



**CHALMERS**  
UNIVERSITY OF TECHNOLOGY



# **Life Cycle Assessment of Organic Waste Treatment**

by Composting and Anaerobic Digestion for  
the City of Cuenca – Ecuador

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Cover: Cuenca's composting facility

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## Abstract

This thesis explores the environmental performance of anaerobic digestion (AD) and composting as waste management solutions for the organic fraction of municipal solid waste (OFMSW) in Cuenca, Ecuador. Using Life Cycle Assessment (LCA) methodologies, it evaluates key environmental impacts such as global warming potential and photochemical oxidant formation, aiming to identify the most suitable method for reducing the amount of organic waste sent to landfills.

The results indicate that anaerobic digestion has strong potential to reduce greenhouse gas emissions, particularly when biogas is effectively captured and used. On the other hand, composting, while less effective in terms of emission reductions, is more cost-efficient and can play a valuable role in improving soil health. Despite these benefits, both technologies face considerable challenges in the Latin American and Caribbean (LAC) region, where the focus is often still on meeting basic waste management needs, such as establishing sanitary landfills. The high costs and limited development of AD in the region also raise concerns about its viability.

The study highlights the importance of understanding the composition of OFMSW, as this has a direct impact on the efficiency of AD systems. Future research should explore the potential of co-digesting OFMSW with other types of organic waste to boost biogas production. Additionally, factoring in socio-economic aspects—such as the costs of implementation, potential economic gains from energy generation, and effects on local communities—will provide a fuller picture of the sustainability and practicality of these technologies.

Ultimately, the findings suggest that while both AD and composting offer clear environmental benefits, their adoption must be guided by local priorities and infrastructure readiness. Addressing these regional factors is crucial for optimizing resource recovery and minimizing environmental impacts.

### Keywords:

Anaerobic digestion, Composting, Life Cycle Assessment (LCA), Organic fraction of municipal solid waste (OFMSW), Greenhouse gas emissions, Biogas, Waste management, Ecuador, Latin America and Caribbean (LAC) region, Socio-economic considerations, Environmental sustainability, Resource Recovery.



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# Notations

## Acronyms

MSW	Municipal Solid Waste
EMAC EP	Municipal Cleaning Company of Cuenca
LCA	Life Cycle Assessment
AD	Anaerobic Digestion
OFMSW	Organic Fraction of Municipal Solid Waste
GHG	Greenhouse Gas
DAD	Dry Anaerobic Digestion
ISO	International Organization for Standardization
VS	Volatile Solids
CFCs	Chlorofluorocarbons
LAC	Latin America and the Caribbean

## Units

Tn	Tonnes
Hp	Horsepower
kW	Kilowatt
GWh	Gigawatt-hour
kWh	Kilowatt-hour
kWh/Tn	Kilowatt-hour per tonne
m <sup>3</sup>	Cubic meter
l/Tn	Liters per tonne
g	Grams
l	Liters
m <sup>3</sup> /kg VS	Cubic meter per kilogram of volatile solids
kg CO <sub>2</sub> -Eq	Kilograms of CO <sub>2</sub> equivalent
kg SO <sub>2</sub> -Eq	Kilograms of SO <sub>2</sub> equivalent
kg 1,4-DCB-Eq	Kilograms of 1,4-dichlorobenzene equivalent
kg PO <sub>4</sub> -Eq	Kilograms of phosphate equivalent
kg ethylene-Eq	Kilograms of ethylene equivalent
m <sup>3</sup> world-eq. depletion	Cubic meters of world-equivalent depletion
MJ	Megajoules
kg sb-Eq	Kilograms of antimony equivalent



# 1. INTRODUCTION

According to Kaza et al. (2018) as of today, in the world 2.01 billion tonnes of municipal solid waste (MSW) is generated annually, with at least 33% of it mismanaged with environmental concerns, and an expectation to grow to 3.40 billion tonnes by the year 2050. This same report projects that waste generation is expected to increase by 40% in low-income countries, while only by 19% in high-income countries by the same year. In Latin America and the Caribbean, the estimation is that by the year 2050 the increase in waste production will be of around 60% and the global composition of food and green waste is around 44% (Kaza et al., 2018).

Ecuador generates approximately 5 million tonnes of waste yearly, with a collection rate of 85.5%, where about 44.2% correspond to solid organic waste. In the country, 51.6% of the collected waste is properly disposed on a controlled landfill, 29.9% in a controlled cell and 18.6% on uncontrolled open dump sites (*Gestión de Residuos Sólidos*, s. f.). Cuenca the city where this project will be carried out, is a small city in the Ecuadorian Andes, with a population of 505.585 habitants (Alcaldía de Cuenca, s. f.), officially uses two different waste management processes, composting and landfilling, but only organic waste from markets, food courts and parks is collected for composting.

The present master thesis has been developed in direct collaboration with the Universidad de Cuenca, and the municipal cleaning company of Cuenca (EMAC EP), which is responsible for the collection and treatment of the MSW generated in the city. The purpose of this master thesis is to compare the environmental performance using an Life Cycle Assessment (LCA) of two possible waste management alternatives, composting, and anaerobic digestion (AD) to manage a projected increase in the organic fraction of the municipal solid waste (OFMSW) segregated reducing the amount of solid waste going into the landfill.

By comparing the different waste management systems, the project aims to identify the most environmentally sustainable, energy-efficient solution to reduce the OFMSW going into the landfill, decrease greenhouse gas emissions, and enhance energy recovery from organic waste.

Reducing the organic fraction of the waste going to landfill is a top priority of EMAC EP, due to not only the environmental burden that this type of waste is responsible for when it ends in a landfill, with GHG emissions, ammonia leakages through leeching among the most relevant (Vasarhelyi, 2021), but also due to operating limitations with the landfills getting full quicker than expected and the difficulties to find new landfill emplacements.

The goal is for the results of this master thesis to provide insights and recommendations to Universidad de Cuenca researchers, EMAC EP, and other decision makers for the future management and expansion of OFMSW treatment in Cuenca, thereby contributing to the region's sustainability and reducing waste production. Also to have a better understanding of their possibilities, and to be part of a broader research including economical and practical aspects for the implementation of AD as a new waste management route for the organic waste generated in the city.

## 2. BACKGROUND AND METHODOLOGY

### 2.1. Organic waste management

As mentioned above organic waste poses a risk for the environment if not managed correctly. According to the hierarchy of waste depicted in Figure 1 (Jain et al., 2018) the most desirable ways of reducing organic waste is through prevention and optimization or reduction. But there is a significant fraction of organic waste that cannot be avoided thus correct organic waste management is essential. Landfilling and incineration without energy recovery are among the worst management strategies followed by incineration with energy recovery. Composting and anaerobic digestion on the other hand are the best methods to deal with this unavoidable fraction of organic waste.

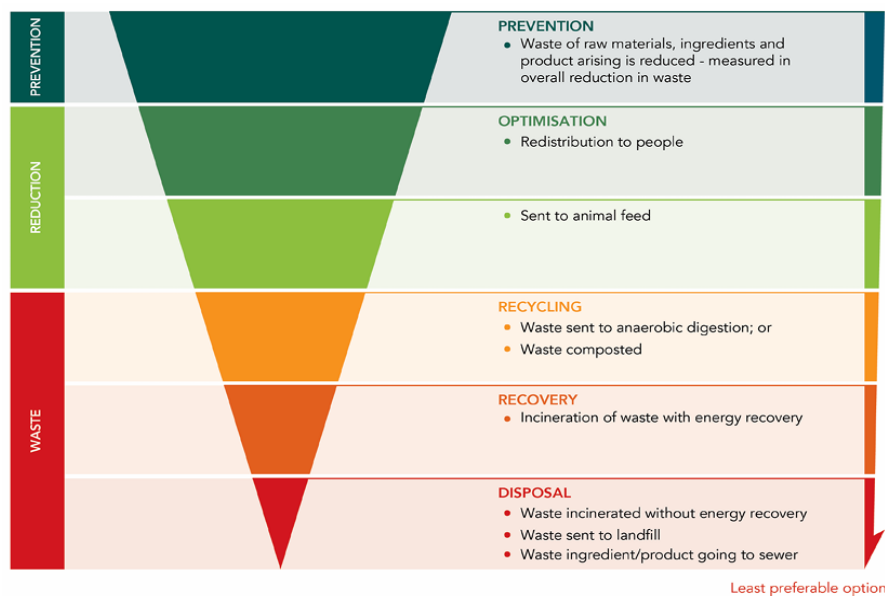


Figure 1 Waste hierarchy (Jain et al., 2018)

#### Composting

Composting is the biological process where under aerobic conditions organic matter is decomposed. Oxygen is a critical factor in the composting process, so it's important to control the oxygen availability during all the procedure (Diaz et al., 2007). Food waste, green waste, or manure are some of the feedstocks that will produce different quality of compost (Brown et al., 2008).

There are different composting processes that differ on how the oxygen is mixed with the organic matter, or if the composting is done in open air or in closed bins with more controlled variables such as temperature. As with the feedstocks, the exact process choice will affect the quality of the compost, and its suitability for agricultural purposes (Ishii & Takii, 2003).

The composting process emits greenhouse gases (GHG), especially methane and nitrous oxide, and odors in the form of ammonia (Li et al., 2023), meaning that although it is a proven method to reduce the mass of organic waste up to 46% (Breitenbeck & Schellinger, 2013) and to reduce the quantity of this waste going into the landfills, it still has negative impacts on the environment and society.

The main output of the composting process is the compost which is used in agriculture, allowing the nutrients present in the organic waste to be reused in crop production, enhancing the circular economy of this particular waste and reducing nitrogen losses (Zhao et al., 2020).

### *Anaerobic digestion*

AD is a waste treatment process employing anaerobic bacteria to break down organic waste in an oxygen-depleted environment (Yan & Salman, 2023). The process results in the production of biogas, which consists of methane and carbon dioxide. Biogas can be used to generate power and heat, and it can be upgraded to biomethane for use as a substitute of natural gas (Hu et al., 2020). The AD can process different feedstocks including biodegradable fractions of municipal solid waste, industrial waste, animal manure, food waste and wastewater sludge (Röder & Welfle, 2019).

The efficiency and stability of the AD process depends on several factors such as the type of feedstock, the operating conditions or the type of digester used. AD can be done at different temperatures between 25° and 45°, the process can be continuous or batch-based, and the resulting biogas can be upgraded to biomethane or directly used as combustible for heat and power generation (Yan & Salman, 2023).

The byproduct of AD, called digestate can be used as fertilizer and can undergo different treatment processes according to the needs of its intended use (O'Shea et al., 2022). The properties of the digestate vary based on the operating conditions and the feedstock (Kovačić et al., 2022).

