Toward Sustainable Waste Solutions: Estimating GHG Emissions in Solid Waste Management

A Case Study of Pouso Alegre, Brazil, Proposing Scenarios Based on Lessons from Lahti, Finland

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Title

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Degree: Master in Urban Climate & Sustainability

Abstract

Managing the resulting household waste of cities becomes essential as urbanization keeps increasing, with UN-Habitat forecasting that the global urban population will increase by 2.2 billion, reaching 68% by 2050. Since the waste sector generates around 5% of all anthropogenic greenhouse gas emissions, efficient waste management is critical to minimizing climate change effects. It is a fact that waste management becomes a crucial component of climate policies as cities grow. Without significant action, the IPCC forecasts global temperatures to climb by 1.1°C to 6.4°C this century.

This study aims to evaluate and model the management of MSW in Pouso Alegre using advanced waste management strategies and technologies from Lahti, Finland, considering both countries' social, economic, and environmental differences. This study also brings light to the difference of waste management practices and challenges between North Hemisphere and South Hemisphere countries.

This thesis uses a GHG calculator based on the LCA aproach to examine the effects of different proposed scenario alternatives on MSW treatment on GHG emissions in Pouso Alegre, Brazil. The study investigates landfill, incineration, anaerobic digestion, composting, and material recovery to identify the most effective technical options for minimizing greenhouse gas emissions. The objective is to select the most viable and sustainable solid waste management alternatives for Pouso Alegre, considering local situations and resource availability. Four scenarios for Pouso Alegre's waste management are examined in the thesis; each includes a variation of anaerobic digestion, controlled landfills, material recovery, composting, and incineration. On this basis, the potential of each scenario to decrease GHG emissions is being assessed.

The present study stresses the importance of appropriate and effective treatment processes, prioritizing reducing or minimizing waste at source, and following the Waste Hierarchy. Maximizing recycling and composting activities becomes essential for lowering greenhouse gas emissions and preserving resources when waste output cannot be avoided. It connects waste management techniques to their effects on greenhouse gas emissions and the environment, offering suggestions for MSW management decision-makers. By using sustainable waste management techniques, cities like Pouso Alegre may dramatically lower their carbon footprint and promote a circular economy. The conclusions and suggestions are meant to stimulate more research studies and direct the formulation of policy, ultimately advancing a waste management strategy that is more ecologically conscious and sustainable.

Keywords

Solid waste management, Greenhouse gases, emissions

Originality statement. I hereby declare that this Master's dissertation is my own original work, does not contain other people's work without this being stated, cited, and referenced, and has not been submitted elsewhere in fulfillment of the requirements of this or any other award.	**Signature**

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GLOSSARY

ACAMPA - Pouso Alegre Recyclable Material Collectors Association
BAU – Business as usual
CO2 - Carbon dioxide
CO2EQ- Carbon dioxide equivalent
CH4 – Methane
EU – European Union
GDP – Gross Domestic Product
GHG – Greenhouse gases
IPCC - The Intergovernmental Panel on Climate Change
LCA – Life Cycle Assessment
MSW – Municipal solid waste
MSWM – Municipal solid waste management
N2O - Nitrous oxide
NPSW - National Policy on Solid Waste
PMGIRS - Municipal Plan for Integrated Solid Waste Management Plan

SWM – Solid waste management

CHAPTER 1: INTRODUCTION

1.1. Rationale

Despite a slowdown in urbanization during the pandemic, UN-Habitat (2022) estimates that the global urban population will have an addtional of 2,2 billion people, reaching 68% by 2050. The megatrend phenomenon of urbanization is closely connected to the significant challenges that have confronted the world over the past five decades, such as climate change, increasing inequality, and the emergence of zoonotic viruses, with the most recent example being the COVID-19 pandemic.

As urban populations expand, waste production rises since they are recognized as catalysts for development. One of the critical factors exacerbating climate change is the management of municipal solid waste (MSW), which involves the release of harmful substances beyond national borders during waste treatment and disposal processes.

