to CH<sub>4</sub> and CO<sub>2</sub>, the SWDS employs a chain of reactions and parallel reactions. A full model will most likely be highly sophisticated and will change depending on the SWDS conditions. However, laboratory and field studies on CH<sub>4</sub> production data suggest that first-order kinetics can match the total decomposition process, which is widely accepted (Hoeks, 1983).

As a consequence, the IPCC has estimated CH<sub>4</sub> emissions from SWDS using the relatively simple FOD model. The half-lives of various types of trash range from a



few years to several decades or longer. The FOD approach requires data to be collected or estimated for past waste disposals over a time period of 3 to 5 half-lives in order to achieve an acceptable level of accuracy. As a result, it is recommended that disposal data be used for at least 50 years, as this time span provides an adequate level of accuracy for the majority of common disposal techniques and situations. If a shorter time period is specified, the inventory compiler must demonstrate that the emissions will not be significantly understated.

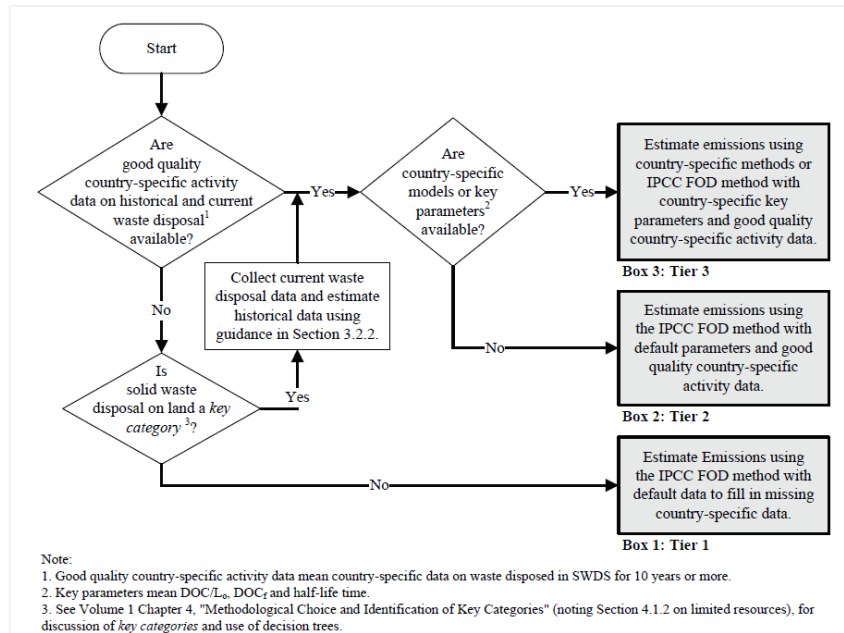
The following are three stages for estimating CH<sub>4</sub> emissions from SWDS:

**Tier 1:** The estimations of the Tier 1 methods are based on the IPCC FOD method using mainly default activity data and default parameters (IPCC, 2006).

**Tier 2:** Tier 2 methods use the IPCC FOD method and some default parameters but require good quality country-specific activity data on current and historical waste disposal at SWDS. Historical waste disposal data for ten (10) years or more should be based on country-specific statistics, surveys, or other similar sources. Data are needed on amounts disposed of at the SWDS (IPCC, 2006).

**Tier 3:** Tier 3 methods are based on the use of good quality country-specific activity data (see Tier 2) and the use of either the FOD method with (1) nationally developed key parameters or (2) measurement derived country-specific parameters (IPCC, 2006). The inventory compiler may employ country-specific approaches that are equal to or better than the FOD-based Tier 3 method described above. The half-life and either the methane generation potential (Lo) or the DOC content in the trash and the fraction of DOC that decomposes should be key parameters (DOCf). Likewise, to account for the time dependency of emissions, it is recommended that all nations utilize the FOD approach or a verified country-specific method.

Figure 13: Decision Tree for CH<sub>4</sub> emissions from Solid Waste Disposal Sites



Source: IPCC, 2006

Based on the analysis of the decision tree, Tier 2 is the approach that fits this research aiming to predict methane emission of the El Zapallal landfill until 2050. Due to that, in this study, we will use default parameters and good-quality country-specific activity data on current and historical waste disposal. Also, the waste disposal data is for more than ten (10) years, based on country-specific statics.

### 3.7 First Order Decay (FOD)

The IPCC 2006 guideline described a model for the IPCC based on the FOD technique. This method assumes that the waste's degradable organic component, also known as DOC or "degradable organic carbon," deteriorates steadily over several decades while emitting CH<sub>4</sub> and CO<sub>2</sub> (IPCC, 2006). This method assumes that the amount of carbon in the trash determines the amount of Methane produced. It does, however, influence how quickly Methane from waste is produced. After the first few years, the rate of CH<sub>4</sub> production decreases due to a decrease in biodegradable organic waste in the garbage.

Bacterial consumption of waste is the responsible process for reducing organic carbon in waste (IPCC, 2006). Several parallel and chain reactions are used in this method (IPCC, 2006). The FOD strategy could be thought of as a population of atoms being transformed into another form.

### 3.7.1 Methane Emissions Calculation

The emissions of Methane from the El Zapallal landfill could be estimated using IPCC Waste Model. Methane is produced as a byproduct of organic material degradation in anaerobic conditions. Part of the Methane produced is oxidized in the landfill cover or can be recovered for energy or flaring. As a result, methane emissions from a landfill will be lower than the amount generated.

#### *Equation 4: Methane Emissions Calculation*

$$\text{(CH}_4\text{) Methane Emissions} = [\sum x \text{ CH}_4 \text{ generated}_{x,T} - R_T] \cdot (1 - OX_T)$$

Where:

*CH<sub>4</sub> Emission* = Methane emitted in year *T*, Gg

*T* = inventory year *x* = waste category or type/material

*R<sub>T</sub>* = recovered CH<sub>4</sub> in year *T*, Gg

*OX<sub>T</sub>* = oxidation factor in year *T*, (fraction)

The amount of recovered CH<sub>4</sub> must be deducted from the total amount produced. Oxidation will only affect the portion of CH<sub>4</sub> that is not recovered in the SWDS cover layer.

### 3.7.2 Methane Generation Calculation

The equation below is used to estimate methane (CH<sub>4</sub>) generation. Based on the quantities and composition of the trash dumped at El Zapallal Landfill and the procedures of waste management there, the potential for methane generation over time will be calculated. The amount of decomposable degradable organic carbon (DDOC<sub>m</sub>), the portion of organic carbon that will decompose under anaerobic circumstances in a landfill, serves as the basis for the computation.

#### *Equation 5: Decomposable Degradable Organic Carbon (DDOC<sub>m</sub>)*

$$DDOC_m = W \cdot DOC \cdot DOC_f \cdot MCF$$

Where:

*DDOC<sub>m</sub>* = mass of decomposable DOC deposited, Gg

*W* = mass of waste deposited, Gg

*DOC* = degradable organic carbon in the year of deposition, fraction, Gg C/Gg

*DOC<sub>f</sub>* = fraction of DOC that can decompose (fraction)

*MCF = CH<sub>4</sub> correction factor for aerobic decomposition in the year of deposition (fraction)*

The equation of transformation mass of decomposable DOC deposited to methane generation potential is given in the following equation:

*Equation 6: Methane Potential per unit Mass of Waste*

$$L_o = DDOC_m \cdot F \cdot 16/12$$

Where:

*L<sub>o</sub> = CH<sub>4</sub> generation potential, Gg CH<sub>4</sub>*

*F = fraction of CH<sub>4</sub> in generated landfill gas (volume fraction)*

*16/12 = molecular weight ratio CH<sub>4</sub>/C (ratio)*

Accumulated and decomposed of DDOC<sub>m</sub> in the landfill at the end of the year (T) are given in the following equation:

*Equation 7: DDOC<sub>m</sub> accumulated in the SWDS at the end of year T*

$$DDOC_{ma_T} = DDOC_{md_T} + (DDOC_{ma_{T-1}} \cdot e^{-k})$$

*Equation 8: DDOC<sub>m</sub> decomposed in the SWDS in year T*

$$DDOC_{m\ decomp_T} = DDOC_{ma_{T-1}} \cdot (1 - e^{-k})$$

Where:

*T = inventory year*

*DDOC<sub>ma\_T</sub> = DDOC<sub>m</sub> accumulated in the SWDS at the end of year T, Gg*

*DDOC<sub>ma\_{T-1}</sub> = DDOC<sub>m</sub> accumulated in the SWDS at the end of the year (T-1), Gg*

*DDOC<sub>md\_T</sub> = DDOC<sub>m</sub> deposited into the SWDS in year T, Gg*

*DDOC<sub>m\ decomp\_T</sub> = DDOC<sub>m</sub> decomposed in the SWDS in year T, Gg*

*k = reaction constant,  $k = \ln(2)/t_{1/2}$  (y<sup>-1</sup>)*

*t<sub>1/2</sub> = half-life time (y)*

The equation below shows how methane is generated from decomposable material.

*Equation 9: Methane generated*

$$\text{Methane generated}_T = DDOC_{m\ decomp_T} \cdot F \cdot 16/12$$

### 3.7.3 Factors and Parameters for the FOD method

#### *Degradable Organic Carbon (DOC)*

Degradation of organic carbon (DOC) in waste is a biologically degradable organic carbon fraction that can decompose via biological processes. DOC is measured in gigagrams of carbon per gram of waste (Gg carbon/Gg waste). This parameter heavily influences methane production at a waste disposal site. There is no methane generation potential in any waste disposal site trash (referring to volume 5 of IPCC 2006). In the case of the Tier 1 technique, the IPCC's default data may be used. The DOC estimation equation is provided below.

#### *Equation 10: Degradable Organic Carbon (DOC)*

$$DOC = \sum_i (DOC_i * W_i)$$

Where:

*DOC* = fraction of degradable organic carbon in bulk waste, Gg C/Gg waste

*DOC<sub>i</sub>* = fraction of degradable organic carbon in waste type *i*

*W<sub>i</sub>* = fraction of waste type *i* by waste category. (IPCC 2006).