## 2.2. LCA studies on Composting and Anaerobic digestion

There are several LCA studies regarding organic waste management that include composting as one of the studied alternatives, including a review of 56 papers (Oviedo-Ocaña et al., 2023) that focuses on the challenges of applying the LCA methodology to the composting of organic waste. Comparing composting with other waste management systems is also a common practice with few authors using anaerobic digestion as the alternative (Lewerenz et al., 2023; Nordahl, 2018; Salemdeeb et al., 2018; Weligama Thuppahige & Babel, 2022) but also landfilling (Buratti et al., 2015). According to Oviedo-Ocaña et al. (2023) when studying composting, several studies are gate to gate (Morsink-Georgali et al., 2022) while others include the use phase, especially the benefits of not using industrial fertilizers (Andrea Blengini, 2008; Buratti et al., 2015) but there is no consensus on the best methodology.

In a LCA study conducted by Lewerenz et al. (2023), when comparing different composting and anaerobic digestion technologies and a combination of them, determine that some composting configurations are less harmful for the environment, this study is a complete LCA including an uncertainty analysis using a Montecarlo simulation to add robustness to its results, and the impacts are weighted using the Ecological Scarcity Method (Lambrecht et al., 2020). Similar results are shown in a study by Salemdeeb et al., (2018) where Composting shows better performance in most areas when compared with AD and incineration. But most of the literature accounts anaerobic digestion for better environmental performance (Lin et al., 2018; Nordahl, 2018; Weligama Thuppahige & Babel, 2022).

A study in Sri Lanka (Weligama Thuppahige & Babel, 2022) compares a composting and an anaerobic digestion plant already in operation, the results show that anaerobic digestion is preferable. In this study both systems are credited by their avoided emissions either for the

substitution of industrial compost and the electricity production in the anaerobic digestion plant.

In San Jose California, a study comparing anaerobic digestion against composting and landfilling found that anaerobic digestion is also a better option (Nordahl, 2018), but only GHG were measured. This study found that anaerobic digestion largely benefits from crediting the energy production presenting even negative emissions if the energy avoided is considered to be generated with a natural gas combined cycle power plant, but also without the crediting still performs better than its composting and landfilling alternative.

### 2.3. Organic waste management in Cuenca

EMAC EP is considered to be a forerunner and innovator in collection and treatment of solid waste in Ecuador and the region. They were the first to successfully implement a controlled landfill in the country, implement composting later on, and they are currently using a bioreactor to collect the gas from the landfill to produce energy.

However, the waste management and especially the collection system in place needs to be improved, since household waste is collected only with two different collection streams. Currently, there is a house-to-house collection once a week; waste should be placed in two different bags, one blue, containing the recyclables (cardboard, plastics, metal, and glass) and the second, white, with the rest of the waste. Independent collectors dive through the blue bags to recover any valuable materials, mainly metals, cardboard and glass and some high-quality plastics that can be sold to private recyclers. Then what is left is mixed with the white bag and sent to a landfill following a previous sorting to recover any valuables left.

This means that as of today, there is still a high percentage of the organic solid waste going into the landfill since it is only the organic solid waste from markets, food courts and “green waste” (organic solid waste collected from the gardening activities of municipal parks and green spaces) is sent to the composting plant once it is characterized. The organic solid waste from households' collection still goes to the landfill (Figure 2).

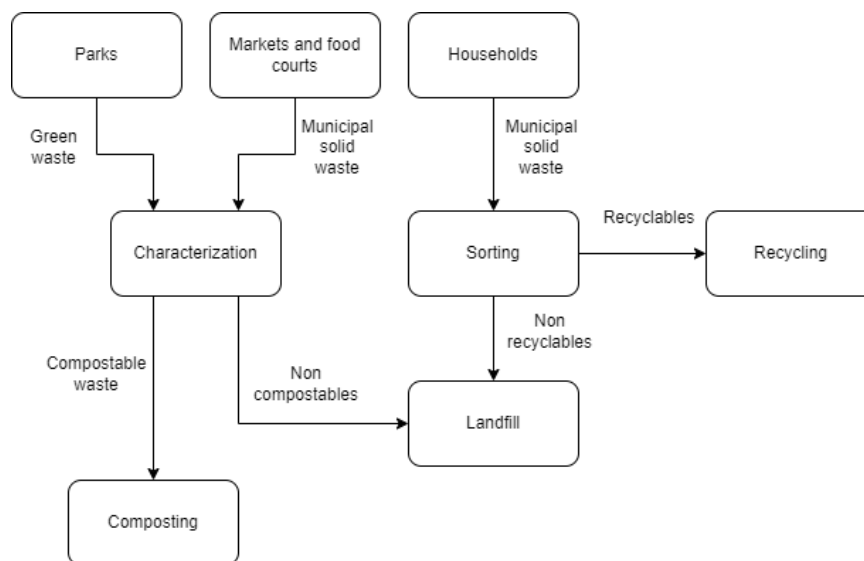


Figure 2 Diagram depicting the current waste management operations in the city of Cuenca

The current composting operations have been a success in the sense of collection and treatment, but according to EMAC, the operations are too costly, and the final product price is

too high for the region, having very little market appreciation outside the public market since there are cheaper options. This leads to accumulation of compost and therefore an increase in storage that leads to higher operation costs and possible environmental burdens.

Moreover, there are plans to expand the collection of organic waste, including the household organic waste with the implementation of a green bag where only organic waste should be discarded. While composting is a referent, EMAC understands that there is a need to study alternatives to absorb the expected increment of the organic waste separated.

The obvious choice is to expand the composting system (Figure 3), but due to the aforementioned difficulty to sell the compost and the known disadvantages of the composting operations such as high land requirements or odors (ISWM-Tinos Life, 2011) a viable alternative is to convert the unavoidable biowaste into energy, in the form of biogas, through AD (Figure 4).

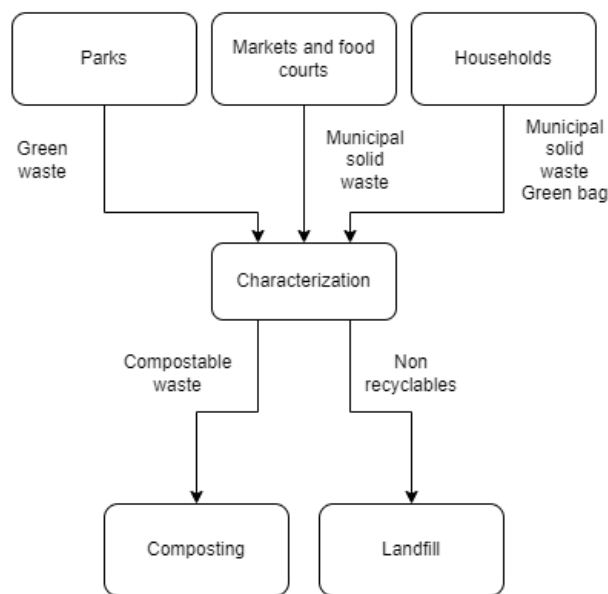


Figure 3 Diagram depicting a scenario where composting is used to absorb the extra organic waste collected in the implementation of the green bag in the households of the city of Cuenca.

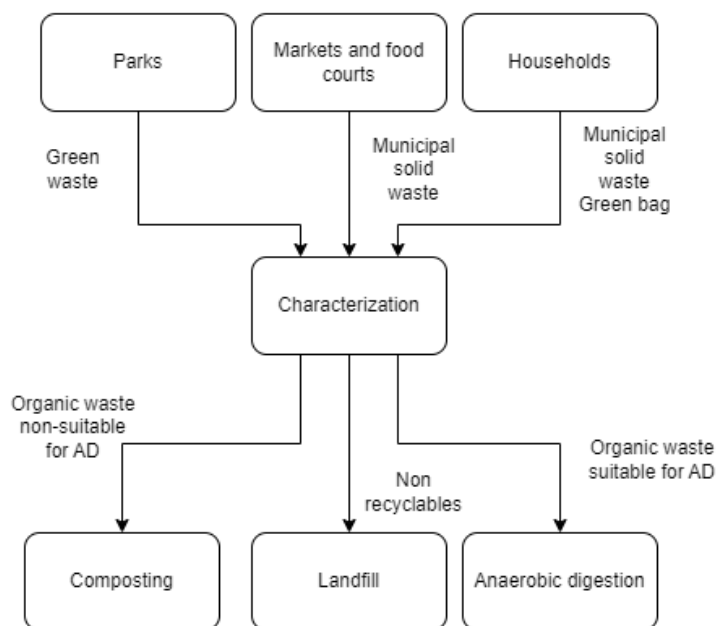


Figure 4 Diagram depicting a scenario where AD is used to absorb the extra organic waste collected in the implementation of the green bag in the households of the city of Cuenca.

The implementation of this technology could alleviate the amount of organic solid waste going into the landfill, reduce the amount of greenhouse gas emissions by land filling and composting, and the energy produced can serve as input for the electricity and heat needed for composting. The energy produced also has the potential to make the treatment process cheaper, reducing operational and storage costs, thus reducing the price of the compost, and facilitating its sale.

Furthermore, the financial situation of EMAC usually requires outside financing to implement new projects, so the results of this life cycle assessment can be used as part of the information used to search for new funding opportunities.

The university of Cuenca which is assisting the development of this thesis has also interest into the study of the implementation of an AD plant, since they already have semi-industrial digesters, and there have plans to start a research project at PhD level on the suitability of the AD of the food waste in the city of Cuenca.

#### Current composting operations

The composting process description is based on the field trips, personal observations, and answers from the workers and responsible of the composting plant reflecting the actual composting process since the proposed escalation of the composting to include the new organic waste is to follow the same procedures, with some modifications due to the characteristics of this new waste. It's depicted in Figure 5 and detailed in this section.

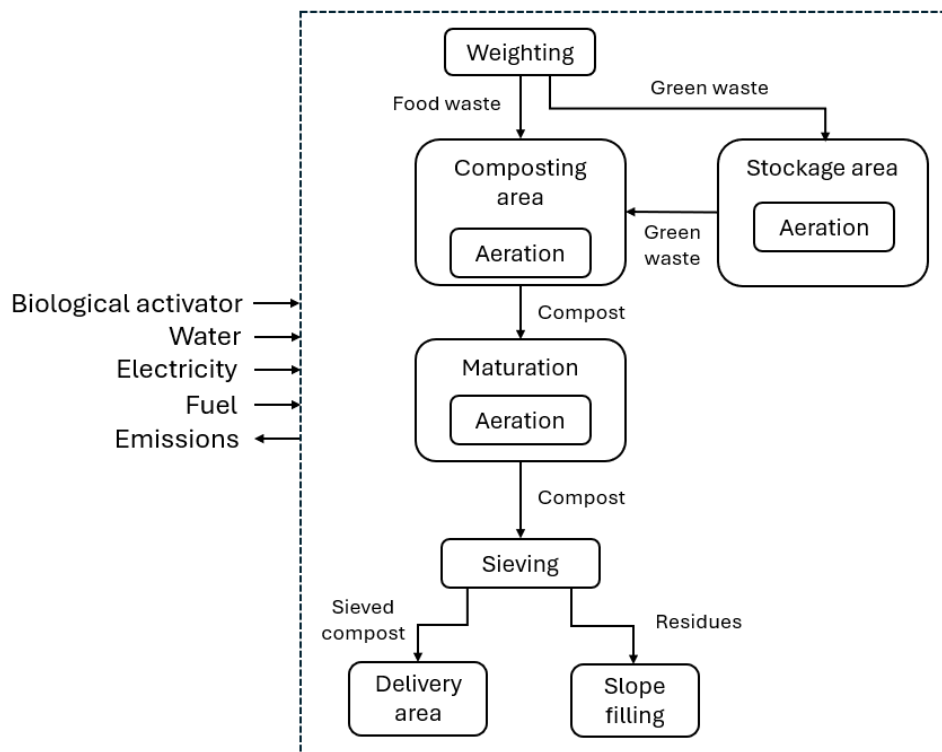


Figure 5 Current composting operations

Nowadays two types of waste arrive at the facility through trucks, green waste and food waste from markets and food courts. The trucks are weighed to measure the quantity of waste that enters, and the green waste goes to a stockage area while the food waste goes straight to the composting area. According to the EMAC data 7457 Tn of organic waste enters the composting plant yearly, being 50% green waste and the rest food waste.