The correlation between urbanization, waste management, and climate change becomes more evident when considering anthropogenic greenhouse gas (GHG) emissions. Since the mid-20th century, human-caused greenhouse gases have been the most dominant driver of observed climate change. According to the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2023), if corrective measures are not implemented, the Earth's temperature is projected to rise 1.1 °C to 6.4 °C during the 21st century. Within the spectrum of anthropogenic GHG contributors, the electricity and land use sectors are the two most significant causes, jointly responsible for approximately 50% of these emissions. Waste management is a noteworthy player in GHG emissions, with 5% of the total anthropogenic GHG emissions.

GHGs are emitted across all stages of waste management suppression. A wide range of procedures, including storage, collecting, transport, recycling, dumping, and landfilling, are included in the definition of waste management, which also considers the costs and implications for the environment and public health. MSW is an overarching issue that impacts various aspects of sustainable development across the environmental, economic, and social domains.

Moreover, MSW management continues to pose a challenge globally, particularly in the southern regions where many cities lack regular waste collection and proper disposal services. According to UN-HABITAT (2022), 90 percent of solid waste is openly dumped or burned in low-income countries, and 33 percent of municipal waste is not managed in an environmentally safe way, partly due to the high cost of waste management.

A meaningful progress in addressing the increasing environmental and climate change concerns is recognizing that waste management, although conducted locally, has global implications. It is essential to acknowledge that while the challenges of municipal solid waste management (MSWM) and climate change are global, variations exist in the types and severity of these issues and the capacities and priorities of regions, countries, and cities in addressing them.

Considerable advancements have been achieved in Global North cities through the implementation of the principles of circular economy and technological innovations that promote environmentally friendly waste disposal methods, including co-combustion in cement kilns, refuse-derived fuel, incineration with energy recovery, aerobic composters, anaerobic digesters, landfill bioreactors, and landfill gas recovery (Kristanto, 2019). In addition, policies to phase out waste entering landfills in the European Union, incentives for using landfill gas recovery to generate energy in the United Kingdom, and mandate landfill gas recovery at large landfill sites in the United States have been made. In contrast, progress in southern cities of the Globe has been more limited. Nowadays, policies are being introduced to restrict the number of uncontrolled waste dumping sites.

For instance, in Lahti, Finland, waste recovery is remarkably high. In 2018, the overall recovery rate was 97%. Currently, recycling rates are at 43%. The city's objective is to reduce the quantity of waste utilized to produce energy and boost recycling (Päijät-Häme, 2018). On the other hand, in Brazil, cities like Pouso Alegre deliver 95% of the waste produced to landfills. Moreover, only 1.5% of the MSW of Pouso Alegre is used for material recovery (SNIS, 2022). Observing these data makes it possible to perceive three insights: notable differences among cities around the world regarding solid waste management, practices adopted for a circular economy to enhance societal sustainability in the Global North, and inefficient waste management in the South Hemisphere, generating more greenhouse gases than necessary.

Looking at the situation in Pouso Alegre, it is necessary to search for technological alternatives that are more efficient than simply disposing of municipal solid waste in landfills, including reuse, recycling, and energy recovery. Considering the various options available, choosing the best MSW management system is not easy. In light of this, the Life Cycle Assessment (LCA) and its concepts have been in use for the past 15 years (Luiz, 2023) to support decision-making towards developing an integrated and sustainable MSW management.

This work aims to use the LCA approach to estimate how much GHG emissions the municipality of Pouso Alegre is currently reducing with the use of MSW treatment. As well as to suggest the use of new technologies in realistic scenarios that could be put into practice, having Lahti and its technologies as reference, providing quantitative information on the potential reductions in these scenarios.

1.2.Aims & Objectives

The aim is to conduct a comprehensive analysis and comparison of GHG emissions estimations resulting from MSW management scenarios in Pouso Alegre, Brazil, in order to orientate the most suitable and sustainable waste management option, drawing inspiration from Lahti, Finland, as a model scenario.