#### *Degradable organic carbon fraction (DOCf)*

The fraction of degradable organic carbon that decomposes (DOCf) is an estimate of the fraction of carbon that is ultimately degraded and released from SWDS, and it reflects the fact that some degradable organic carbon does not degrade or degrading very slowly in the SWDS due to anaerobic conditions. The default value for DOCf is 0.5 (assuming the SWDS environment is anaerobic and the DOC values include lignin). (IPCC, 2006)

The DOCf value is affected by a variety of factors, including temperature, moisture, pH, waste composition, and so on. National or comparable country values for DOCf can be used, but they must be based on well-documented research. (IPCC, 2006)

#### *Methane correction factor (MCF)*

MCF is determined by how landfills are managed. In managed landfills, anaerobic degradation processes produce a high MCF, whereas semi-aerobic degradation processes produce a low MCF. The MCF of an unmanaged landfill is determined by its depth. Waste with a depth greater than 5 meters has an MCF of 0.8, while waste with a depth less than 5 meters has an MCF of 0.4.

### *Fraction of the Methane is generated in landfill gas (F)*

According to the IPCC, the F level is 0.5, and most landfills account for 50% of the Methane in their gases. If the waste contains a lot of fat or oil, landfill gas is more likely to contain a lot of CH<sub>4</sub>.

### *Oxidation factor (OX)*

Since CH<sub>4</sub> oxidizes in the soil and cover of a landfill, the amount of oxidation is determined by the amount of CH<sub>4</sub> oxidized in this area. The IPCC recommends a value of 0 for the OX. Oxidation values of 0.1 can be used to estimate diffusions through the cap and escape through cracks and fissures in well-managed, covered SWDS. For each country's circumstances, we must justify any amount greater than 0.1 for OX.

## Chapter 4. Findings and Discussions

### 4.1 Population Attended by the El Zapallal Landfill

This study obtained the population attended by the El Zapallal Landfill with the use of international data (World Population Review, 2022) and domestic data provided by the National Institute of Statistics and Informatics (INEI) of Peru, through its Environmental Statistics Yearbook from different years that include information from various government entities, among them, local governments, Ministry of Environment, and the Municipality of Lima. The report issued in the Environmental Statistics Yearbook shows the amounts of the MSW deposited in the El Zapallal landfill regarding the amount of total MSW generated and controlled in landfill sites in Lima province.

Likewise, the information provided by the Ministry of Environment in its *List of landfills in Peru – 2021* allowed us to determine how many districts are attended by the El Zapallal Landfill, which currently, in total, are 09 districts of Lima province.

*Table 8: Population attended by the El Zapallal landfill (1990 to 2020)*

Year	Population Metropolitan Lima (Urban Data)	(*) Population attended by the landfill (controlled MSW)	% of MSW disposed of in El Zapallal Landfill (controlled waste)	Lima Province Level (ton) MSW controlled	Zapallal Landfill (ton) MSW
1990	5836537	311435	5.3%	534551.45	28523.45
1991	5992365	333313	5.6%	68380.99	30073.73
1992	6152576	1165705	18.9%	166911.11	31624.01
1993	6316612	789584	12.5%	265391.79	33174.29
1994	6448579	615475	9.5%	363823.07	34724.57
1995	6582251	682399	10.4%	349898.00	36274.85
1996	6718884	553645	8.2%	459035.00	37825.13
1997	6857966	436560	6.4%	618552.00	39375.40
1998	7000124	405340	5.8%	706777.00	40925.68
1999	7145230	418914	5.9%	724494.00	42475.96
2000	7293549	552291	7.6%	581410.00	44026.24
2001	7444526	572116	7.7%	593054.00	45576.52
2002	7598844	565805	7.4%	632920.00	47126.80
2003	7756360	161838	2.1%	1686545.00	35190.00
2004	7917365	264292	3.3%	1603710.00	53534.00
2005	8081255	358362	4.4%	1620888.00	71878.00

2006	8248771	265683	3.2%	1730400.00	55734.00
2007	8419760	212815	2.5%	1857601.00	46952.00
2008	8585977	219476	2.6%	1920340.00	49088.00
2009	8751162	238157	2.7%	2059684.00	56053.00
2010	8919759	268588	3.0%	2058381.00	61981.00
2011	9091604	476333	5.2%	2191989.00	114844.00
2012	9267004	760499	8.2%	2467012.00	202456.00
2013	9445291	667081	7.1%	2680749.00	189330.00
2014	9627261	558482	5.8%	2846053.00	165101.00
2015	9812737	1554580	15.8%	3121073.00	494455.00
2016	10002049	1639859	16.4%	2160253.20	530125.00
2017	10194477	1753450	17.2%	2172446.90	576319.00
2018	10390607	1953434	18.8%	2213422.50	657328.00
2019	10554712	2174271	20.6%	2370938.60	752813.00
2020	10719188	2186714	20.4%	2420481.60	720019.00

Source: World Popular  
Review

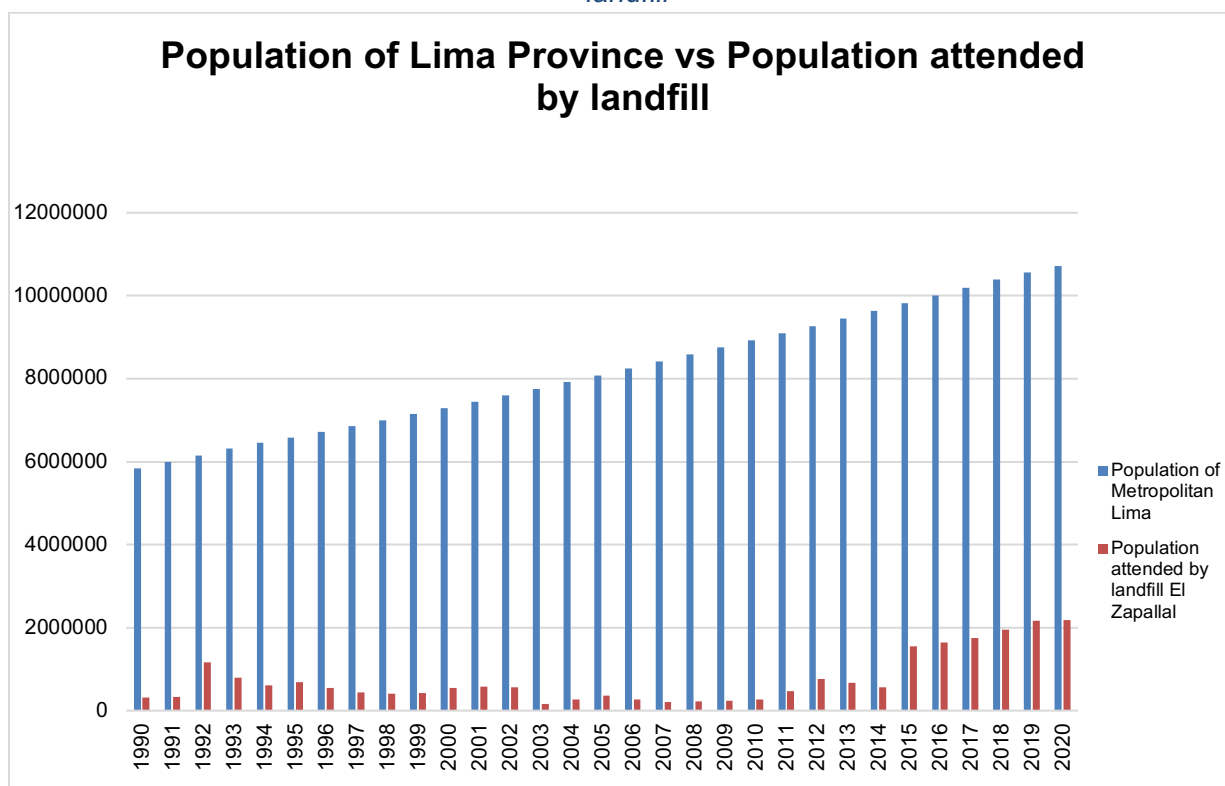
Source: INEI & projections  
based on INEI data

Source: Elaborated by the Author based on information from World Popular  
Review & INEI

The column selected shows the percentage of the MSW deposited in the El Zapallal landfill respected of the total MSW produced in Lima province. This information was directly given by the National Institute of Statistics and Informatics (INEI) for the years 2015 to 2020. For the previous years, it was calculated using the information of the deposited amounts and generated in the province of Lima, based on the information given for the same institution (INEI). According to the ratio in percentage, the portion of the population attended by El Zapallal was calculated, with respect to the global population in Lima province. The shaded column in yellow present the population attended by the mentioned landfill.



Figure 14: Population of Lima province v.s population attended by El Zapallal landfill



Source: Elaborated by the Author

With the previous information, we determined the population for the following years until 2050 using the Incremental Increase Method, described in the methodology section.

Table 9: Projection of population attended by the El Zapallal landfill until 2050

Year	Population attended by the landfill (controlled MSW)
1990	311435
1991	333313
1992	1165705
1993	789584
1994	615475
1995	682399
1996	553645
1997	436560
1998	405340
1999	418914

2000	552291
2001	572116
2002	565805
2003	161838
2004	264292
2005	358362
2006	265683
2007	212815
2008	219476
2009	238157
2010	268588
2011	476333
2012	760499
2013	667081
2014	558482
2015	1554580
2016	1639859
2017	1753450
2018	1953434
2019	2174271
2020	2186714
2021	2598710
2022	3010706
2023	3422701
2024	3834697
2025	4246693
2026	4658689
2027	5070684
2028	5482680
2029	5894676
2030	6306671
2031	6412045
2032	6517419
2033	6622793
2034	6728166
2035	6833540
2036	6938914
2037	7044287
2038	7149661

2039	7255035
2040	7360409
2041	7871573
2042	8382737
2043	8893901
2044	9405065
2045	9916229
2046	10427394
2047	10938558
2048	11449722
2049	11960886
2050	12472050

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Source: Elaborated by the Author

## 4.2 Waste Amount Landfilled

This study obtained the data for the municipal solid waste amount landfilled in the El Zapallal landfill for a period of 1996 to 2020 from different government entities, such as the Municipality of Lima (data from 1990 to 2002), which is the local government in charge of the administration of the landfill in mention; and through the National Institute of Statistics, and Informatics (INEI, in its Spanish acronym), (data from 2003 to 2020).

In the case of the Municipality of Lima, we got the data from documents as the Consultancy for the development of a baseline to support the definition of prioritized measures in the CAP, the Local Plan of Climate Change of Lima Province 2021, as well as we complementary use the Integral Plan of Waste Management in Lima Province 2015-2025.