The stockage area is used mainly due to the seasonality of the green waste, its stocked so it can be mixed to get a constant mix of green waste and food waste of around half each during all the year. In the stockage area the green waste is left in the open air, crushed, and moved with an excavator model *John Deere 410 K SN* once or twice a week, and usually left there around 2-3 months where it starts to decompose.

The food waste that arrives in the composting area, a covered area with open walls as it can be seen in Image 1, is mixed with the old green waste and left there for two weeks, it is turned by a compact wheel loader model *BOBCAT S750* with 85 hp of power 2-3 times a week, during this time a complex liquid biological activator (*Soluzione d.p. from Eurovix*) consisting of enzymes, bacteria, and plant extracts is used nebulized on the composting area to reduce the odors (17750 liters per year). The compact wheel loader is committed 3 hours every day into the composting area.



*Image 1 Composting area in the composting facility of EMAC*

The mix is moved to the maturation area where it stays 2 months, every 2 weeks the mix is turned and moved with the same compact wheel loader. Here the compact wheel loader is committed 4 hours every day. Finally, the mix is sieved using either an electric sieve or a manual sieve if the automatic is out of service, and the compost is ready to be picked up by the clients while the refuse, mainly consisting of plastics that arrived mixed with the organic waste is used to stabilize a slope within the composting plant. The compost production of this facility is nearly 1000 tonnes yearly, according to the data obtained from EMAC.

#### *Current anaerobic digestion in Latin America*

Most of the studies and reports on anaerobic digestion in Latin America come from small and medium scale digesters. These are mostly purposed for cooking and heating, and they have been successfully implemented due to the low investment cost and low maintenance these digesters require, also the low complexity of their input, being mostly agricultural residues, and giving the users an efficient way to improve sanitation and decrease direct environmental impacts, besides the energy carrier produced (Silva-Martínez et al., 2020). Examples of these type of digesters can be found in Costa Rica, Chile, Colombia, Cuba or Paraguay (Torroba et al., 2023).

On the other hand, large scale anaerobic digesters have a high investment, high maintenance costs, and high technical complexity, which has rendered their implementation in the region, only having Argentina, Chile, Colombia, Brazil and Mexico, which are fairly bigger and wealthier nations, as large scale implementers, using up flow anaerobic sludge blanket and continuous stirred tank reactors for wastewater and animal manure treatment (Rodríguez-Nuñez & Castillo Baltazar, 2020).

Most of the current implementations and study suggestions on the large scale tend to use one type or a simple mix of raw materials, such as vinasses from sugarcane production (Silva dos Santos et al., s. f.), residues from meat industry, palm oil residues and wastewater through cogeneration (Arrieta et al., 2007), sewage, cactus and vegetable waste (*Proyectos de Aprovechamiento Energético a partir de Residuos Urbanos en México*, s. f.), forest and agricultural residues (Moreda, 2016), among other ongoing projects.

There are few large-scale digesters that have OFMSW as the main input. There are various reasons that inhibit the implementation of this type of plant, the main one being a lack of waste sorting systems. Nevertheless, Mexico and Brazil have started working on the implementation of dry anaerobic digestion (Silva-Martínez et al., 2020).

Brazil is a country with a large potential for biogas generation and the leader in the region for bioenergy (Silva-Martínez et al., 2020). Currently 37% of municipal wastewater treatment plants use anaerobic reactors but the use of biogas for energy is low with only 8 out of 1300 plants using it effectively (Torroba et al., 2023). Regarding the treatment of OFMSW using AD Brazil has at least two plants in the south-west of the country (Torroba et al., 2023), one being a dry anaerobic digestion (DAD) pilot plant, a project which is an effort between a private company and the Federal University of Minas Gerais, located in the state of Rio de Janeiro, with the capacity of managing 50 tons per day and generating 250 kW, with plans to be expanded (Silva-Martínez et al., 2020).

By 2023 Argentina had at least five plants using anaerobic digestion for OFMSW with up to 548 kg treated every day in the biggest plant (Torroba et al., 2023). There is also a relevant paper (Morero et al., 2017) that conducts an LCA on AD of the OFMSW and compares the effects of different options on the use of the Biogas and the Digestate on the environmental performance of anaerobic digestion plants. Also, relevant from this study is to note that at the time when it was conducted, only 6% of the AD plants were used to generate energy and that the main feedstock used was industrial and agro wastes.

There are as well, ongoing studies and efforts to implement AD for the OFMSW, that usually start studying the OFMSW composition in order to determine the degradation and methane production capacity, these, to create and implement a small scale prototype of anaerobic digester, and evaluate its functionality, such as the one made by (Torres, 2023) in the municipality of Muzo in Colombia; small educational plants in Paraguay and Chile (Torroba et al., 2023), the study conducted in Manta, Ecuador by *Universidad Laica Eloy Alfaro de Manabí* in collaboration with the Cuban *Universidad Central Martha Abreu de las Villas* (Belén et al., 2020) or the ongoing study by the *Universidad de Cuenca*.

In the city of Quito in Ecuador, biogas was found to be the most optimal technology for the treatment of organic waste into electricity via an anaerobic digester, mobilizing a big portion of the residential organic waste and generation 3.9 GWh, that could be sold at 351000 USD. This would also reduce significantly the amount residential waste going into landfills, landfill greenhouse gas emissions and leachate produced (Davis et al., 2016). It is important to consider that the waste generated in Quito and Quito's geographical conditions are very similar to Cuenca's.

## 2.4. Methodology description

The methodology used in this master thesis is the Life Cycle Assessment (LCA) approach.

LCA is a comprehensive methodology that studies the possible environmental impacts derived from a product or service (Horne et al., 2009). It was conceived in the 1960s and is today widely accepted by industries and academics as a relevant tool to analyze processes. The standardization of the LCA methodology commenced in 1993 (Pryshlakivsky & Searcy, 2013), leading to the establishment of a recognized framework for conducting LCAs known as International Organization for Standardization (ISO) 14040:2006, which is widely accepted today.

LCA studies take into consideration the emissions, resource, and energy use, as well as any other flow that can have impacts on the environment, then it ties each flow to a specific environmental burden. These studies can be conducted from the acquisition of the raw materials to the impacts of the end of life of the product or service, named cradle to grave analysis (Nieuwlaar, 2013) or, taking into consideration only some steps of its life cycle; for example, only production impacts are taken in consideration in gate-to-gate LCA studies.

According to the ISO 14040:2006 standard the LCA methodology accounts for 5 different phases (fig1) that will be described in the following sections of this chapter.

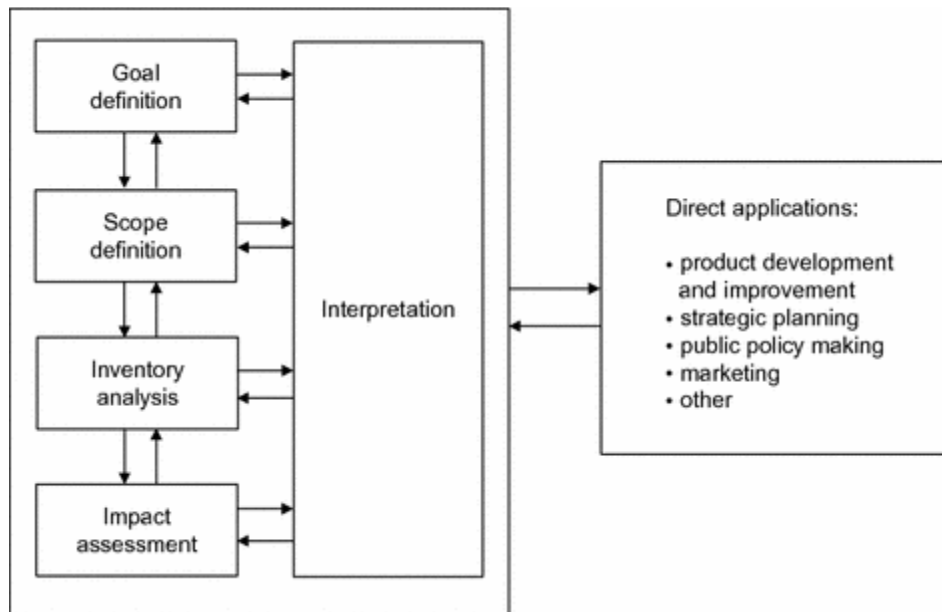


Figure 6 LCA methodology phases (Hauschild, 2018)

### 2.4.1. Goal definition

The goal definition should state the application, the reason, and the intended audience of the study according to the ISO 14040 standard (International Organization for Standardization, 2006). Moreover, the goal definition should include whether the results are intended for comparative assertions and public disclosure.

This information will help to increase the transparency of the study contextualizing its purpose and specifying the stakeholders it aims to address. Clearly stating the intended use of the results, whether for internal decision-making, system comparison or public information, the goal establishes the lines for the following phases of the LCA.

### 2.4.2. Scope definition

In the scope definition aspects such as the options modelled, functional units, the impacts that will be included and the system boundaries need to be stated along with the data quality requirements. This should be closely related to the goal of the study stated (Baumann & Tillman, 2004).

The first step is defining the options that will be modeled, especially important in comparative LCAs (Baumann & Tillman, 2004), where it is important to make sure that the systems are comparable and a correct functional unit is chosen.

The functional unit needs to express the function of the system, the same system can be studied with different functional units depending on the goal, for instance, a composting plant that is studied on the perspective of the waste management system the functional unit can be 1 Tn of organic waste going in, while if it's studied on the perspective of the production then a better functional unit will be 1 Tn of compost going out.

The impacts categories selected should be related to the set of environmental concerns that are relevant to the system studied considering the goal and scope of the LCA. One relevant aspect is to decide whether midpoint or endpoint categories are chosen, midpoint categories represent intermediate points in the cause-effect chain, while endpoint categories represent final environmental impacts.