The objectives of this work are:

1. Propose scenarios of SWM treatments for Pouso Alegre with a view to reducing greenhouse gas emissions, having the city of Lahti as a reference;
2. Compare, using the LCA approach and tools, the different technological alternatives to be suggested in the management of MSW in the municipality of Pouso Alegre;
3. Identify and compare operational practices, infrastructure, investments, and cultural factors in the solid waste management of Pouso Alegre, Brazil, and Lahti, Finland;
4. Propose practical recommendations for Pouso Alegre, integrating adapted practices from the Lahti waste management model, suggesting sustainable waste treatment technologies, and outlining strategies for government, community engagement, and environmental education to achieve reduced greenhouse gas emissions.

1.3. Outlines

This thesis uses a GHG calculator based on the Life Cycle Assessment (LCA) technique to investigate the effects of different technological approaches to the treatment of municipal solid waste (MSW) on greenhouse gas (GHG) emissions in Pouso Alegre, Brazil. The study's justification is presented in Chapter 1, highlighting the importance of efficient waste management in urban settings, given the global trends toward urbanization. It describes the goals and objectives, particularly recommending long-term MSW management plans for Pouso Alegre utilizing scenarios taken from Finland's successful Lahti model.

The relationship between cities and solid waste, different SWM practices, the idea of a circular economy in waste management, the effect of greenhouse gas emissions on climate change, the methodology and applications of LCA, and a comparative analysis of SWM practices between the Global North and South—with a particular focus on Brazil and Finland—are all covered in detail in Chapter 2's extensive literature review. In Pouso Alegre and Lahti, the current SWM systems are diagnosed, scenario descriptions are based on Lahti's model, GHG emissions are quantified using LCA simulation tools, and the findings are interpreted. The technique is described in depth in Chapter 3.

In Chapter 4, the results are discussed together with the implications for policy and practice in Pouso Alegre and beyond. The viability and sustainability of the scenarios are assessed. A summary of the main conclusions, suggestions for environmentally friendly MSW management techniques, directions for further research, and thoughts on the study's contributions to the discourse on waste management and environmental sustainability are included in the conclusion. In Pouso Alegre and other similar situations worldwide, this structured approach guarantees a thorough examination of MSW management techniques to lower GHG emissions and foster sustainable urban growth.

CHAPTER 2: Literature Review

This research is grounded in a theoretical framework that comprehensively explores critical themes such as solid waste and cities, waste management, circular economy, greenhouse gas emissions from waste management, life cycle analysis, and differences in waste management practices between the Northern and Southern Hemispheres. The literature review encompasses significant contributions in these areas, aiming to provide a thorough and interconnected understanding of the addressed phenomena. Integrating these fundamental themes offers a comprehensive perspective for subsequent analyses, enriching the discussion and contributing to constructing a robust approach throughout this study.

2.1.Cities and solid waste

Prior to the mid-18th century, consumer items were primarily produced using an artisanal or small-scale manufacturing technique. As a result, the production process was characterized by slow progress, low resource intensity, and moderate output volume. The Industrial Revolution resulted in a substantial change in manufacturing and urbanization, laying the foundation for the current linear economic structure. As cities grew fast during this time, the linear production model arose, which involved the extraction of raw materials, manufacture, consumption, and disposal of items. This linear paradigm produced a tremendous amount of waste and an unsustainable depletion of natural resources.

Nevertheless, since the Industrial period, cities have been acknowledged as agents of progress and development, but they are also recognized as significant contributors to climate change through their involvement in emitting harmful substances such as carbon dioxide and greenhouse gases. According to Koop (2017), although cities occupy only a small portion (around 2%) of the Earth's land surface, they have a disproportionately large impact on energy consumption (60-80%) and global CO_2 emissions (75%). Similarly, cities also account for a significant share of raw material usage, such as metals, wood, and plastics, in constructing infrastructure, buildings, vehicles, and consumer goods. In addition, acting as concentrated centers of production, consumption, and waste generation, cities often exceed their ecological footprint by a substantial margin (10-150 times).