Related to the INEI, it annually elaborates the Environmental statistics yearbook (available from 2005 onwards) with information collected from different entities, such as the Ministry of Environmental, Municipality of Lima, local governments, and others related to the topic. Likewise, we use the report of the World Bank (What a Waste 2.0: Global Snapshot of Solid Waste Management to 2050, 2018), which also has some data about waste management in Peru.

*Table 10: Amount of municipal solid waste landfilled in Lima Province and in the El Zapallal landfill*

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**Amount of Municipal Solid Waste landfilled  
(ton)**

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Year	National Institute of Statistics and Informatics (INEI)		C40 - IDOM & Municipality of Lima
	Lima Province (ton) MSW- controlled	Zapallal Landfill (ton) MSW	
1990	534551.45		28523.45
1991	68380.99		30073.73
1992	166911.11		31624.01
1993	265391.79		33174.29
1994	363823.07		34724.57
1995	349898.00		36274.85
1996	459035.00		37825.13
1997	618552.00		39375.40
1998	706777.00		40925.68
1999	724494.00		42475.96
2000	581410.00		44026.24
2001	593054.00		45576.52
2002	632920.00		47126.80
2003	1686545.00	35190.00	35190.00
2004	1603710.00	53534.00	53534.00
2005	1620888.00	71878.00	
2006	1730400.00	55734.00	
2007	1857601.00	46952.00	
2008	1920340.00	49088.00	
2009	2059684.00	56053.00	
2010	2058381.00	61981.00	
2011	2191989.00	114844.00	
2012	2467012.00	202456.00	
2013	2680749.00	189330.00	
2014	2846053.00	165101.00	
2015	3121073.00	494455.00	492125.00
2016	2160253.20	530125.00	530125.00
2017	2172446.90	576319.00	576319.00
2018	2213422.50	657328.00	657328.00
2019	2370938.60	752813.00	752812.00
2020	2420481.60	720019.00	761845.74

Source: Prepared by the author

### 4.3 Municipal Solid Waste Generation Rates (SWGR)

Based on the amount of waste landfilled in the El Zapallal landfill, we obtained the Municipal Waste Generation Rates (SWR) in kg/day/person. Likewise, to get mentioned data, it was necessary to calibrate with the WRG provided by the

national government, which is 0.60 kg/day/person on average in Lima Province, as well as the international standard given by the World Bank, which is 0.75 kg/capita/day.

In the particular case of the El Zapallal landfill, it experienced a visible increase in the amount of MSW landfilled from the year 2015, in which the amount received during that year increased by almost 200% in comparison with the previous year (2014). After the mentioned year, the increase of the MSW until 2020 (available data) was rising in an average ratio of 4%. Whereby, also the MSWG Rate notably increased in the reporting period.

*Table 11: Municipal Solid Waste Generation Rates - MSWGR (kg/day/person)*

<b>Year</b>	<b>(*) Population attended by the landfill (controlled MSW)</b>	<b>Zapallal Landfill (ton MSW)</b>	<b>Generation (kg/day)</b>	<b>MSWG Rate (kg/person/day)</b>
1990	311435	28523.45	78146.43	<b>0.25</b>
1991	333313	30073.73	82393.77	<b>0.25</b>
1992	1165705	31624.01	86641.11	<b>0.07</b>
1993	789584	33174.29	90888.45	<b>0.12</b>
1994	615475	34724.57	95135.80	<b>0.15</b>
1995	682399	36274.85	99383.14	<b>0.15</b>
1996	553645	37825.13	103630.49	<b>0.19</b>
1997	436560	39375.40	107877.81	<b>0.25</b>
1998	405340	40925.68	112125.15	<b>0.28</b>
1999	418914	42475.96	116372.49	<b>0.28</b>
2000	552291	44026.24	120619.84	<b>0.22</b>
2001	572116	45576.52	124867.18	<b>0.22</b>
2002	565805	47126.80	129114.52	<b>0.23</b>
2003	161838	35190.00	96410.96	<b>0.60</b>
2004	264292	53534.00	146668.49	<b>0.55</b>
2005	358362	71878.00	196926.03	<b>0.55</b>
2006	265683	55734.00	152695.89	<b>0.57</b>
2007	212815	46952.00	128635.62	<b>0.60</b>
2008	219476	49088.00	134487.67	<b>0.61</b>
2009	238157	56053.00	153569.86	<b>0.64</b>
2010	268588	61981.00	169810.96	<b>0.63</b>
2011	476333	114844.00	314641.10	<b>0.66</b>
2012	760499	202456.00	554673.97	<b>0.73</b>
2013	667081	189330.00	518712.33	<b>0.78</b>
2014	558482	165101.00	452331.51	<b>0.81</b>
2015	1554580	494455.00	1354671.23	<b>0.87</b>
2016	1639859	530125.00	1452397.26	<b>0.89</b>
2017	1753450	576319.00	1578956.16	<b>0.90</b>

2018	1953434	657328.00	1800898.63	<b>0.92</b>
2019	2174271	752813.00	2062501.37	<b>0.95</b>
2020	2186714	720019.00	1972654.79	<b>0.90</b>

Source: Prepared by the author

#### 4.4 GDP per capita Given and Estimated

Regarding the GDP value, it was obtained from the website of the World Bank for the years from 1990 to 2020; thereafter, we projected for the future years, from 2021 to 2050, using the exponential model, as it was shown in figure 9 of the methodology section. We obtained the following results:

*Table 12: GDP per capita given and estimated*

<b>Year</b>	<b>GDP (US\$) Per Capita</b>
1990	\$1,196.6
1991	\$1,524.8
1992	\$1,566.0
1993	\$1,488.0
1994	\$1,881.7
1995	\$2,194.0
1996	\$2,232.1
1997	\$2,306.4
1998	\$2,163.1
1999	\$1,924.5
2000	\$1,955.6
2001	\$1,941.5
2002	\$2,021.2
2003	\$2,145.6
2004	\$2,417.0
2005	\$2,729.5
2006	\$3,154.3
2007	\$3,606.1
2008	\$4,220.6
2009	\$4,196.3
2010	\$5,082.4
2011	\$5,869.3
2012	\$6,529.0
2013	\$6,756.8
2014	\$6,672.9
2015	\$6,229.1
2016	\$6,205.0

2017	\$6,710.5
2018	\$6,957.8
2019	\$7,027.6
2020	\$6,126.9
2021	\$10,408.3
2022	\$11,063.0
2023	\$11,758.8
2024	\$12,498.4
2025	\$13,284.6
2026	\$14,120.1
2027	\$15,008.3
2028	\$15,952.3
2029	\$16,955.7
2030	\$18,022.2
2031	\$19,155.7
2032	\$20,360.6
2033	\$21,641.3
2034	\$23,002.5
2035	\$24,449.3
2036	\$25,987.2
2037	\$27,621.7
2038	\$29,359.1
2039	\$31,205.7
2040	\$33,168.6
2041	\$35,254.8
2042	\$37,472.3
2043	\$39,829.3
2044	\$42,334.5
2045	\$44,997.3
2046	\$47,827.6
2047	\$50,835.9
2048	\$54,033.4
2049	\$57,432.0
2050	\$61,044.5

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Source: Prepared by the Author

#### **4.5 Estimation of Municipal Solid Waste Generation Rates (MSWGR) period of 2021 to 2039**

As we mentioned in item 3.3 of Chapter 3, we applied Multiple Linear Regression to calculate the SWGR in the period from 2021 to 2039, using the MSWDR known (1990 to 2020), population attended by El Zapallal landfill, and the GDP per capita in the same period.

Analyzing the relationship between the independent variables (Population attended by the landfill, and GDP per capita) and the dependent variable (MSWGR), we obtained that there is no relationship between the dependent variable (MSWGR) and the independent variable: Population attended (one variable does not affect the other) since the p-value of this independent variable is greater than 0.05.

On the other hand, with regards to the dependent variable (MSWGR) and the independent variable of GDP per capita, there is a strong relationship because of the results obtained (p-value), as we can see in the table below:

*Table 13: Multiple Linear Regression (MLR) Analysis*

Summary								
<b>Regression Statistics</b>								
Multiple R		0.920694696						
R Square		0.847678723						
Adjusted R Square		0.836798632						
Standard Error		0.116907873						
Observations		31						
<b>ANOVA</b>								
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>			
Regression	2	2.129689355	1.064844678	77.91099404	0.000000000004			
Residual	28	0.382688622	0.013667451					
Total	30	2.512377977						
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	0.028404627	0.044465172	0.63880618	0.528140393	-0.06267815	0.119487	-0.06267815	0.119487403
GDP (US\$) Per Capita	0.000125	0.000012	10.700569	0.00000000002	0.000100685	0.000148	0.000100685	0.00014836
Population attended by the landfill (controlled MSW)	0.00000002	0.000000	0.399382	0.692642	-6.22111E-08	9.23E-08	-6.22111E-08	9.23453E-08

Source: Elaborated by the Author

According to the results of the MLR analysis, we estimated the Municipal Solid Waste Generation Rates (MSWGR) with a Logarithmic Regression Model shown below, over the values of MSWGR and the GDP per capita, for the available 31 years (1990 to 2020) as it is shown in figure 15.