There are multiple default impact categories lists such as ReCiPe (Huijbregts et al., 2017) or CML 2016 that usually include default classification lists that connect each emission to the corresponding impact categories (Guinée, 2015).

The system boundaries define what will be included in the studied and what will not, usually the boundaries that should be defined refer to the natural systems, geographical boundaries, time boundaries and boundaries within the technical systems.

In relation to the boundaries within the technical systems it is also important to decide how the possible overlapping with other systems will be handled. If it is not possible to further detail the process, then allocation through partition or system expansion needs to be done (Baumann & Tillman, 2004). Allocation via partitioning involves dividing inputs and outputs based on physical or economic relationships, distributing environmental burdens while system expansion broadens system boundaries, considering additional environmental impacts from production changes, providing a comprehensive view of overall consequences.

The data quality requirements reference the type of data that will be used during the LCA analysis. The type of data used will affect the results of the LCA (Bicalho et al., 2017), the characteristics of data quality established by the ISO 14040 are: time-related coverage, geographical coverage, technological coverage, precision, completeness, representativeness, consistency, reproducibility, sources of the data, and uncertainty of the information (International Organization for Standardization, 2006). The best data for LCA is sourced from the specific system under study, preferably through direct measurements. But if measurements are impractical, other data sources such as other LCA studies, papers or databases can become viable options. However, either during the measurements or the selection of the sources of information it is important to follow the data quality requirements criteria, so the LCA results are relevant and accurate.

Finally, according to the ISO standard, assumptions and limitations should also be described in the goal and scope definition (Baumann & Tillman, 2004), these should include all major assumptions regarding the system, the data or the background and the limitations of the study results, which might be only suitable for a certain time period or geographical area.

### 2.4.3. Inventory analysis

The inventory analysis encompasses the examination and registration of the resource utilization, energy consumption and emissions to the environment that occur during all the phases of the system studied (Chen & Wang, 2017).

This mandatory step of any LCA can be divided in three different phases, construction of the flowchart, collection of all the data regarding all activities in the system and calculation of all the flows according to the functional unit.

The flowchart should be constructed according to the system boundaries established in the goal and scope, the process of the creation of the definitive flowchart starts in the goal and scope definition but is an iterative process and during the data collection it is possible that new information of the process is gathered resulting in changes in the initial flowchart.

The data collection is shaped by the data quality requirements, is usually the most consuming activity in the LCA (Baumann & Tillman, 2004), not only quantitative data is needed, also qualitative data such as descriptions of the processes, how the data is collected, origin and termination points of the flows are important for a comprehensive understanding and assessment of data quality. (Leroy & Froelich, 2010).

The calculation of the flows according to the functional unit includes the necessary allocation processes following the guidelines defined in the goal and scope so only the burdens that can be referred to the studied system are included in the results.

#### 2.4.4. Impact assessment

In this phase of the LCA the inventory results are translated into the impact categories selected in the goal and scope. According to the ISO standard there are three mandatory steps, impact category definition, classification, and characterization and four optional, normalization, grouping, weighting and data quality analysis (International Organization for Standardization, 2006).

Impact category definition in this phase consists in a specification of the impacts already identified in the goal and scope. During the classification phase, the results of the inventory analysis are linked to their respective impact categories and during the characterization the magnitude of each flow's contribution to the impact categories is calculated providing a quantitative measure of their environmental significance (Baumann & Tillman, 2004).

Normalization, grouping and weighting, can refine and enhance the interpretability of LCA results, providing a more understanding of the environmental implications associated with the studied system.

Data quality analysis studies the results to try to identify certain aspects of the system environmental loads, it helps to identify the most polluting activities, the most important data or methodological choices that will affect the results if modified or de uncertainty of the results due to estimations.

#### 2.4.5. Interpretation

This phase of the life cycle assessment involves combining the results of the impact assessment and sometimes the inventory analysis, with the established goal and scope to formulate conclusive insights and recommendations (International Organization for Standardization, 2006).

The presentation of the results varies according to the goal and scope, the audience, and the results themselves, but there are three main levels where the results can be presented. First at inventory analysis level, where all the flows entering or leaving the systems are presented but without relation to the associated environmental burdens.

The results can also be presented at characterization level, where the load in each impact category is presented, while it produces a more aggregated result than the inventory results, it might hide some information related to specific pollutants (Baumann & Tillman, 2004).

Finally results can be weighted, and each impact category is given a specific value to reflect the decided importance.

There are also further analyses that can be conducted to the results themselves, to identify which parts of the life cycle have more impact to the environment, or which environmental loads have more impact among the lifecycles. It's also possible to test the robustness of the results using uncertainty or sensitivity analysis.

## 3. APPLIED METHOD AND RESULTS

In this chapter, the processes and actions taken at every stage of the life cycle assessment for this thesis will be outlined and examined.

### 3.1. Goal definition and scope definition

The goal of this study is to compare the environmental impacts related to the treatment of a portion of the OFMSW generated in the city of Cuenca – Ecuador, of two different treatment options:

- Composting of the organic fraction of municipal solid waste.
- Anaerobic digestion of the organic fraction of municipal solid waste.

The specific question that is expected to be answered by this LCA is, how does the environmental performance of the current composting system compare to a potential implementation of AD to absorb the projected increase in organic waste diverted from landfilling, considering the generation of biogas and its use for energy production?

The aim of this LCA is to give insights into the current system and the possibility of anaerobic digestion to the two major stakeholders, which are Universidad de Cuenca and EMAC EP. The results of this LCA will be used for informational purposes by EMAC EP, to evaluate the implementation of this new technology and by a doctoral program on the categorization of the organic fraction of municipal solid waste with the main purpose of implementing anaerobic digestion, so the main audience of this LCA will be both, the workers of EMAC EP and the researchers at Universidad de Cuenca.

Functional Unit:

The purpose for both treatment options is to treat the organic fraction of municipal solid waste. For the composting treatment the main output is the production of fertilizer, while for the anaerobic digestion treatment, is energy production; therefore, the functional unit chosen is 1 Tn of organic waste from the households therefore the reference flow is 1 Tn of this OW entering the organic waste treatment facility.

#### *Environmental Impact categories:*

The most relevant impact categories that have been identified by the authors, after meetings with the main stakeholders are presented in the following paragraphs:

*Climate change*

This impact category measures the emission of GHGs like carbon dioxide, methane, and nitrous oxide which contribute to climate change. Climate change is a critical environmental issue with far-reaching consequences for ecosystems, human health, and socio-economic systems.

#### *Acidification*

Acidification measures the process by which pollutants such as sulfur dioxide and nitrogen oxides that are released into the atmosphere and deposited on land or water bodies leading to a decrease in pH levels therefore causing ecological damage. Acidification can damage ecosystems, degrade soil quality, and affect biodiversity.

#### *Eutrophication*

Eutrophication happens when an excess of nutrients is released into water bodies leading to algae blooms, oxygen depletion and disruption of aquatic ecosystems, some of the most important elements responsible for eutrophication are nitrogen and phosphorus. It poses a significant threat to freshwater ecosystems impacting water quality, biodiversity, and recreational activities.

#### *Photochemical oxidant formation*

Oxidant formation measures the formation of ground-level oxidants as a result of the reaction between precursor pollutants such as volatile organic compounds and nitrogen oxides in the presence of sunlight. The formation of these oxidants can cause respiratory problems, damage vegetation and contribute to smog formation.

#### *Ecotoxicity freshwater and terrestrial*

This impact category evaluates the potential toxicity of waste and its constituents to aquatic and terrestrial organisms, including fish, plants, and soil microorganisms.

#### *Water consumption*

Water consumption measures the amount of freshwater used including collection, treatment and disposal. Freshwater is a finite resource essential for human survival, agriculture, ecosystem functioning and in Ecuador also for energy generation

#### *Energy resources non-renewable*

This impact category assesses the use of energy resources including fossil fuels and electricity, the use of energy from the national grid causes emissions due to its production, and while anaerobic digestion is expected to be more energy demanding the production of biogas and its use to generate energy might balance the energy needs.

#### *Human toxicity*

Human Toxicity measures the potential health impacts of chemicals released into the environment. This category evaluates the toxicity of substances and their effects on human health, including respiratory issues, cancer, and other health problems. It helps in understanding and comparing the human health risks associated with different products and processes.

#### *Material Resources: Metals/Minerals*

This impact category evaluates the depletion of non-renewable metal, and mineral resources used in the production and consumption of goods and services. It considers the extraction rates and the remaining reserves of these materials, aiming to measure the sustainability of resource use. Depletion of metals and minerals can lead to increased extraction costs, environmental degradation, and supply risks, impacting industries and economies dependent on these resources.

#### *Type of LCA*

This study consists of an attributional comparative LCA of the two studied systems.

#### *System boundaries*

This study will be cradle-to-gate, considering the input of organic fraction of municipal solid waste from households into the systems and finalizing the study with the result output of each treatment. The reason to exclude any processes prior to entering the waste management facility is that are presumed to be the same, in both scenarios, and the reason to exclude the use of the compost, digestate and residues is due to the goal of the LCA is to compare the technologies themselves, so the use of the products result of the processes is deemed not relevant.

Inside the operating plants, the sorting and weighting of the waste are also excluded from the system boundaries outside since it's the same and the same for all upstream processes after arriving to the facility.

The impacts related to the infrastructure construction and dismantling stages are outside the system boundaries since are found to be insignificant compared to the operation (Liamsanguan & Gheewala, 2008; Oviedo-Ocaña et al., 2023)

In the geographical boundary, this study will take place in the city of Cuenca, specifically in the parish of Santa Ana, where the landfill, new composting plant and possible anaerobic digestion will take place, making it a site-specific study.

The time horizon of this study is 25 years since that will be the lifespan of each plant. More elaborate information about assumptions and limitations is detailed in the section Assumptions and Limitations.

#### *Data Quality Requirements*

The data used for the composting process will primarily come from experts who work directly in the process, non-available data of the process will come from literature, and the Ecoinvent database version 3.10 cutoff and expert estimations. The data used for the anaerobic digestion system will come primarily from papers and similar studies in the region, the Ecoinvent database and expert estimations from interviews.

#### *Assumptions and Limitations*

The main limitations of this project are related to data availability. There is little data available on the collection and treatment processes that EMAC currently implements; moreover, there are no direct measurements on the composting area to identify possible emissions, and with the current equipment and timeframe available, it has not been possible to conduct measurements in the composting plant for the emissions so data from academic papers and databases have been used to fill the information gaps encountered.

Another important limitation is that the technology for the AD treatment hasn't been established by EMAC yet, so the decision on the AD methodology is based on interviews with the EMAC workers, University of Cuenca and current literature.

Also, the study will be limited to the composting and AD operations, including the use of the produced biogas to generate energy since it will also be conducted in the same facilities and would replace electricity produced using the national mix, and the composting of the digestate out of the AD process, but the use phase of the compost, will be excluded for the lack of data and difficulty to predict what will be its destination.