Significant efforts have been made to reduce waste production in most developed countries, although there has been a substantial increase in waste generation in urban areas over the past century. From 1900 to 2000, waste production multiplied more than tenfold, going from less than 300,000 tons per day to over 3 million tons per day, nearly proportional to the population growth in those areas (Foster, 2016). This trend is also expected to continue in emerging countries, where economic growth is anticipated. As waste generation tends to correlate with the increase in Gross Domestic Product (GDP), it is predicted that the rise in waste generation will primarily occur in emerging nations.

Poor waste management, ranging from inadequate collection systems to ineffective disposal methods, causes air, water, and land contamination. Open and unclean landfills contaminate drinking water, raise the risk of infection, and spread disease. Open dump landfilling produces approximately 1000 kg CO2-eq per tonne of solid waste in greenhouse gas emissions. However, traditional landfilling treatments may significantly decrease these emissions to approximately 300 kg CO2-eq. per tonne (Koop, 2017).

Effective solid waste management is a frequent challenge for communities ranging from huge metropolises to small towns and villages.

2.2. Solid Waste Management

Solid waste management is indeed considered one of the fundamental essential services provided by municipal authorities in a country to ensure the cleanliness of urban centers. Municipalities are responsible for organizing and implementing waste management processes of collecting, treating, disposing, and managing solid waste generated by animal and human activities. It involves the organized handling of various types of solid waste, such as household, commercial, industrial, construction, demolition, and agricultural, to minimize their environmental impact and promote sustainability.

The waste hierarchy concept has been widely acknowledged and integrated into national, regional, and international waste management strategies and policies in recent years. It has become fundamental in promoting sustainable waste management practices because it outlines a preferred sequence of actions to manage waste while minimizing its environmental impact effectively.

Waste minimization or reduction comes second in the hierarchy, with waste prevention being the first need. The following phase is recovery, which most EU countries use during incineration, and the final and least preferred option is disposal in sanitary landfills. The waste hierarchy is often divided into five categories (Figure 1) in descending order of priority. The first step is prevention, which aims to eliminate waste generation. Prevention strategies seek to reduce waste output by tackling it at the source. Prevention techniques can take several forms and be employed at different stages of product lifecycles, manufacturing processes, and consumption habits.

Figure 1: Waste Hierarchy

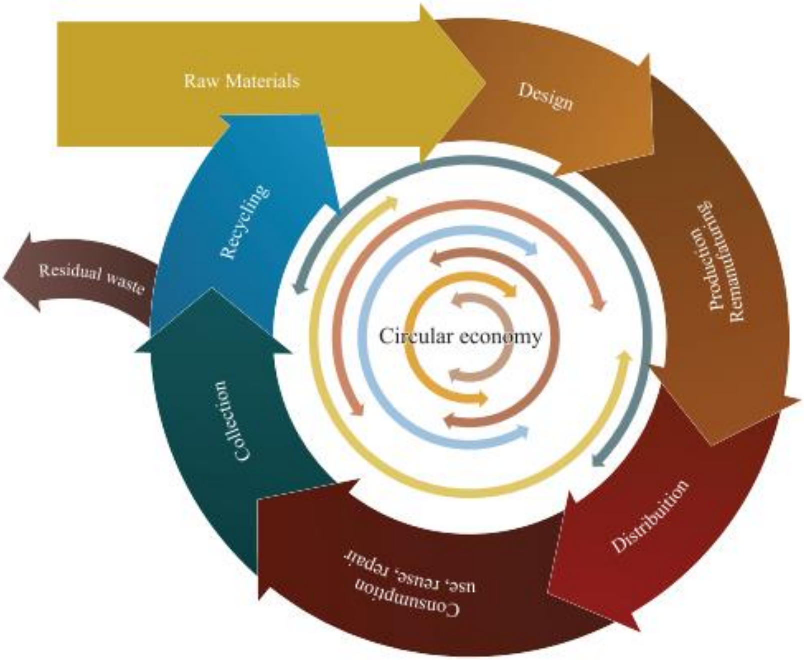
Source: European Commission (2014)