*Equation 11: Logarithmic Regression Model between MSWGR and GDP per capita*

$$\text{MSWGR} = 0.4628\ln(\text{GDP per capita}) - 3.2279$$

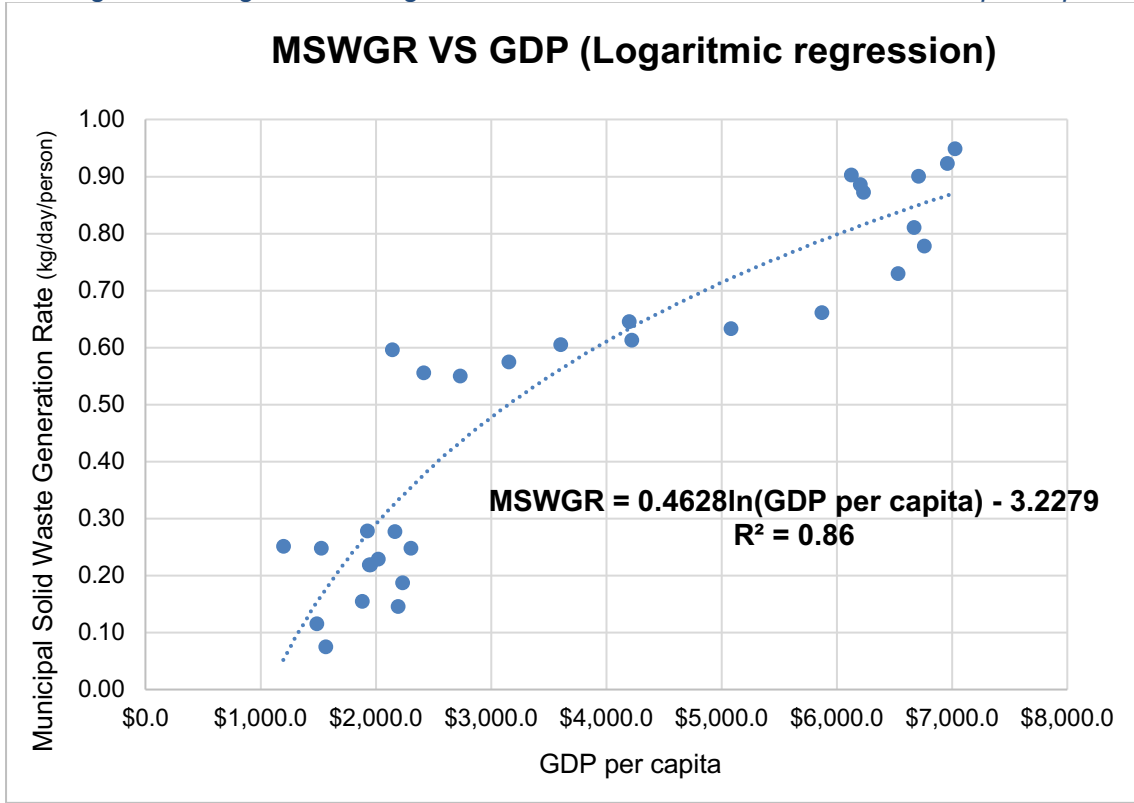
Where:

*MSWGR: Municipal Solid Waste Generation Rates projected in kg/day/person*

*GDP per capita: Values of GDP per capita known (period: 2021 to 2039)*



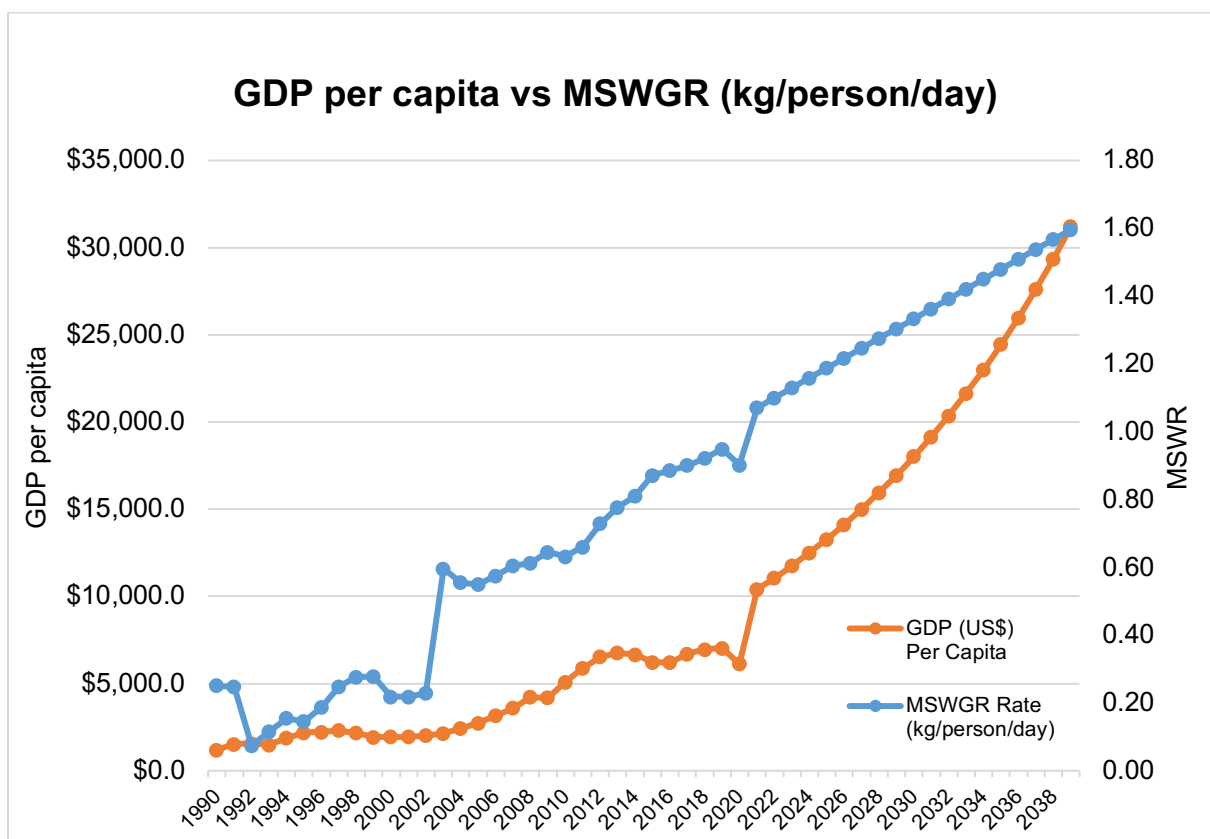
Figure 15: Logarithmic Regression Model between MSWGR and GDP per capita



Source: Elaborated by the Author

Furthermore, the relationship between GDP per capita and MSWGR over the years is presented in figure 16. The projected Municipal Solid Waste Generation Rate values in the period 2021 to 2039 for the El Zapallal landfill of Lima Province are shown in table 14.

Figure 16: Relation between the GDP per capita and MSWGR over the years



Source: Elaborated by the Author

Table 14: Estimation of MSWGR for the period 2021 to 2039, using the Logarithmic Regression Model

Year	GDP (US\$) Per Capita	MSWGR (kg/day/person)
1990	\$1,196.6	0.04
1991	\$1,524.8	0.08
1992	\$1,566.0	0.12
1993	\$1,488.0	0.16
1994	\$1,881.7	0.19
1995	\$2,194.0	0.23
1996	\$2,232.1	0.26
1997	\$2,306.4	0.29
1998	\$2,163.1	0.32
1999	\$1,924.5	0.28
2000	\$1,955.6	0.22
2001	\$1,941.5	0.22
2002	\$2,021.2	0.23
2003	\$2,145.6	0.60

2004	\$2,417.0	0.55
2005	\$2,729.5	0.55
2006	\$3,154.3	0.57
2007	\$3,606.1	0.60
2008	\$4,220.6	0.61
2009	\$4,196.3	0.64
2010	\$5,082.4	0.63
2011	\$5,869.3	0.66
2012	\$6,529.0	0.73
2013	\$6,756.8	0.78
2014	\$6,672.9	0.81
2015	\$6,229.1	0.87
2016	\$6,205.0	0.89
2017	\$6,710.5	0.90
2018	\$6,957.8	0.92
2019	\$7,027.6	0.95
2020	\$6,126.9	0.90
<b>2021</b>	<b>\$10,408.3</b>	<b>1.07</b>
<b>2022</b>	<b>\$11,063.0</b>	<b>1.10</b>
<b>2023</b>	<b>\$11,758.8</b>	<b>1.13</b>
<b>2024</b>	<b>\$12,498.4</b>	<b>1.16</b>
<b>2025</b>	<b>\$13,284.6</b>	<b>1.19</b>
<b>2026</b>	<b>\$14,120.1</b>	<b>1.22</b>
<b>2027</b>	<b>\$15,008.3</b>	<b>1.25</b>
<b>2028</b>	<b>\$15,952.3</b>	<b>1.28</b>
<b>2029</b>	<b>\$16,955.7</b>	<b>1.30</b>
<b>2030</b>	<b>\$18,022.2</b>	<b>1.33</b>
<b>2031</b>	<b>\$19,155.7</b>	<b>1.36</b>
<b>2032</b>	<b>\$20,360.6</b>	<b>1.39</b>
<b>2033</b>	<b>\$21,641.3</b>	<b>1.42</b>
<b>2034</b>	<b>\$23,002.5</b>	<b>1.45</b>
<b>2035</b>	<b>\$24,449.3</b>	<b>1.48</b>
<b>2036</b>	<b>\$25,987.2</b>	<b>1.51</b>
<b>2037</b>	<b>\$27,621.7</b>	<b>1.54</b>
<b>2038</b>	<b>\$29,359.1</b>	<b>1.57</b>
<b>2039</b>	<b>\$31,205.7</b>	<b>1.60</b>

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Source: Elaborated by the Author

## Amount of waste in the future

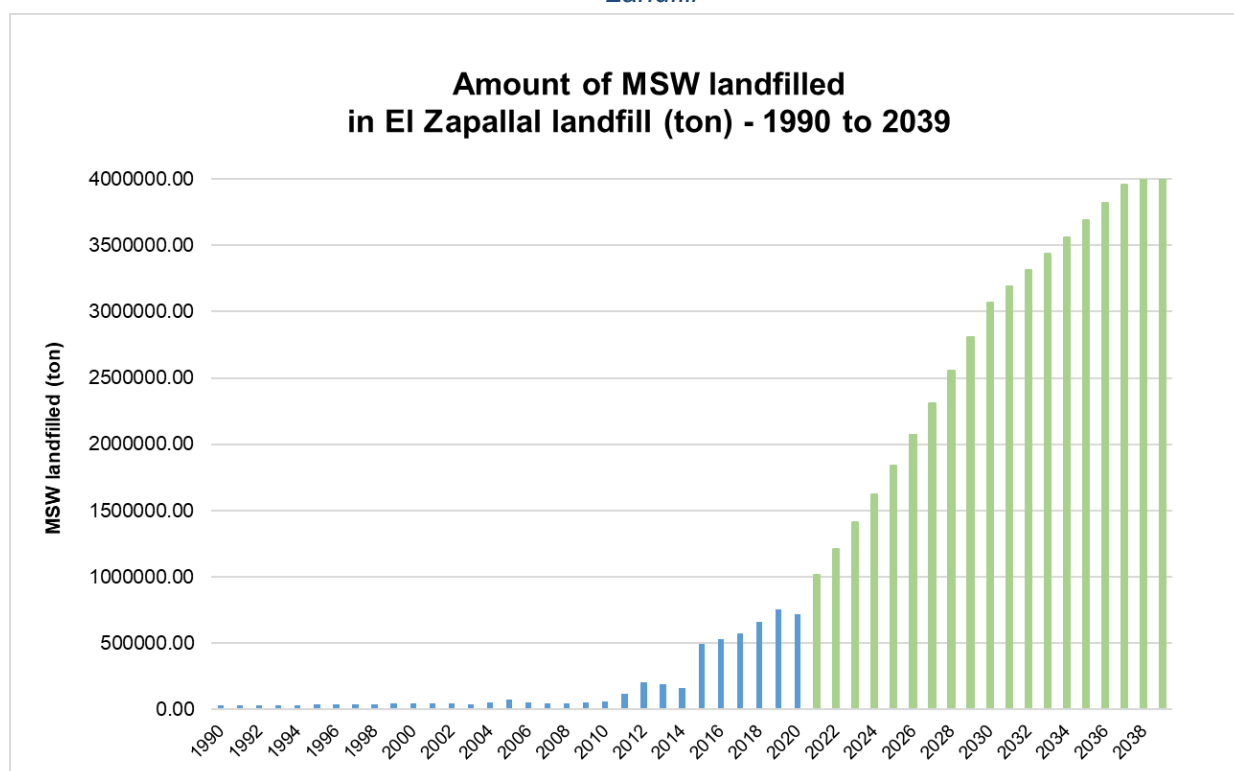
After obtaining the MSWGR for the period required (2021 to 2039), we estimated the total Municipal Solid Waste generated by the population attended and collected by the El Zapallal landfill.