Assumptions on the future scenario of the organic waste that is expected to be redirected to the new waste management system using the new system of green bags for household organic waste is based on the predictions of the EMAC workers but its implementation, and results may vary once implemented.

The environmental impacts such as emissions and resource consumption may vary according to the geographical location. Cuenca - Ecuador, has special conditions since it is located at 2538 m. above sea level (Alcaldía de Cuenca, s. f.), having a significant temperature fluctuation during the day.

There is no consensus in the literature on how to handle CO<sub>2</sub> and CH<sub>4</sub> emissions from composting and Anaerobic digestion.

Regarding composting most authors in the field (Amlinger et al., 2008; Bjarnadóttir et al., 2002; California Environmental Protection Agency, 2017; IPCC, 2007; Nordahl et al., 2023) don't include CO<sub>2</sub> emissions in the climate change category while CH<sub>4</sub> emissions are included, on the other hand there is literature (Bastian et al., 2013) that consider all the emissions of CO<sub>2</sub> and CH<sub>4</sub> climate neutral.

While looking into the Anaerobic digestion literature some authors (IPCC, 2007; Timonen et al., 2019) consider all CO<sub>2</sub> and CH<sub>4</sub> emissions from Anaerobic Digestion to contribute to climate change. However there are authors that consider CO<sub>2</sub> from AD also climate change neutral (Malet et al., 2022; Miranda et al., 2015; Moraes et al., 2017) and finally (Bastian et al., 2013) considers CO<sub>2</sub> and CH<sub>4</sub> emissions from AD process as not contributors to climate change.

Moreover, regarding CH<sub>4</sub> non-fossil emissions, in OpenLCA are treated with similar characterization factors than CH<sub>4</sub> fossil emissions, for instance CML 2016 or TRACI v2.1, treats both emissions with the same impact on climate change following most of the literature, other frameworks like Recipe, the difference is very low, 84 kg CO<sub>2</sub> equivalent for CH<sub>4</sub> non fossil in front of 85 kg CO<sub>2</sub> equivalent for fossil emissions.

After the literature research, in this LCA only CO<sub>2</sub> emissions from composting were considered non fossil so excluded from the calculations regarding climate change following the majority of the literature. Regarding AD, the literature consensus is lower, so in this LCA the AD scenarios consider CO<sub>2</sub> and CH<sub>4</sub> emissions as climate change relevant but in the climate change impact category a sensitivity analysis regarding the impact of considering CO<sub>2</sub> non fossil has been conducted to see how the results are altered.

## 3.2. Inventory analysis

### 3.2.1. Identifying processes for the LCI model

#### *Composting*

The expected process for the new stream of organic waste arriving from the households is similar to the actual process described in 2.3 *Organic waste management in Cuenca*, but this waste will arrive in green plastic bags that will need to be opened, and the content sorted to extract any non-compostable waste that can compromise the process and quality of the final product.

Also, the organic waste expected from the households is mainly food waste that can go straight to the composting area, so no need for extra space for the stocking area or use of the excavator is expected.

With the boundaries and limitations stated in the goal and scope the studied process, represented in Figure 7 as a flowchart, is the following.

Waste already sorted and weighed enters the composting area where it sits for 3 weeks, during this time the biological activator to control odors is nebulized, and the organic waste is moved and turned 2–3 times a week using a compact wheel loader model *BOBCAT S750* with 85 hp of power.

Then it's moved to the maturation area where it stays for 2 months, and every two weeks is turned using the same compact wheel loader.

Finally, the compost is sieved using the automatic sieve and ready to be picked up by the final users.

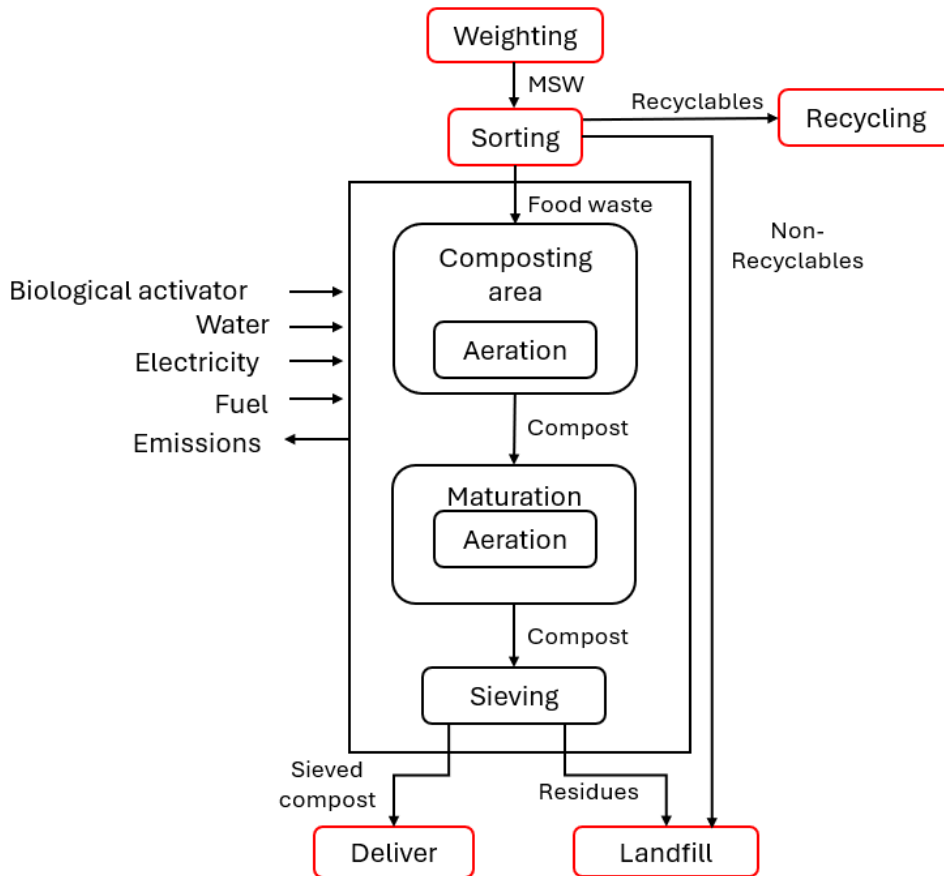


Figure 7 Composting process flowchart, red boxes depict processes outside the system boundaries of the LCA.

### Anaerobic digestion

As described in the composting process, the green plastic bags containing the household organic waste will be weighed and opened and the waste not suitable for anaerobic digestion will be further divided into waste suitable for composting, recyclable or non-recoverable waste that will go to the landfill.

Since there are no specific plans, the process analyzed follows the Ecoinvent Anaerobic digestion process were once weighed and depicted in Figure 8, the waste suitable for anaerobic digestion will be shredded and sent to the reactors. Digestate will be dewatered and sent to the composting plant.

The biogas produced is used to generate electricity in the same location.

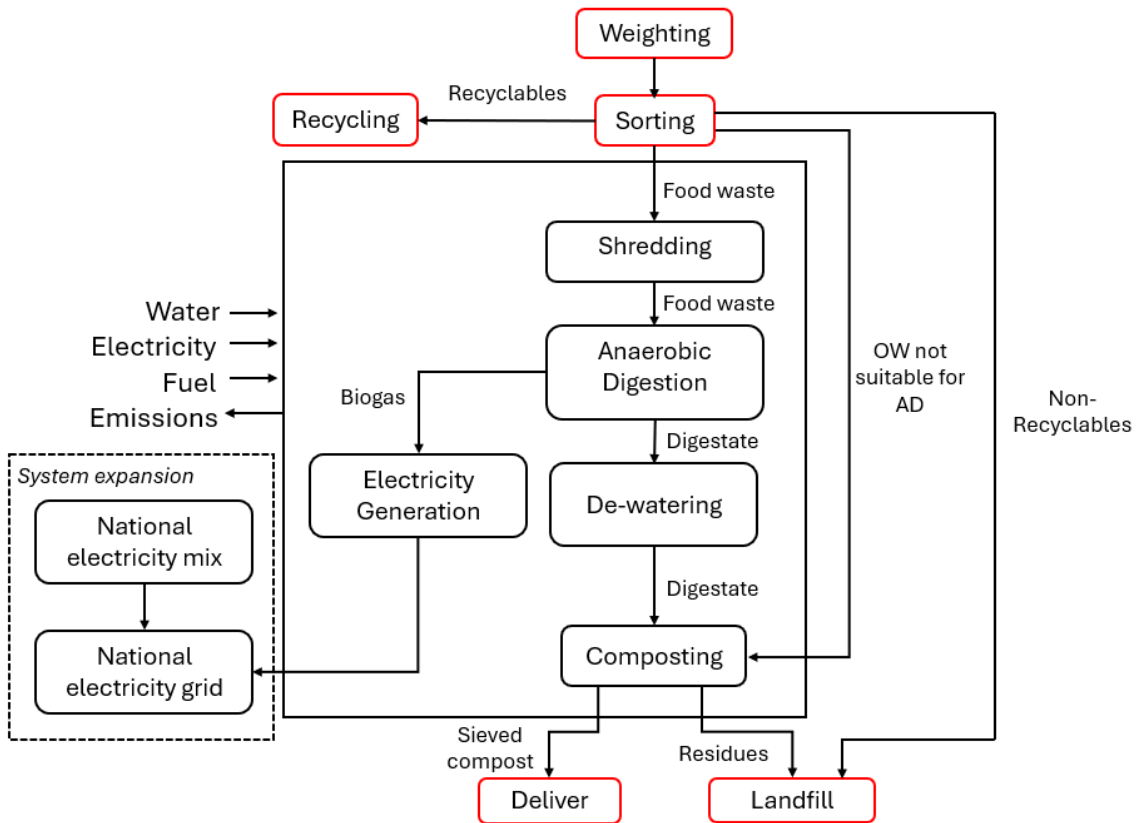


Figure 8 AD diagram flow, red boxes depict processes outside the system boundaries of the LCA.

### 3.2.2. Data Collection

In this project, data from the actual composting plant in operation is used and complemented, when necessary, with information from scientific literature and the database Ecoinvent version “ecoinvent\_v3\_10\_Cutoff\_Unit\_Processes\_2024\_01\_22”.

#### Composting

The main inputs in the composting plant are, apart from the biowaste, electricity, water, the diesel needed to operate the different machinery present and the biological activator to control odors.

The electricity consumption of the year 2023 was found using the actual invoices for the period, all energy consumption for the year is sum and divided by the number of tons of biowaste treated in the plant in 2023. The electricity consumption annually is 571.2 kWh according to the invoices issued this period, divided by the 7457 Tn of biowaste entering the composting plan the result is 0.0766 kWh/Tn.