2.3.Circular Economy

According to the United Nations projection, the global population will grow 25-35% by 2050 (Koefender, 2020). The current economic development model, considered linear, is already outdated and unsustainable in the face of environmental problems generated by solid waste, making it necessary to create a new perspective on the production-consumption relationship. This consumption model (extraction, production, consumption, disposal) and economic development can accelerate the increased use of natural resources, greenhouse emissions, and their associated impacts. Since these resources are finite and, in many cases, non-renewable, it is natural to question the current consumption model and all its associated impacts.

The circular economy, a subject that has already been discussed within the context of environmental economics, gained notoriety for seeking to balance human consumption and production practices with preserving the natural world. In this sense, it becomes crucial to practice the concepts of the circular economy to help preserve the environment, reaffirming preventive actions by the government aimed at improving the solid waste management system. Figure 2 shows the different phases of a Circular Economy model, starting with the entry of raw materials, passing through the production stages, moving on to the phases of use, reuse, and repair, being sent for collection and recycling, disposing of waste, and reintroducing the reused material back into the system as raw material.

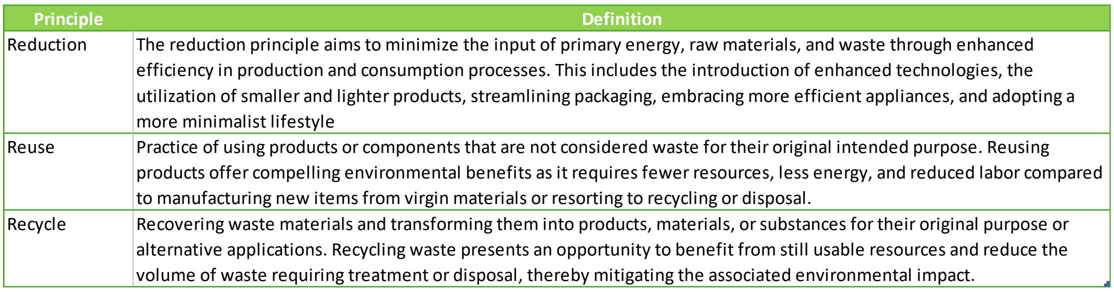
Figure 2– Phases of a circular economy cycle



Source: European Commission (2014)

The idea of a circular economy seeks to replace the conventional linear economic model with a focus on circularity and promoting the 3R principles: reduce, reuse, and recycle. It envisions an ideal economic system where waste is minimized and resources are reused and recycled within closed-loop systems (Ghisellini, 2016). Table 1 exemplifies these principles concept.

Table 1 – 3R's Principles concept



Principle	Definition
Reduction	The reduction principle aims to minimize the input of primary energy, raw materials, and waste through enhanced efficiency in production and consumption processes. This includes the introduction of enhanced technologies, the utilization of smaller and lighter products, streamlining packaging, embracing more efficient appliances, and adopting a more minimalist lifestyle
Reuse	Practice of using products or components that are not considered waste for their original intended purpose. Reusing products offer compelling environmental benefits as it requires fewer resources, less energy, and reduced labor compared to manufacturing new items from virgin materials or resorting to recycling or disposal.
Recycle	Recovering waste materials and transforming them into products, materials, or substances for their original purpose or alternative applications. Recycling waste presents an opportunity to benefit from still usable resources and reduce the volume of waste requiring treatment or disposal, thereby mitigating the associated environmental impact.

Source: Ghisellini, 2024

By following the waste hierarchy principles, the circular economy enhances both resource and economic efficiency throughout the system. Implementing the 3R principles involves adopting technological innovations, facilitating social transitions, and developing new business models to improve the efficiency of resource and energy utilization (Ghisellini, 2016).