### *Equation 12: Projection of Future Municipal Solid Waste Amount*

$$\text{Amount of waste (tons per year)} = {}^5\text{Population} \times \text{MSWGR} \times 365 \times 10^{-3}$$

The municipal solid waste amount is rather linked to the population, as well as consumer habits. Figure 17 shows the total amount of Municipal Solid Waste delivered to the El Zapallal landfill of Lima Province. The waste amount during the period of 1990 to 2010 was going stable, with an amount below 70000 tons per year. After 2011, the levels of waste significantly increased up to over 750000 tons in 2019, which is the peak amount in the period of 1990 to 2020. In our projection, it is estimated using the equation above (Equation 2), and it is very evident that the total municipal solid waste amount between 2021 to 2039 will be likely to increase and will reach over 4200000 tons in 2039.

*Figure 17: Amount of Municipal Solid Waste (MSW) landfilled in El Zapallal Landfill*



Source: Elaborated by the Author

<sup>5</sup> Population attended by the landfill

## 4.6 Total Amount of Methane (CH<sub>4</sub>) Emissions Produced in El Zapallal landfill

In this section with the data about the Municipal Solid Waste landfilled in the El Zapallal landfill of Lima Province, the Methane (CH<sub>4</sub>) emissions were calculated, for the period from 1990 to 2050.

*Table 15: Total methane (CH<sub>4</sub>) emissions produced from El Zapallal landfill*

Year	MSW Total landfilled (ton)	Waste Compositions		Food Waste				Paper Waste				Total Generation	Total Emission
		Food (ton)	Papers (ton)	DDOCmaT	DDOCmdT	DDOCm decompT	Q CH <sub>4</sub> (ton)	DDOCmaT	DDOCmdT	DDOCm decompT	Q CH <sub>4</sub> (ton)		
1990	28523.45	14261.72	2281.88	534.81	534.81	0.00	0.00	228.19	228.19	0.00	0.00	0.00	0.00
1991	30073.73	15036.86	2405.90	1067.55	563.88	31.15	20.76	459.83	240.59	8.95	5.96	26.73	26.73
1992	31624.01	15812.00	2529.92	1598.33	592.95	62.17	41.45	694.79	252.99	18.03	12.02	53.47	53.47
1993	33174.29	16587.14	2653.94	2127.27	622.02	93.08	62.05	932.94	265.39	27.24	18.16	80.22	80.22
1994	34724.57	17362.28	2777.97	2654.47	651.09	123.88	82.59	1174.16	277.80	36.58	24.39	106.98	106.98
1995	36274.85	18137.42	2901.99	3180.04	680.15	154.58	103.06	1418.32	290.20	46.04	30.69	133.75	133.75
1996	37825.13	18912.57	3026.01	3704.07	709.22	185.19	123.46	1665.31	302.60	55.61	37.08	160.54	160.54
1997	39375.40	19687.70	3150.03	4226.65	738.29	215.71	143.81	1915.01	315.00	65.30	43.53	187.34	187.34
1998	40925.68	20462.84	3274.05	4747.87	767.36	246.14	164.09	2167.33	327.41	75.09	50.06	214.15	214.15
1999	42475.96	21237.98	3398.08	5267.80	796.42	276.49	184.33	2422.15	339.81	84.98	56.65	240.98	240.98
2000	44026.24	22013.12	3522.10	5786.52	825.49	306.77	204.52	2679.39	352.21	94.97	63.32	267.83	267.83
2001	45576.52	22788.26	3646.12	6304.10	854.56	336.98	224.65	2938.94	364.61	105.06	70.04	294.69	294.69
2002	47126.80	23563.40	3770.14	6820.60	883.63	367.12	244.75	3200.72	377.01	115.24	76.83	321.57	321.57
2003	35190.00	17595.00	2815.20	7083.21	659.81	397.20	264.80	3356.74	281.52	125.50	83.67	348.47	348.47
2004	53534.00	26767.00	4282.72	7674.48	1003.76	412.49	275.00	3653.39	428.27	131.62	87.75	362.74	362.74
2005	71878.00	35939.00	5750.24	8575.27	1347.71	446.93	297.95	4085.16	575.02	143.25	95.50	393.45	393.45
2006	55734.00	27867.00	4458.72	9120.90	1045.01	499.38	332.92	4370.85	445.87	160.18	106.79	439.71	439.71
2007	46952.00	23476.00	3756.16	9470.09	880.35	531.16	354.11	4575.08	375.62	171.38	114.26	468.36	468.36

2008	49088.00	24544.00	3927.04	9838.99	920.40	551.49	367.66	4788.40	392.70	179.39	119.59	487.26	487.26
2009	56053.00	28026.50	4484.24	10317.01	1050.99	572.98	381.99	5049.06	448.42	187.76	125.17	507.16	507.16
2010	61981.00	30990.50	4958.48	10878.33	1162.14	600.82	400.54	5346.94	495.85	197.98	131.98	532.53	532.53
2011	114844.00	57422.00	9187.52	12398.15	2153.33	633.50	422.34	6056.03	918.75	209.66	139.77	562.11	562.11
2012	202456.00	101228.00	16196.48	15472.19	3796.05	722.01	481.34	7438.22	1619.65	237.46	158.31	639.65	639.65
2013	189330.00	94665.00	15146.40	18121.10	3549.94	901.03	600.69	8661.20	1514.64	291.66	194.44	795.12	795.12
2014	165101.00	82550.50	13208.08	20161.45	3095.64	1055.29	703.53	9642.40	1320.81	339.61	226.41	929.93	929.93
2015	494455.00	247227.50	39556.40	28258.37	9271.03	1174.11	782.74	13219.96	3955.64	378.08	252.06	1034.80	1034.80
2016	530125.00	265062.50	42410.00	36552.58	9939.84	1645.64	1097.09	16942.59	4241.00	518.36	345.57	1442.67	1442.67
2017	576319.00	288159.50	46105.52	45229.90	10805.98	2128.66	1419.10	20888.82	4610.55	664.33	442.89	1861.99	1861.99
2018	657328.00	328664.00	52586.24	54920.82	12324.90	2633.98	1755.99	25328.38	5258.62	819.06	546.04	2302.03	2302.03
2019	752813.00	376406.50	60225.04	65837.72	14115.24	3198.34	2132.23	30357.74	6022.50	993.14	662.09	2794.32	2794.32
2020	720019.00	360009.50	57601.52	75503.99	13500.36	3834.09	2556.06	34927.55	5760.15	1190.34	793.56	3349.62	3349.62
2021	1015989.53	507994.77	81279.16	90156.78	19049.80	4397.01	2931.34	41685.94	8127.92	1369.53	913.02	3844.36	3844.36
2022	1209118.39	604559.19	96729.47	107577.43	22670.97	5250.32	3500.21	49724.36	9672.95	1634.53	1089.69	4589.90	4589.90
2023	1411020.38	705510.19	112881.63	127769.24	26456.63	6264.82	4176.55	59062.80	11288.16	1949.72	1299.81	5476.36	5476.36
2024	1621695.50	810847.75	129735.64	150735.33	30406.79	7440.70	4960.47	69720.48	12973.56	2315.89	1543.92	6504.39	6504.39
2025	1841143.77	920571.89	147291.50	176478.63	34521.45	8778.14	5852.09	81715.85	14729.15	2733.78	1822.52	7674.61	7674.61
2026	2069365.17	1034682.59	165549.21	205001.91	38800.60	10277.32	6851.54	95066.65	16554.92	3204.12	2136.08	8987.63	8987.63
2027	2306359.72	1153179.86	184508.78	236307.78	43244.24	11938.38	7958.92	109789.91	18450.88	3727.62	2485.08	10444.00	10444.00
2028	2552127.40	1276063.70	204170.19	270398.67	47852.39	13761.49	9174.33	125902.00	20417.02	4304.92	2869.95	12044.28	12044.28
2029	2806668.21	1403334.11	224533.46	307276.91	52625.03	15746.79	10497.86	143418.66	22453.35	4936.69	3291.13	13788.99	13788.99
2030	3069982.17	1534991.08	245598.57	346944.66	57562.17	17894.41	11929.61	162354.99	24559.86	5623.53	3749.02	15678.63	15678.63
2031	3189546.16	1594773.08	255163.69	386544.17	59803.99	20204.48	13469.66	181505.33	25516.37	6366.03	4244.02	17713.68	17713.68
2032	3311354.01	1655677.01	264908.32	426121.47	62087.89	22510.58	15007.05	200879.24	26490.83	7116.93	4744.62	19751.67	19751.67
2033	3435405.72	1717702.86	274832.46	465719.95	64413.86	24815.38	16543.59	220485.90	27483.25	7876.59	5251.06	21794.65	21794.65
2034	3561701.28	1780850.64	284936.10	505380.43	66781.90	27121.42	18080.95	240334.13	28493.61	8645.38	5763.58	23844.53	23844.53
2035	3690240.69	1845120.34	295219.25	545141.38	69192.01	29431.06	19620.71	260432.42	29521.93	9423.64	6282.42	25903.13	25903.13
2036	3821023.95	1910511.98	305681.92	585039.01	71644.20	31746.56	21164.37	280788.91	30568.19	10211.70	6807.80	27972.18	27972.18