Regarding water the same procedure is done, the consumption of water in the plant, according to the invoices lays between 31 and 52 m<sup>3</sup> per month, but two months have very high consumptions, April and October with 123 and 80 m<sup>3</sup> per month respectively, according to the financial responsible of EMAC, these two months abnormal water consumption were due to water leakage that were later fixed so not part of the normal operation of the plant, regarding this these two months were excluded of the calculus and an average of 40.8 m<sup>3</sup> per month of water is calculated to be consumed by the standard operation. When dividing this number for the 621 Tn of biowaste treated monthly in the composting plant the result is 65.7 l/Tn.

Only the *BOBCAT S750* is considered for fuel consumption since in the modelled process is the only machinery consuming diesel, the *BOBCAT S750*, rented with the fuel and driver and billed monthly, according to the invoices from the provider the average fuel consumption per month is 174 gallons, transformed to liters and divided by the number of tons of organic waste treated in the composting plant, the result is 1.06 l/Tn.

Regarding the emissions of the compost, different literature sources have been studied (Amlinger et al., 2008; Komilis & Ham, 2004; Nordahl et al., 2023; Saer et al., 2013), and finally the emissions from (Amlinger et al., 2008) have been used due to it being an experimental study and with the most similar procedures than the ones used in EMAC, according to this study the emissions per Tn of organic waste are the following 115 kg of CO<sub>2</sub> (non-fossil), 0.12 kg of N<sub>2</sub>O, 0.53 kg of H<sub>2</sub>S, 0.24 kg of CH<sub>4</sub>, and 0.58 kg of NH<sub>3</sub>.

Since there is no collection or control over the leaching from the organic waste piles, is assumed that the emissions will run away and end up in the ground waters, for these emissions the study conducted by Weligama Thuppahige & Babel, 2022 was used, and their findings are that per kg of organic waste the following emissions can be expected: 0.0616 g of PO<sub>4</sub><sup>3-</sup>, 0.0938 g of NH<sub>4</sub><sup>+</sup>, 1.42 g of NO<sub>3</sub><sup>-</sup> and also 0.239 l of leachate.

A response from the biological activator manufacturer has not been obtained, nor has any EPD or information regarding the emissions of the manufacture of the complex been found. While the quantity is small (2.38 l per Tn of organic waste), emissions from this transport have been accounted for due to the long distance between Ecuador and the production site in Italy. Airfreight from Rome to Guayaquil and road transport using a Lorry EURO3 have been considered.

#### *Anaerobic digestion*

Since there are no specific plans for which type of anaerobic digestion plant will be built, the anaerobic digestion process from Ecoinvent has been used and adjusted according to the data found in the literature and presented below to include the electricity production in the Ecuadorian electricity mix.

According to Bong et al., 2018, the volatile solid fraction in segregated organic waste from households is 24.4 % and the CH<sub>4</sub> yield is 0.642 m<sup>3</sup>/kg VS, for 1 kg of organic waste then 0.1567 m<sup>3</sup> of CH<sub>4</sub>, and with an electrical conversion efficiency of 35% (Suhartini et al., 2019), 1m<sup>3</sup> of methane will yield 10 kWh. Therefore, the electricity expected from 1kg of organic waste is 1.567 kWh.

Other sources like Xin et al., 2018, depicts a scenario where from 1kg of food waste about 54.4 L of methane could be obtained which is the equivalent to about 0.213 kWh electricity, this result is similar to the one found by Davis et al. in 2016 which is 0.225 kWh being conservative per kg of organic waste from households.

There are also experimental studies that give an intermediate electricity production (Mydin et al., 2014) with about 0.647 kWh per Kg of food waste entering the plant.

Due to the discrepancies on the quantity of energy that can be generated three scenarios will be compared with the composting scenario, the anaerobic digestion scenarios are named AD Low, AD Md and AD Hg representing AD Low a production of 0.213 kWh, AD Md 0.647 kWh, and AD Hg 1.567 kWh per kg of organic waste entering the plant.

### 3.3. Impact assessment and interpretation

The results are weighted and presented at the midpoint level, based on the categories from CMLv4.8 (2016) while excluding Ecotoxicity Marine and Ozone Depletion. Additionally, water use data from EF v3.0 is included.

#### Climate change

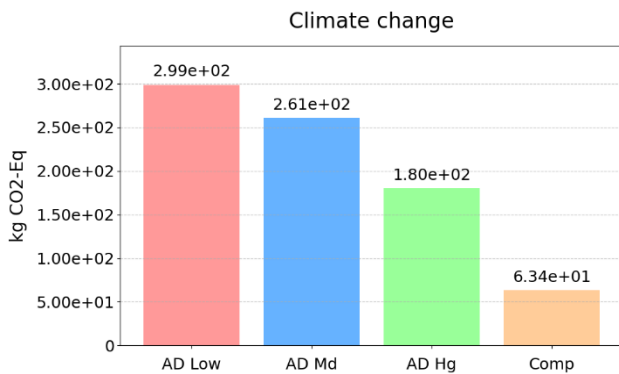


Figure 9 Impacts on Climate Change for each waste management scenario

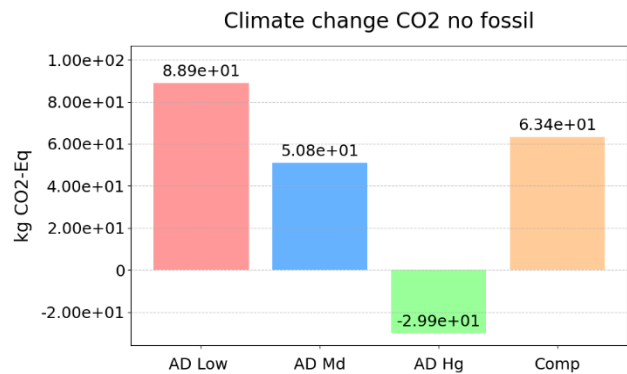


Figure 10 Impacts on Climate Change for each waste management scenario if CO<sub>2</sub> is considered not climate relevant in AD

Climate change category is, as expected, heavily dependent on the methodological choices regarding the consideration of CO<sub>2</sub> emissions climate neutral or not, and regarding the quantity of electricity produced in each AD scenario.

In Figure 9, where CO<sub>2</sub> emissions from AD digestion are considered climate relevant, composting is the best alternative, outperforming all AD scenarios, and cutting in half the emissions from even the best-case scenario with high electricity production. In this case, the impact on climate change is 60.34 kg CO<sub>2</sub>-Eq per tonne of waste for composting, and the AD scenarios have 180 kg CO<sub>2</sub>-Eq, 261 kg CO<sub>2</sub>-Eq and 299 kg CO<sub>2</sub>-Eq respectively.

When CO<sub>2</sub> is considered climate neutral for the AD scenarios as it is for composting the results are severely impacted as it can be seen in Figure 10, now, composting only outperforms the worst case AD scenario with the lowest energy production that sees its impact reduced to less than a third ( 88.9 kg CO<sub>2</sub>-Eq), the AD scenario with the highest energy production modelled now it has a positive impact, saving 29.9 kg CO<sub>2</sub>-Eq, while the medium production scenario lays between with and impact of 50.8 kg CO<sub>2</sub>-Eq.

In the AD scenarios CO<sub>2</sub> emissions are the main contributor to climate change if considered relevant, followed by CH<sub>4</sub> and N<sub>2</sub>O emissions. In the composting scenario N<sub>2</sub>O emissions are the main contributor followed by the CO<sub>2</sub> emissions linked to the transportation of the bioactivator.

Regarding the sensitivity of the results to electricity production, there is a significant difference of approximately 120 kg CO<sub>2</sub>-eq between the scenario with the lowest and highest predicted electricity production. This difference represents a 40% reduction in emissions if CO<sub>2</sub> is considered climate relevant. However, if CO<sub>2</sub> is not considered relevant to climate change, the reduction becomes even more substantial, leading to a nearly 135% decrease, which results in a net positive impact by saving environmental burdens.

If compared with the rest of impact categories the reduction of 40% is the lowest reduction in percentage while a 135% would be 3rd lowest, meaning that Climate Change is not among the most sensitive categories regarding the quantity of electricity produced.

### Acidification

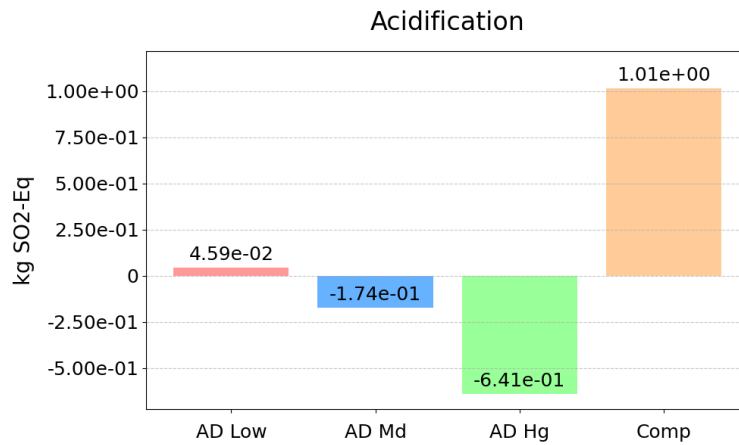


Figure 11 Impacts on Acidification for each waste management scenario

Regarding acidification, anaerobic digestion outperforms composting, even in the worst-case scenario compared. The impact of composting in acidification is 1.01 kg SO<sub>2</sub>-Eq, while anaerobic digestion even in its least favorable outcome, results in a significantly lower impact of 4.59 e-2 kg SO<sub>2</sub>-Eq. The scenarios AD Md and AD Hg have a positive impact due to the substitution of the electricity produced avoiding 1.74 e-1 kg SO<sub>2</sub>-Eq and 6.41 e-1 kg SO<sub>2</sub>-Eq respectively.

In the acidification category, the difference between the AD Hg and AD Low scenarios is minimal in absolute terms, as the overall impact is already quite low. The 1.354 kWh difference in electricity production between AD Hg and AD Low results in a reduction of only 0.69 kg SO<sub>2</sub>-eq. However, this reduction represents a nearly 15-fold decrease in the impact, leading to a net environmental benefit by reducing burdens.

The main contributor to Acidification in the composting alternative is the ammonia emissions, which are directly linked to the composting process of the organic waste.

### Human toxicity

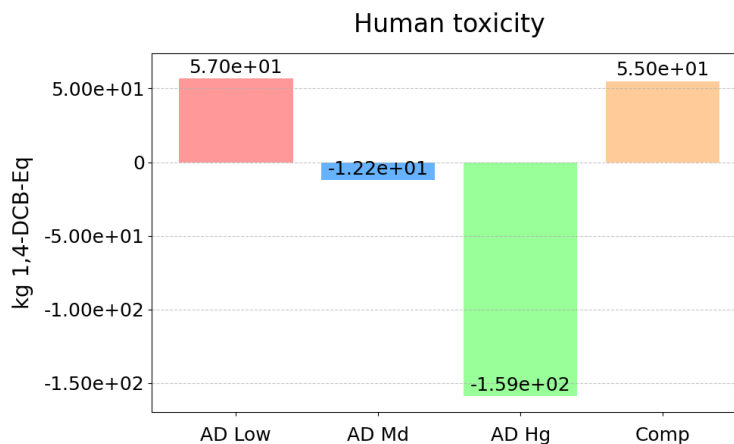


Figure 12 Impacts on Human Toxicity for each waste management scenario

For human toxicity, Composting only outperforms AD in the lowest electricity production scenario and with a very similar impact, 55.04 kg 1,4-DCB-Eq for composting and 56.96 kg 1,4-DCB-Eq for AD Low. AD Md and AD Hg scenarios are options beneficial for the environment saving 12.24 kg and 158.94 e-1 kg 1,4-DCB-Eq. respectively due to the electricity generated.