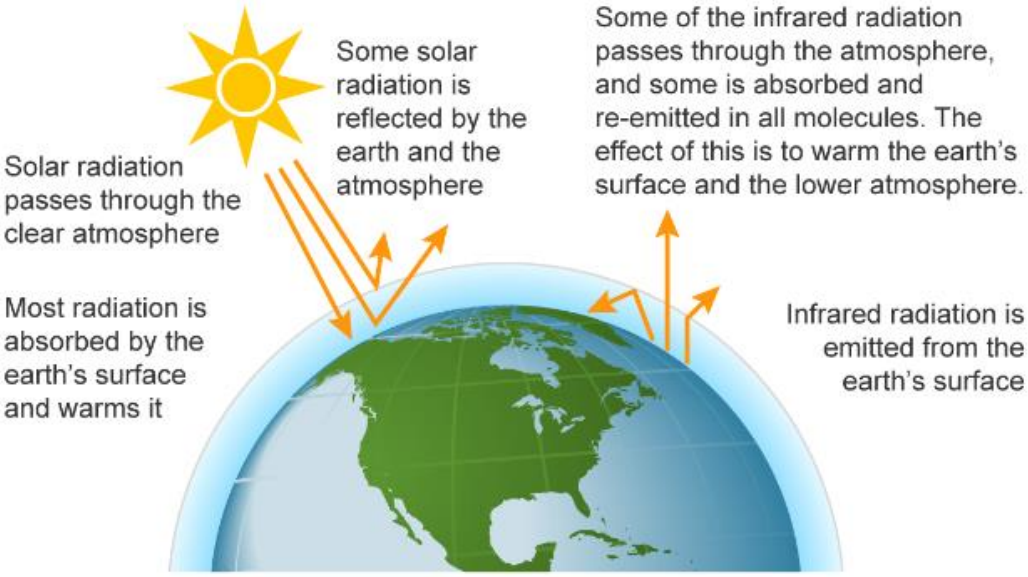
To conclude, Ghisellini (2016) points out that for the transition from the linear model of production to the circular model, in addition to the principles of the 3Rs, the circular economy should incorporate three additional principles: *eco-design* (It emphasizes the importance of the design stage in finding solutions to avoid dumping waste in landfills. Products must be designed for a disassembly and reuse cycle), *reclassification of materials* (Introduces a reclassification of materials between technical and nutrient, technical materials, metals, and plastics are designed to be reused at the end of their life cycle, while biological nutrients, which are generally non-toxic, can be safely returned to the biosphere), and *renovation* (Places renewable energy as the primary energy source for the circular economy, reducing dependence on fossil energy and improving the resilience of the economic system to the harmful effects of oil).

Transitioning to a circular economy mitigates the negative impacts of the linear economy. It brings new business opportunities, environmental and societal benefits, and long-term resilience to the global economy (Dong, 2021).

2.4.Climate Change and Greenhouse Gas Emissions

It is impossible to mention greenhouse gas emissions (GHG) without mentioning climate change in the 21st century. The accumulation of GHGs traps heat in the Earth's atmosphere, creating a greenhouse effect (see Figure 3). This natural process is essential for maintaining a suitable temperature for life on Earth. However, there is no doubt that human activity has contributed to global warming, with greenhouse gas emissions being the primary contributor to the enhanced greenhouse effect, resulting in an imbalance, causing the planet to warm at an accelerated rate.