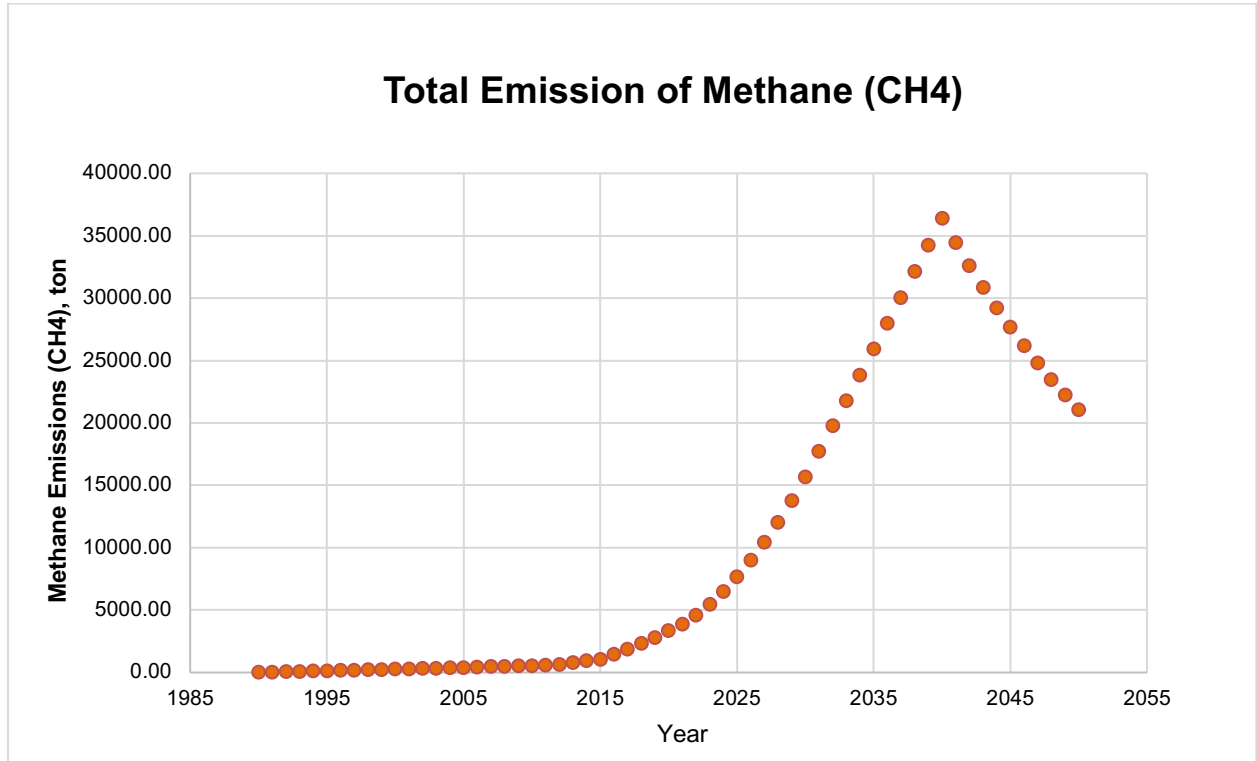
2037	3954051.07	1977025.54	316324.09	625107.45	74138.46	34070.02	22713.35	301411.43	31632.41	11009.89	7339.93	30053.27	30053.27
2038	4089322.05	2044661.02	327145.76	665378.82	76674.79	36403.42	24268.95	322307.49	32714.58	11818.51	7879.01	32147.96	32147.96
2039	4226836.87	2113418.44	338146.95	705883.36	79253.19	38748.65	25832.43	343484.33	33814.69	12637.86	8425.24	34257.67	34257.67
2040	0.00	0.00	0.00	664775.91	0.00	41107.45	27404.96	330016.12	0.00	13468.21	8978.81	36383.77	36383.77
2041	0.00	0.00	0.00	626062.38	0.00	38713.54	25809.02	317076.00	0.00	12940.12	8626.74	34435.77	34435.77
2042	0.00	0.00	0.00	589603.34	0.00	36459.03	24306.02	304643.27	0.00	12432.73	8288.49	32594.51	32594.51
2043	0.00	0.00	0.00	555267.52	0.00	34335.83	22890.55	292698.04	0.00	11945.23	7963.49	30854.04	30854.04
2044	0.00	0.00	0.00	522931.26	0.00	32336.26	21557.51	281221.18	0.00	11476.85	7651.24	29208.74	29208.74
2045	0.00	0.00	0.00	492478.11	0.00	30453.15	20302.10	270194.34	0.00	11026.84	7351.23	27653.32	27653.32
2046	0.00	0.00	0.00	463798.42	0.00	28679.69	19119.79	259599.87	0.00	10594.47	7062.98	26182.78	26182.78
2047	0.00	0.00	0.00	436788.90	0.00	27009.52	18006.34	249420.82	0.00	10179.06	6786.04	24792.38	24792.38
2048	0.00	0.00	0.00	411352.30	0.00	25436.61	16957.74	239640.89	0.00	9779.93	6519.95	23477.69	23477.69
2049	0.00	0.00	0.00	387397.00	0.00	23955.29	15970.20	230244.43	0.00	9396.45	6264.30	22234.50	22234.50
2050	0.00	0.00	0.00	364836.76	0.00	22560.25	15040.16	221216.42	0.00	9028.01	6018.68	21058.84	21058.84

Source: Elaborated by the Author

The total amount of methane (CH<sub>4</sub>) emissions produced in the El Zapallal landfill is 652688.39 tons (652.69 Gg) for 61 years (1990 to 2050). Likewise, the CH<sub>4</sub> emissions for the next 29 years (from 2022 to 2050) is 627503.86 tons (627.50 Gg). The amount of generated CH<sub>4</sub> for food and paper waste is given in the table above in the shaded columns separately. In the case of food waste, the CH<sub>4</sub> generated was 19156.93 tons (19.16 Gg) in the period of 1990 to 2021, whereas for the period of 2022 to 2050, it is 468967.05 tons (468.97 Gg). Regarding paper waste, it produced 6027.59 tons (6.03 Gg) in the period of 1990 to 2021, while in the next years (2022 to 2050), it will generate 158536.81 tons (158.54 Gg) of CH<sub>4</sub>.

For the closing year of the landfill (2039), the amount of CH<sub>4</sub> emissions will be 34257.67 tons (34.26 Gg). The maximum CH<sub>4</sub> emitted will be in 2040, 36383.77 tons (36.38 Gg), after one (1) year of the closing year. After this time, the amount of CH<sub>4</sub> from the landfill will decrease over the years. The decreasing and peak slopes of CH<sub>4</sub> production during the time are shown in figure 18 below.

Figure 18: Total Methane (CH<sub>4</sub>) Emissions produced in El Zapallal landfill (1990 to 2050)



Source: Elaborated by the Author

#### 4.7 Capturing of Biogas in El Zapallal Landfill as a Measure to Reduce GHG Emissions (Scenario with Measure)

Improvement of the System of Capturing Biogas is a proposed measure instead of releasing the Landfill Gas (LFG) into the air, and it would be applied from the year 2023. This measure is used in emergency situations and is the ultimate solution for security and mitigation against global warming (Ecothane, sf). This measure is proposed based on the fact that the activity of El Zapallal landfill has been operating since 1990, and the conditions to convert and uses the LFG as a renewable energy source could imply more requirements.

According to the United States Environmental Protection Agency [EPA] (2022), the LFG is a natural byproduct of the decomposition of organic material in landfills. LFG is composed of approximately 50 percent methane (the primary component of



natural gas), 50 percent carbon dioxide (CO<sub>2</sub>), and a small amount of non-methane organic compounds.

Furthermore, to estimate the Greenhouses Gases (GHG) associated with this proposed measure, it is necessary to establish a percentage of capturing of biogas generated in the landfill. The amount of biogas captured will be sent to a torch for burning. In this way, the biogas that will be emitted directly into the atmosphere, the one that has not been able to capture, will be lower than that emitted in a Business As Usual (BAU) scenario (Municipality of Lima, 2020). Moreover, the biogas flaring of biogas captured from El Zapallal Landfill, according to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, mentioned that emissions from flaring are insignificant, and this CO<sub>2</sub> is of biogenic origin and are therefore not included as a reporting item in the waste sector<sup>6</sup>.

Methane emissions in this scenario will consider a capture of the biogas generated in the landfill of 60%, based on the information of the Municipality of Lima (2020), which considers that ratio due to it being the more common value in that facility. Therefore, also considering that the biogas contains 50% methane in its composition, an R value (methane recovery) of 30% would be obtained.

The implementation of capturing the biogas generated in the El Zapallal landfill translates into a reduction in GHG emissions. The emission reduction potential of this measure is represented below:

*Table 16: Application of measures to reduce GHG emissions in El Zapallal landfill (Scenario with measure)*

<b>Scenario with measure</b>				
<b>Year</b>	<b>CH4 Total Emission (ton)</b>	<b>CH4 recovered ( R )</b>	<b>CH4 Total Emission (ton)</b>	<b>CO2eq emitted in the landfill (tCO2e/year)</b>
1990	0.00	0	0.00	0.00
1991	26.73	0	26.73	748.39
1992	53.47	0	53.47	1497.06
1993	80.22	0	80.22	2246.03
1994	106.98	0	106.98	2995.32
1995	133.75	0	133.75	3744.98
1996	160.54	0	160.54	4495.01
1997	187.34	0	187.34	5245.44
1998	214.15	0	214.15	5996.29

<sup>6</sup> CO<sub>2</sub> emissions of biogenic origin are either covered by the methodologies and reported as carbon stock change in the AFOLU Sector, or do not need to be accounted for because the corresponding CO<sub>2</sub> uptake by vegetation is not reported in the inventory (e.g., annual crops).