The amount of electricity produced also plays a significant role in the environmental impact regarding Human Toxicity. The reduction in impact due to differences in electricity production is one of the highest in absolute terms, with a decrease of nearly 216 kg 1,4-DCB-eq, representing a fourfold reduction. This results in net environmental benefits by reducing overall burdens in the AD Hg scenario.

### Eutrophication

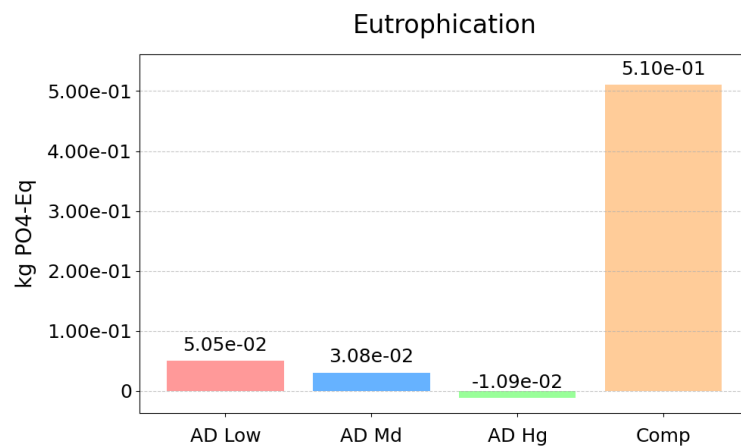


Figure 13 Impacts on Eutrophication for each waste management scenario

Composting has the highest impact on Eutrophication with 5.10 e-1 kg PO<sub>4</sub>-Eq, the three AD scenarios have lower impacts with AD Low and Md impacting the equivalent of 5.05 e-2 and 3.08 e-5 kg of PO<sub>4</sub>, while AD Hg would have a small positive impact saving -1.09 e-2 kg PO<sub>4</sub>-Eq.

The main contributor to Eutrophication can be identified as the emissions of Ammonia from the composting process.

The impact of the quantity of electricity produced is low in absolute and relative terms when comparing the AD Low scenario and the AD Hg scenario. Only 0.061 kg PO<sub>4</sub>-Eq. are saved, however the result is the small positive impact in the environment of AD Hg.

## Photochemical oxidant formation

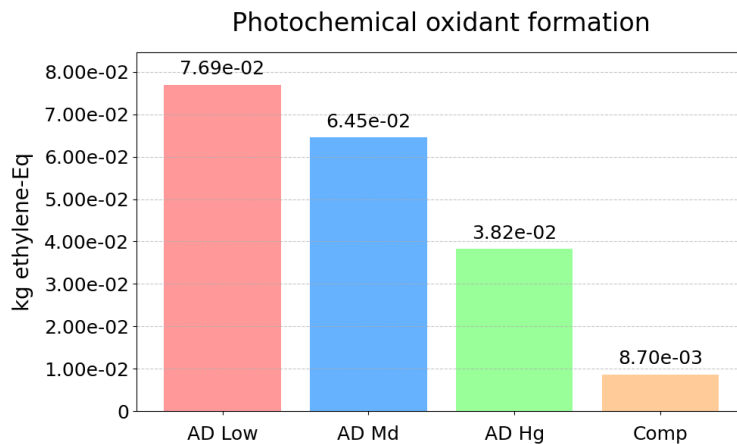


Figure 14 Impacts on Photochemical Oxidant Formation for each waste management scenario

Regarding Photochemical oxidant formation, is the only impact category where composting is the best alternative with an impact of 8.70 e-3 kg ethylene-Eq and outperforms Anaerobic Digestion in all scenarios. The impacts for AD are 7.69 e-2, 6.45 e-2 and 3.82 e-2 kg ethylene-Eq for the AD Low, AD Md and AD Hg respectively. It's important to note that the impacts per ton of organic waste treated are low, between 0.07 and 0.009 kg ethylene-Eq.

In anaerobic digestion scenarios, the primary contributor to photochemical oxidant formation are the emissions from heat production during the process, especially CO emissions. Composting in contrast benefits from not requiring heat and it's the only impact category that outperforms the AD Md and AD Hg scenarios. However, this impact is highly dependent on the source of the heat used in AD, meaning that switching to greener heat sources could potentially reduce the environmental burden in this category.

Notably, although the impact is low, this is the only category where the AD Hg scenario has a negative impact on the environment and the electricity produced is not enough to compensate the impacts from the heat used.

When looking at the sensitivity of the results on the electricity produced, it's possible to note that the impact is low, in both absolute and relative terms, only 0.039 kg ethylene-Eq are saved between the AD Low and AD Hg scenarios, and it represents only half of the impacts of the AD Low scenario. It's the second least impacted category surpassed only by climate change—assuming CO<sub>2</sub> is considered climate-relevant in that context.

## Ecotoxicity (Freshwater, Terrestrial)

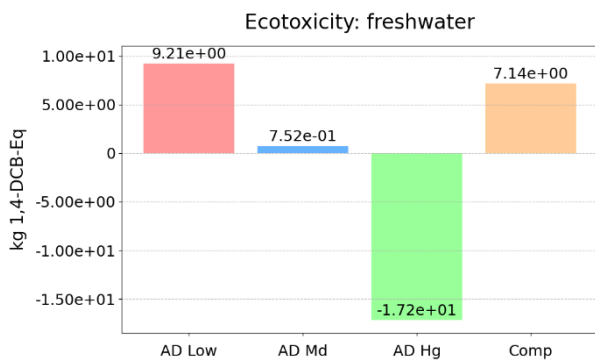


Figure 15 Impacts on Ecotoxicity: Freshwater for each waste management scenario

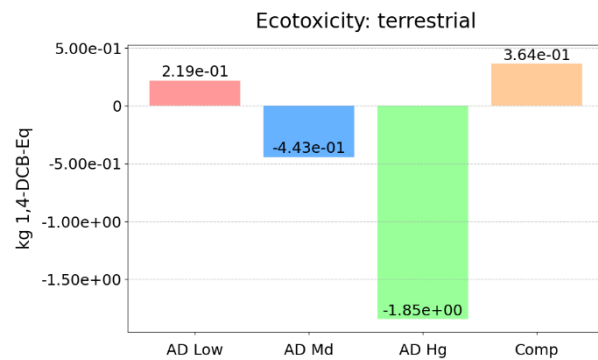


Figure 16 Impacts on Ecotoxicity: Terrestrial for each waste management scenario

Freshwater ecotoxicity is one of the categories where Composting outperforms AD Low. It has an impact of 7.14 kg 1,4-DCB-Eq. AD Low performs slightly worse with an impact of 9.21 kg 1,4-DCB-Eq, followed by AD Md with 7.52 e-1 kg 1,4-DCB-Eq. and AD Hg has a positive impact saving 17.19 kg 1,4-DCB-Eq.

The impact on Freshwater ecotoxicity is reduced by 26.39 kg 1,4-DCB-Eq. between the scenarios AD Low and AD Hg, it supposes a 287% reduction therefore it means that the AD Hg scenario would have a positive impact reducing the environmental load in this category.

On the other hand, for terrestrial ecotoxicity Composting is the worst alternative with an impact of 3.64 e-1 kg 1,4-DCB-Eq. followed by AD Low with an impact of 2.19 e-1 kg 1,4-DCB-Eq. AD Md and AD Hg, both have a positive impact and save 4.43 e-1 and 1.85 kg 1,4-DCB-Eq. respectively.

In this category, the impacts are low, therefore the absolute reduction between AD Low and AD Hg is also low, 2.06 kg 1,4-DCB-Eq. On the other hand, this represents reducing more than 9 times the total impact of the scenario AD Low, so the relative reduction is relevant, among the highest, meaning that the results are sensitive to the amount of energy expected to be generated.

## Water use

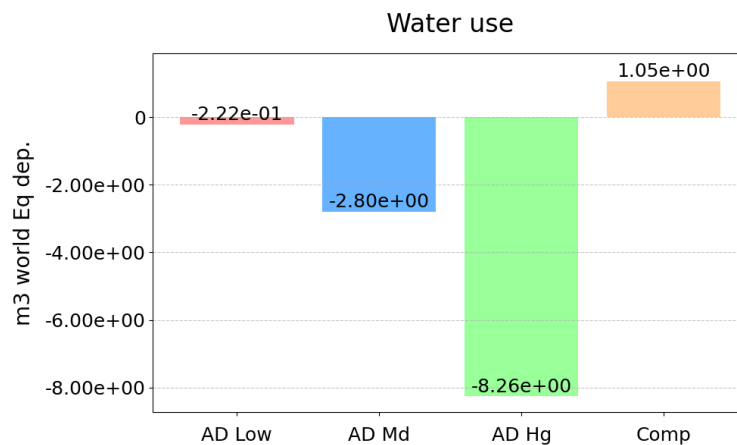


Figure 17 Impacts on Water Use for each waste management scenario

Composting is the alternative that has higher impact on water use with 1.05 m<sup>3</sup> world-equivalent depletion. In contrast, the three Anaerobic Digestion scenarios have a positive impact on water use and save 0.22, 2.80 and 8.26 m<sup>3</sup> world-eq. depletion, respectively.

This is the only category where the three AD scenarios contribute to relieve the environmental burden, at the same time it's possible to see that the reduction of the impact, or in this case the increment of the relieve is relatively high when the electricity predicted to be produced during the AD process increments, while AD Low have a positive impact of only 0.22 m<sup>3</sup> world-eq. depletion, AD Hg performs more than 36 times better saving up to 8.26 m<sup>3</sup> world-eq. depletion per tonne of organic waste.