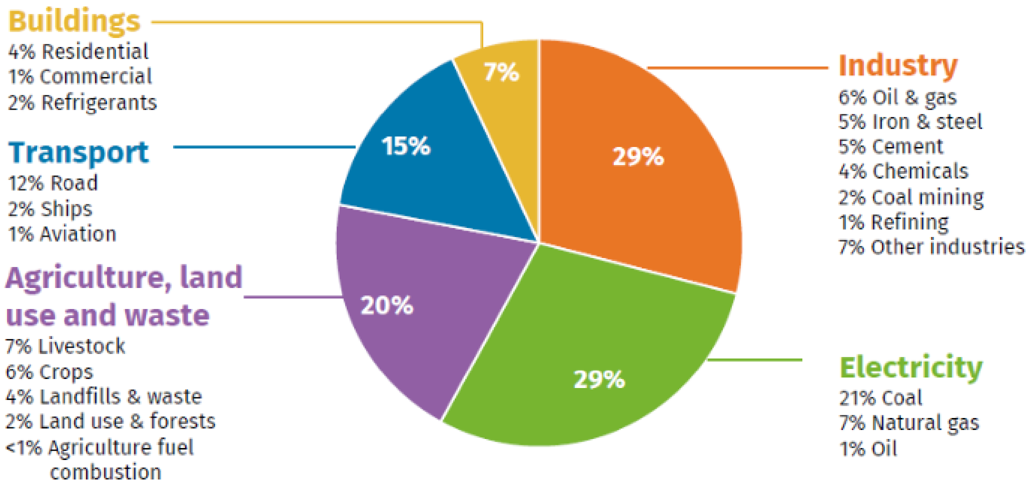
Figure 3 – The greenhouse effect



Source U.S. Environmental Protection Agency, 2021

Between 2011 and 2020, the average global surface temperature rose by 1.1°C over 1850–1900. Emissions of greenhouse gases into the atmosphere have increased globally, with uneven historical and current contributions (see Figure 4) brought about by unsustainable energy usage, land use, and land-use change, and patterns of production and consumption within and between nations, as well as between individuals (IPCC 2023).

Figure 4 - Percent share of 2021 net GHG emissions source



Source:Rhodium Group, 2021

Emissions of methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) have occurred naturally since the planet was formed. These gases have particular properties, formation methods, and capacity to influence the atmosphere. CO_2 is an essential component of the atmosphere, released by anthropogenic actions such as deforestation, burning fossil fuels and production systems, and natural processes such as respiration and volcanic eruptions (Luiz, 2023). Natural activities produce CH_4, a hydrocarbon, through anaerobic decomposition and anthropogenic activities, such as the decomposition of MSW. Methane is around 25 times more dangerous than CO2 when considering the global warming potential, which is the probability of a molecule causing an increase in the greenhouse effect and its consequences over a given period. Nitrogen gas (N2O), with a potency 298 times greater than carbon dioxide, is a powerful agent of the greenhouse effect. The nitrification and denitrification processes, along with other cultivation processes of anthropogenic and natural origin, produce nitrous oxide (Luiz, 2023).

Waste produces significant and increasing amounts of greenhouse gas emissions. Based on estimates, waste is responsible for approximately 5% of world CO2-equivalent (CO2e) emissions and up to 20% of global methane emissions, totaling 1.6 billion tonnes in 2016. These are direct emissions that, in the absence of an appropriate landfill gas management system, are released into the atmosphere. They mainly result from organic waste breaking down in anaerobic conditions in open dumps and landfills. Methane and black carbon are the two most important short-lived climatic pollutants that are produced by improper waste management. However, there are other others as well (World Bank, 2022).

Under a business scenario as usual, direct emissions from waste are expected to rise to 2.6 billion tonnes of CO2 by 2050, with methane accounting for a large portion of this increase. Methane is a short-lived substance with the most significant potential to cause climate change. Waste creation is expected to expand faster than other primary sources of anthropogenic methane emissions, such as the oil and gas industry and agriculture. This increase is primarily due to population expansion and increased waste generation per capita.
In addition to direct emissions, greenhouse gases (GHGs) are released during the production of goods and materials that, with the support of a waste management system, may be recycled, reused, or otherwise prevented. The collection of such items and whether or not goods are made and designed to be recycled or reused. When new virgin material, whose manufacturing is linked to greater energy intensity, is substituted with recycling, there are indirect reductions in greenhouse gas emissions. For instance, recycling steel uses 10-15% of the energy needed to produce primary steel, with much lower emissions. On the other hand, recycling a tonne of plastics lowers emissions by 1.1-3.0 tonnes of CO2 when compared to producing the same tonne of plastics from virgin fossil feedstock (World Bank, 2022).