1999	240.98	0	240.98	6747.56
2000	267.83	0	267.83	7499.27
2001	294.69	0	294.69	8251.43
2002	321.57	0	321.57	9004.04
2003	348.47	0	348.47	9757.12
2004	362.74	0	362.74	10156.79
2005	393.45	0	393.45	11016.66
2006	439.71	0	439.71	12311.90
2007	468.36	0	468.36	13114.14
2008	487.26	0	487.26	13643.21
2009	507.16	0	507.16	14200.37
2010	532.53	0	532.53	14910.79
2011	562.11	0	562.11	15739.01
2012	639.65	0	639.65	17910.16
2013	795.12	0	795.12	22263.49
2014	929.93	0	929.93	26038.16
2015	1034.80	0	1034.80	28974.32
2016	1442.67	0	1442.67	40394.69
2017	1861.99	0	1861.99	52135.72
2018	2302.03	0	2302.03	64456.87
2019	2794.32	0	2794.32	78240.95
2020	3349.62	0	3349.62	93789.44
2021	3844.36	0	3844.36	107642.06
2022	4589.90	0	4589.90	128517.22
2023	5476.36	0.3	3833.45	107336.68
2024	6504.39	0.3	4553.07	127486.07
2025	7674.61	0.3	5372.23	150422.44
2026	8987.63	0.3	6291.34	176157.48
2027	10444.00	0.3	7310.80	204702.38
2028	12044.28	0.3	8430.99	236067.85
2029	13788.99	0.3	9652.29	270264.15
2030	15678.63	0.3	10975.04	307301.08
2031	17713.68	0.3	12399.57	347188.05
2032	19751.67	0.3	13826.17	387132.74
2033	21794.65	0.3	15256.25	427175.08
2034	23844.53	0.3	16691.17	467352.78
2035	25903.13	0.3	18132.19	507701.43
2036	27972.18	0.3	19580.52	548254.64
2037	30053.27	0.3	21037.29	589044.16
2038	32147.96	0.3	22503.57	630099.95
2039	34257.67	0.3	23980.37	671450.31
2040	36383.77	0.3	25468.64	713121.96
2041	34435.77	0.3	24105.04	674941.06
2042	32594.51	0.3	22816.16	638852.36
2043	30854.04	0.3	21597.83	604739.18
2044	29208.74	0.3	20446.12	572491.40

2045	27653.32	0.3	19357.33	542005.15
2046	26182.78	0.3	18327.94	513182.41
2047	24792.38	0.3	17354.67	485930.70
2048	23477.69	0.3	16434.38	460162.73
2049	22234.50	0.3	15564.15	435796.15
2050	21058.84	0.30	14741.19	412753.24

Source: Elaborated by the Author

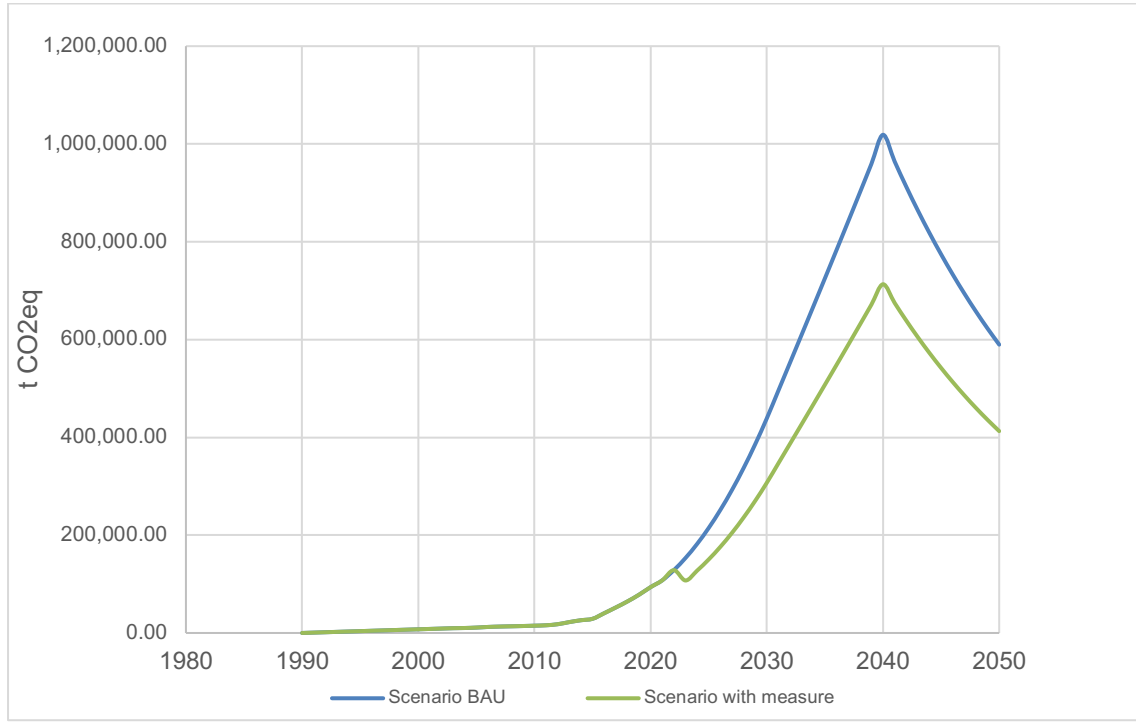
*Table 17: Potential of Reduction of GHG emissions of the Capturing of Biogas in El Zapallal Landfill (Scenario BAU vs. Scenario with measure)*

Year	Scenario BAU		Scenario with measure		Reduction of emissions due to the implementation of the measure (BAU - Measure)	% of emission reduction with respect to BAU
	CH4 Total Emission (ton)	CO2eq emitted in the landfill (tCO2e/year)	CH4 Total Emission (ton)	CO2eq emitted in the landfill (tCO2e/year)		
1990	0.00	0.00	0.00	0.00	0.00	0
1991	26.73	748.39	26.73	748.39	0.00	0%
1992	53.47	1497.06	53.47	1497.06	0.00	0%
1993	80.22	2246.03	80.22	2246.03	0.00	0%
1994	106.98	2995.32	106.98	2995.32	0.00	0%
1995	133.75	3744.98	133.75	3744.98	0.00	0%
1996	160.54	4495.01	160.54	4495.01	0.00	0%
1997	187.34	5245.44	187.34	5245.44	0.00	0%
1998	214.15	5996.29	214.15	5996.29	0.00	0%
1999	240.98	6747.56	240.98	6747.56	0.00	0%
2000	267.83	7499.27	267.83	7499.27	0.00	0%
2001	294.69	8251.43	294.69	8251.43	0.00	0%
2002	321.57	9004.04	321.57	9004.04	0.00	0%
2003	348.47	9757.12	348.47	9757.12	0.00	0%
2004	362.74	10156.79	362.74	10156.79	0.00	0%
2005	393.45	11016.66	393.45	11016.66	0.00	0%
2006	439.71	12311.90	439.71	12311.90	0.00	0%
2007	468.36	13114.14	468.36	13114.14	0.00	0%
2008	487.26	13643.21	487.26	13643.21	0.00	0%
2009	507.16	14200.37	507.16	14200.37	0.00	0%
2010	532.53	14910.79	532.53	14910.79	0.00	0%
2011	562.11	15739.01	562.11	15739.01	0.00	0%
2012	639.65	17910.16	639.65	17910.16	0.00	0%
2013	795.12	22263.49	795.12	22263.49	0.00	0%
2014	929.93	26038.16	929.93	26038.16	0.00	0%
2015	1034.80	28974.32	1034.80	28974.32	0.00	0%
2016	1442.67	40394.69	1442.67	40394.69	0.00	0%
2017	1861.99	52135.72	1861.99	52135.72	0.00	0%

2018	2302.03	64456.87	2302.03	64456.87	0.00	0%
2019	2794.32	78240.95	2794.32	78240.95	0.00	0%
2020	3349.62	93789.44	3349.62	93789.44	0.00	0%
2021	3844.36	107642.06	3844.36	107642.06	0.00	0%
2022	4589.90	128517.22	4589.90	128517.22	0.00	0%
2023	5476.36	153338.11	3833.45	107336.68	46001.43	30%
2024	6504.39	182122.95	4553.07	127486.07	54636.89	30%
2025	7674.61	214889.20	5372.23	150422.44	64466.76	30%
2026	8987.63	251653.54	6291.34	176157.48	75496.06	30%
2027	10444.00	292431.97	7310.80	204702.38	87729.59	30%
2028	12044.28	337239.79	8430.99	236067.85	101171.94	30%
2029	13788.99	386091.64	9652.29	270264.15	115827.49	30%
2030	15678.63	439001.55	10975.04	307301.08	131700.46	30%
2031	17713.68	495982.93	12399.57	347188.05	148794.88	30%
2032	19751.67	553046.77	13826.17	387132.74	165914.03	30%
2033	21794.65	610250.11	15256.25	427175.08	183075.03	30%
2034	23844.53	667646.82	16691.17	467352.78	200294.05	30%
2035	25903.13	725287.75	18132.19	507701.43	217586.33	30%
2036	27972.18	783220.92	19580.52	548254.64	234966.28	30%
2037	30053.27	841491.66	21037.29	589044.16	252447.50	30%
2038	32147.96	900142.79	22503.57	630099.95	270042.84	30%
2039	34257.67	959214.73	23980.37	671450.31	287764.42	30%
2040	36383.77	1018745.65	25468.64	713121.96	305623.70	30%
2041	34435.77	964201.51	24105.04	674941.06	289260.45	30%
2042	32594.51	912646.23	22816.16	638852.36	273793.87	30%
2043	30854.04	863913.11	21597.83	604739.18	259173.93	30%
2044	29208.74	817844.85	20446.12	572491.40	245353.46	30%
2045	27653.32	774293.07	19357.33	542005.15	232287.92	30%
2046	26182.78	733117.73	18327.94	513182.41	219935.32	30%
2047	24792.38	694186.71	17354.67	485930.70	208256.01	30%
2048	23477.69	657375.33	16434.38	460162.73	197212.60	30%
2049	22234.50	622565.93	15564.15	435796.15	186769.78	30%
2050	21058.84	589647.49	14741.19	412753.24	176894.25	30%

Source: Elaborated by the Author

Figure 19: Graphic Representation of the Potential of Reduction of GHG emissions of the Capturing of Biogas in El Zapallal Landfill (Scenario BAU vs. Scenario with measure)



Source: Elaborated by the Author

The results of the implementation of the measures related to the Capturing of Biogas in El Zapallal Landfill, Scenario with measure, obtained a potential reduction of greenhouse gases (GHG) of 30% in comparison to the Scenario BAU (without implementation of any measure). This reduction of GHG starts in the year 2023, which would apply the mitigation measure.