#### Energy resources non-renewable

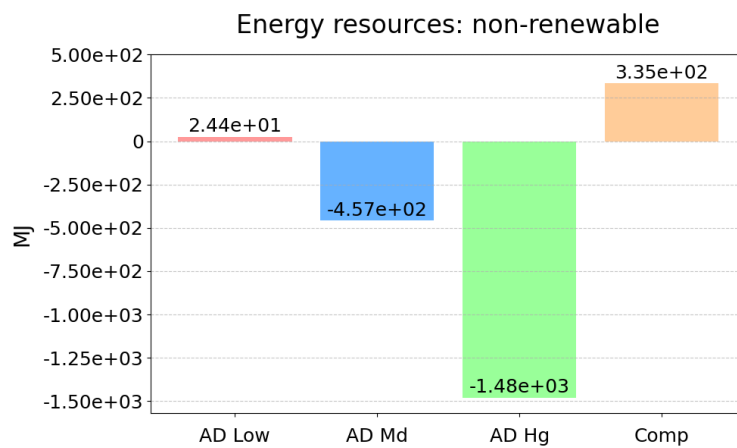


Figure 18 Impacts on Energy Resources: non-renewable for each waste management scenario

The impact on energy resources non-renewable of composting is 334.89 MJ being the highest of the four studied scenarios, AD Low follows it with 24.43 MJ and on the other hand, AD Md and AD Hg would save 457.41 and 1478.85 MJ each.

This category has the highest sensitivity to the electricity predicted to be produced during the AD process, in absolute numbers, with a total improvement of over 1500 MJ from the worst-case scenario to the scenario with the highest electricity production. In relative terms is the second highest with a reduction equivalent to 61 times the impact of AD Low.

#### Material resources, metals/minerals

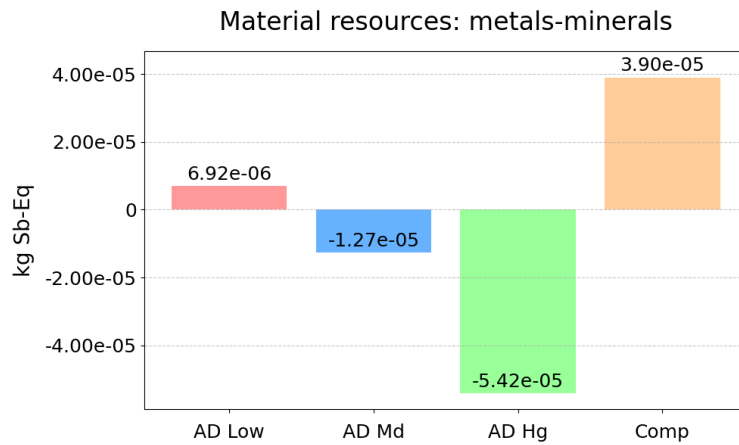


Figure 19 Impacts on Material resources: Metals-Minerals for each waste management scenario

The impact on material resources: metals-minerals impact category is extremely low for all the four compared scenarios. Composting and AD Low scenario present a consumption of material resources: metals-minerals, Composting with an impact of  $4.03 \times 10^{-5}$  kg sb-Eq. and AD Low  $6.92 \times 10^{-6}$  kg sb-Eq. On the other hand, AD Md and AD Hg show net saving of these resources with negative impacts of AD Md will save  $-1.27 \times 10^{-5}$  kg sb-Eq. and AD Hg  $-5.42 \times 10^{-5}$  kg sb-Eq.

## 4. DISCUSSION

As expected, the quantity of electricity produced in each AD scenario is one of the most impactful methodological choices of this study, these choices are based in the current literature regarding biogas yields and the predicted electricity production from this biogas. For some of the categories the impact is especially high such as Acidification or Energy resources non renewables.

It's also important to note regarding this choice that the system was modeled with the assumption that the energy produced by the AD plant would replace the current electricity mix in Ecuador. This means that, if Ecuador's energy mix becomes greener in the future, the environmental benefits of the AD scenarios may be reduced. On the other hand, if the generated energy displaces fossil fuels, the performance of the AD scenarios is expected to improve significantly.

When looking at the results globally we can see that the three AD scenarios results are consistent and the lower the production of energy the higher the burden on the environment and that a difference of 1.3 kWh per Kg of organic waste treated, which is the difference between the lowest and the highest production scenarios, will severely alter the effects on the environment, going from having a negative impact to a positive one in all categories but three, Photochemical Oxidant Formation, Water use, and Climate change if CO<sub>2</sub> is considered not climate neutral in AD.

In Photochemical Oxidant formation the three AD scenarios have negative effects on the environment, but the impact is especially low. Similarly in Climate change, if CO<sub>2</sub> is considered not climate neutral all three AD scenarios contribute to climate change, but in this case the impact can't be considered low with up to 299 kg CO<sub>2</sub>-Eq in the AD Low scenario. On the other hand, for Water Use even if its results are heavily impacted by the quantity of electricity produced, even the worst-case scenario for AD saves water.

Another important aspect of any LCA study is the choice of the protection areas that will be covered, as these determine the impact categories to be analyzed. The selection of impact categories should be guided by the environmental relevance of the processes involved in the study but also the needs of the stakeholders.

For the main stakeholders which are EMAC EP and Universidad de Cuenca, categories related to direct pollution such as acidification, human toxicity, eutrophication are considered hotspots, as well as categories related to consumption like water consumption and energy resources. For possible investors (such as the EU, South Korea, Japan, USA) there is an important interest in reducing GHG, therefore climate change will be a hotspot and focus of the results of this LCA.

In this study CMLv4.8 (2016) was used, but two of the categories were excluded Ecotoxicity Marine and Ozone Depletion, and water use was included from EF v3.0.

Ecotoxicity Marine was considered irrelevant due to the geographical situation of the city of Cuenca, it's situated around 100 kms away from the closest coast which is situated in the west, but the geographical characteristics of the area make that the rivers crossing the city travel to the opposite direction, they flow to the east ultimately discharging into the Amazon River, which in turn empties into the Atlantic Ocean thousands of kilometers away from the city.

Ozone Depletion was considered not relevant for this study, as none of the processes involved are expected to use ozone-depleting chemicals, such as CFCs.

Water use on the other hand has become increasingly important in Ecuador, particularly in recent years as prolonged dry seasons, driven by climate variability, have increased water scarcity. This issue not only affects agricultural and domestic water availability but also impacts energy production, given Ecuador's heavy reliance on hydropower. In fact, recent water shortages have already led to electricity cuts, highlighting the growing vulnerability of the country's energy supply.

The LCA results indicate that anaerobic digestion, especially the scenarios with medium and high electricity production exhibits a lower impact in most categories compared to composting, primarily due to the capture and utilization of biogas to produce electricity.

As stated in the results section, the climate change impact for AD is significantly affected by whether CO<sub>2</sub> is considered climate neutral, with the literature being divided on this issue; therefore, both perspectives are presented. Although some sources argue that CH<sub>4</sub> should also be considered climate neutral due to the biogenic origin of the carbon in both composting and AD, this scenario hasn't been contemplated due to the limited support from authors.

The results of this LCA are consistent with several studies comparing AD with electricity production and composting of OFMSW (ISWM-Tinos Life, 2011; Murphy & Power, 2006; Weligama Thuppahige & Babel, 2022), an study conducted in Ecuador in the city of Manta also states the expected benefits of the implementation of AD as the waste management alternative for the OFSMW (Belén et al., 2020) Ammonia is identified as a major contributor in impact categories such as Eutrophication and Acidification as in other studies like (Lin et al., 2018).

## 5. CONCLUSION

The purpose of this thesis was to compare these two alternatives in the context of organic waste management in Cuenca, Ecuador, and provide insights into which method could be more environmentally sustainable. This study has demonstrated that both anaerobic digestion and composting are effective waste management strategies with different maturity implementation in the region. Anaerobic digestion could be particularly advantageous to reduce the environmental load of the OFMSW management across all categories especially when biogas is efficiently captured and utilized for electricity generation.

In contrast, composting only outperforms AD in the photochemical oxidant formation impact category, and Climate change if CO<sub>2</sub> is considered fossil in the AD scenarios. However, composting is less expensive than AD, and it can contribute to soil health. The choice between these waste management options should be guided by specific local conditions, including environmental objectives, waste characteristics, and the existing infrastructure.

Several contextual factors must be considered when assessing the viability of these technologies in the Latin American and Caribbean (LAC) region. The findings indicate that while AD has strong potential for reducing the environmental burdens of waste management, the underdeveloped infrastructure and high costs present challenges, particularly in regions where more basic waste management solutions, such as proper landfills, are still being implemented. AD on a large scale is still underdeveloped in LAC (Silva-Martínez et al., 2020), and its application for OFMSW is even less common. Cultural and economic aspects play a significant role in this scenario. In many regions, there are more pressing waste management needs, such as the implementation of proper sanitary landfills, which are still a novelty in some countries and some regions in Ecuador (*Gestión de Residuos Sólidos*, s. f.). Given the high costs associated with AD and the possibility that energy generation from biogas may not fully cover its implementation costs, AD, and even composting, may not yet be viable or desirable options.

The main research line needed to further investigate the suitability of AD to treat OFMSW in Ecuador, and more broadly in Latin America, is related to the composition of this organic fraction. Understanding the expected composition, the quantity of impurities, and how these factors affect digester operations and biogas yield is crucial. Addressing these variables will help determine whether AD can be efficiently adapted to the region's specific waste characteristics. This focus on organic waste composition is essential, as it directly impacts the efficiency and feasibility of implementing AD systems (Torres, 2023). The research should combine experimental studies using small scale reactors with field studies of the current AD plants in operation even if there are a small number of them, but there is a data gap on the results of these operations that if filled, would be very beneficial to project, finance and operate new AD plants around the region.

Additionally, the study highlights the importance of thoroughly understanding the type of organic waste available for treatment. The potential to mix OFMSW with other types of organic waste could be explored, as combining different waste streams may yield a larger amount and higher quality of biogas (Arrieta et al., 2007). This could enhance the economic viability of AD systems.

Future research could also benefit from incorporating socio-economic aspects to provide a more comprehensive evaluation of the environmental, financial, and social implications of the scenarios analyzed. By including economic factors such as implementation costs, potential

savings from resource efficiency, and the economic benefits of energy generation, studies could offer a deeper understanding of the feasibility and attractiveness of AD. Additionally, this approach would enable an assessment of how these scenarios might impact local communities, job creation, and overall economic growth, ensuring that the proposed solutions are not only environmentally sustainable but also economically viable and socially beneficial. These socio-economic considerations highlight the broader implications of waste management technologies on communities and their economies, extending beyond environmental outcomes.

The research underscores the importance of methodological rigor in LCA studies, as the results are highly sensitive to the chosen system boundaries, functional units, and impact assessment methods. The uncertainties associated with data quality and emission factors highlight the need for more precise and context-specific assessments in future research. The LCA analysis in this study confirms that the choice of methodology and data can significantly influence the results (Baumann & Tillman, 2004), and thus it requires careful consideration in future work.

In summary, while both anaerobic digestion and composting play crucial roles in sustainable waste management, the selection of the most appropriate strategy should be based on a thorough consideration of the environmental, economic, and social contexts of the specific region in question. This tailored approach, which accounts for the current state of waste management infrastructure and the characteristics of the available organic waste, will be essential in minimizing environmental impacts and optimizing resource recovery. The findings suggest that the feasibility of implementing AD or composting should not be based solely on environmental performance but also on regional technological readiness, economic capacity, and socio-economic benefits, making these technologies sustainable in the long term.

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