## Chapter 5. Conclusions

Based on the research of methane emission estimation in El Zapallal Landfill, the following conclusions can be obtained:

- The predicted amount of the Municipal Solid Waste (MSW) for the period 2021 to 2039 has been determined by using the values of GDP per capita in the same period due to the high relationship between the variables of Municipal Solid Waste Generation Rate (MSWGR) [Dependent Variable] and the GDP per capita [Independent Variable] found in the evaluation of the Multiple Linear Regression, as was described in the item 4.1.5 of this research. Thus, the projected average amount of MSW deposited in El Zapallal Landfill of Lima Province in the period of 2021 to 2039 is 2799102.74 tons/year. Likewise, the average amount of collected MSW by the landfill, in mention, between 1990 and 2020 is 171771.83 tons/year.
- The amount of Methane (CH<sub>4</sub>) emissions from the Municipal Solid Waste disposed of in the El Zapallal landfill of Lima Province, operated under a semi-aerobic management landfill type, was calculated using the IPCC Tier 2 model for the period of 1990 to 2050. The estimation of the CH<sub>4</sub> emissions based on Municipal Solid Waste was risen over the years after the starting year (1990) with 26.73 tons (0.026 Gg) and reached the peak in 2040, after the closing year of the landfill, with values of 36383.77 tons (36.38 Gg). Likewise, the total amount of CH<sub>4</sub> emissions produced for the period of 1990 to 2050 is 652688.39 tons (652.69 Gg), as well as the CH<sub>4</sub> emissions for the period from 2022 to 2050 is 627503.86 tons (627.50 Gg). The high generation potential of CH<sub>4</sub> gases in the El Zapallal landfill is due to the composition of organic waste landfilled on it, which is 50% of the total MSW.

According to our calculations, methane generated from food waste takes the place of 19156.93 tons (19.16 Gg) in the period of 1990 to 2021, whereas for the period of 2022 to 2050, it is 468967.05 tons (468.97 Gg). In the case of paper waste, it produced 6027.59 tons (6.03 Gg) in the period of 1990 to 2021, while in the following years (2022 to 2050), it will generate 158536.81 tons (158.54 Gg) of CH<sub>4</sub>. Whereby according to the results obtained in the contribution of CH<sub>4</sub> generated, we conclude that food waste generation has significantly increased in Lima Province due to rapid urbanization and economic growth. Therefore, recycling food waste is crucial for preventing regionally damaging climate change impacts.

- Some of the efforts to mitigate methane emissions can be carried out through the *improvement of the segregation programs at the source* and the *selective collection of municipal solid waste*, facilitating waste recovery, that the local governments of Lima Province have ongoing since this kind of

waste contributes to high levels of organic waste, between them, food waste, which currently represents a 50% of the Municipal Solid Waste generated in the province of Lima.

Likewise, according to article 51 of the Comprehensive Waste Management Law Solids (CWMLS) - Decree of Law N° 1278 of Peru, the local governments (districts municipalities) must prioritize organic waste from the maintenance of green areas and municipal markets, as well as, if feasible, organic waste from households. So, since the obligation was established in 2016, the year of enacted law, but in practice, this is not working properly, the national government should improve the incentives to make that this obligation works adequately. Similarly, the local governments have to make more effort to create awareness among the citizens to enhance behaviors about the correct segregation of solid waste, especially organic waste.

Moreover, one measure of mitigation of greenhouse gas (GHG) emissions, specifically methane emissions, is the implementation of the Capturing of Biogas in the El Zapallal Landfill (Scenario con measure), which would obtain a potential reduction of GHG of 30% annually, in comparison to the Scenario BAU - Business As Usual (without implementation of any measure). The reduction of these GHG would start from the year 2023 onwards, when the measure is projected to apply it.

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## 페루 리마 지방 도시 고형 폐기물 매립지의 메탄 배출: El Zapallal 매립지 사례 연구

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이 백서의 목적은 페루 메트로폴리탄 리마의 El Zapallal 매립지에서 도시 고형 폐기물의 메탄 배출량과 이러한 배출량을 줄이기 위한 잠재적인 완화 전략을 결정하는 것입니다. 발생한 메탄의 평가 기간은 2039년 연구 대상 매립지의 수명을 고려하여 1990년부터 2050년까지로 하였다.

이를 위해 IPCC 2006 가이드라인, tier 2 방법이 Lima 지방의 El Zapallal 매립지에 있는 도시 고형 폐기물로부터 메탄 양을 계산하는 데 사용되었습니다. 같은 기간 도시 고형 폐기물(1990~2020), 매립에 참여한 인구 및 1인당 GDP에 대한 2차 데이터는 지역, 국가 및 국제 기관에서 사용되었습니다. 앞서 언급한 정보로 매립지에서 발생하는 메탄 배출량을 계산했습니다.

그 결과 2021~2039년 리마주 엘 자팔랄 매립지에 매립된 MSW의 평균 예상량은 2799102.74톤/년인 것으로 나타났다. 마찬가지로 1990년에서 2020년 사이 언급된 매립지에 의해 수거된 MSW의 평균 양은 171771.83톤/년입니다. 반호기성 관리 매립 방식으로 운영되는 Lima 주 El Zapallal 매립지에서 처분되는 MSW의 메탄(CH<sub>4</sub>) 배출량과 관련하여 시작 연도(1990년) 이후 몇 년 동안 26.73톤(0.026Gg) 증가했습니다. 2040년에는 매립지 폐쇄 연도 이후 36383.77톤(36.38Gg)의 값으로 정점에 도달했습니다. 또한 1990년부터 2050년까지 발생한 총 CH<sub>4</sub> 배출량은 652688.39톤(652.69 Gg)입니다. El Zapallal 매립지에서 CH<sub>4</sub> 가스의 높은 생성 가능성은 전체 MSW의 50%에 해당하는 매립된 유기 폐기물의 구성 때문입니다.

El Zapallal 매립지에서 발생하는 CH<sub>4</sub> 배출량을 줄이기 위한 전략의 일환으로 i) El Zapallal 매립지에서 바이오가스 포집(시나리오 콘 측정)을 구현하여 연간 30%의 잠재적 GHG 감소를 얻을 수 있습니다. , Scenario BAU - Business As Usual(어떤 조치도 실행하지 않음)과 비교합니다. 이러한 온실가스의 감축은 조치가 적용될 것으로 예상되는 2023년부터 시작됩니다. 메탄 배출을 줄이기 위한 노력 중 일부는 ii) 소스 분리 프로그램의 개선과 리마 지방의 지방 정부가 진행 중인 도시 고형 폐기물의 선택적 수집, 폐기물 회수 촉진을 통해 수행될 수 있습니다. 이러한 종류의 폐기물은

높은 수준의 유기 폐기물에 기여하기 때문에 그 사이에는 현재 리마 지방에서 발생하는 도시 고형 폐기물의 50%를 차지하는 음식물 쓰레기가 있습니다. 마지막으로 국가에서 발생하는 유기성폐기물의 관리책임을 이행하도록 중앙정부에 지방정부에 개선 인센티브를 부여하여 CH<sub>4</sub> 배출 비용을 발생시킨다. 그런 식으로 지방 정부는 일부 국가 규정에서 정한 책임을 준수할 수 있습니다.

주제어 : 메탄 배출, 도시 고형 폐기물, 매립지에서 바이오가스 포획, 리마, 페루

## Methane Emissions from Landfills of Municipal Solid Waste in Lima Province, Peru: Case Study of El Zapallal Landfill

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Response to Climate Change Master's Degree

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The objective of this paper is to determine the methane emissions of Municipal Solid Waste from El Zapallal Landfill in Metropolitan Lima, Peru, and the potential mitigation strategies to reduce these emissions. The period of the evaluation of the methane generated was between 1990 to 2050, considering the lifespan of the studied landfill in the year 2039.

For this purpose, IPCC 2006 Guidelines, tier 2 method has been used for the calculation amount of methane from Municipal Solid Waste in the El Zapallal Landfill of Lima Province. Secondary data on Municipal Solid Waste (1990 to 2020), Population attended by the Landfill, and GDP per capita in the same period were used from local, national, and international institutions. With previous information mentioned, we calculated the methane emissions generated by the landfill.

As a result, we found that the projected average amount of MSW deposited in El Zapallal Landfill of Lima Province in the period of 2021 to 2039 is 2799102.74 tons/year. Likewise, the average amount of collected MSW by the landfill in mention, between 1990 and 2020, is 171771.83 tons/year. Related to the Methane (CH<sub>4</sub>) emissions from the MSW disposed of in the El Zapallal Landfill of Lima Province, operated under a semi-aerobic management landfill type, rose over the years after the starting year (1990) with 26.73 tons (0.026 Gg) and reached the peak in 2040, after the closing year of the landfill, with values of 36383.77 tons (36.38 Gg). Moreover, the total CH<sub>4</sub> emissions produced for the period of 1990 to 2050 is 652688.39 tons (652.69 Gg). The high generation potential of CH<sub>4</sub> gases in the El Zapallal landfill is due to the composition of organic waste landfilled on it, which is 50% of the total MSW.

As part of the strategies to reduce the CH<sub>4</sub> emissions generated by the El Zapallal Landfill, are i) the implementation of the Capturing of Biogas in the El Zapallal Landfill (Scenario con measure), which would obtain a potential reduction of GHG of 30% annually, in comparison to the Scenario BAU - Business As Usual (without implementation of any measure). The reduction of these GHG would start from the year 2023 onwards, when the measure is projected to apply it. Some of the efforts to mitigate

methane emissions can be carried out through ii) the *improvement of the segregation programs at the source* and the *selective collection of municipal solid waste*, facilitating waste recovery, that the local governments of Lima Province have ongoing. Since this kind of waste contributes to high levels of organic waste, between them is food waste, which currently represents 50% of the Municipal Solid Waste generated in the province of Lima. Finally, improvement incentives are given to the national government to the local government to make them fulfill responsibilities for the management of the organic waste generated in their jurisdiction, which costs the release of CH<sub>4</sub> emissions. In that way, the local government will be able to comply with the responsibilities established in some national regulations.

**Keywords:** Methane Emissions, Municipal Solid Waste, Capturing of Biogas  
in landfills, Lima, Peru