2.5. Life Cycle Assessment

A scientific framework known as life cycle assessment (LCA) assesses how a product or service affects the environment at each stage of its life, from manufacture to disposal. The ISO 14040 and ISO 14044 standards establish a robust framework for carrying out Life Cycle Analysis (LCA), a valuable methodology for assessing environmental impacts throughout the life cycle of products and services. ISO 14040 defines the general principles and framework for LCA, while ISO 14044 provides detailed guidelines for its practical implementation.

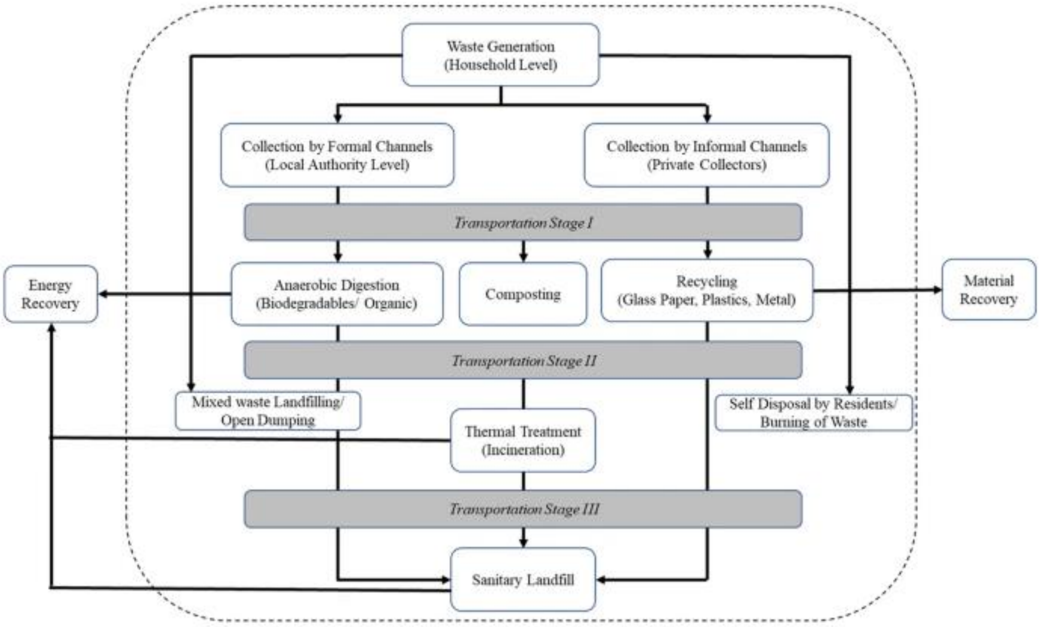
LCA has been widely used to convert resource management from linear to circular routes to secure sustainability in urban services. As a result, many academic fields have started using LCA to analyze resource management, environment impact, and GHG emissions from the standpoint of particular goods, services, and processes (Peiris, 2023).

LCA framework consists of four consecutive steps in its application. The primary steps involved in the application of LCA include:

- Definition of System Boundary, Goals, and Scope: The first step, aim and scope definition, establishes the framework by defining the objectives of the LCA and the parameters of the research. This guarantees consistent LCA performance.. The system boundary identifies which processes and activities will be considered within the life cycle assessment.
- Inventory of Life Cycle Activities: The second step involves inventorying all relevant activities within the defined system boundary. When doing an inventory analysis of extractions and emissions, all environmental inputs and outputs related to a good or service are examined. Environmental input refers to anything that is extracted from the environment and used in the life cycle of a product, such as energy and raw materials. Environmental outputs are substances released into the environment during its life cycle, such as waste streams and pollution emissions.
- Assessment of Impacts in Each Category: The third step assess the possible effects on the environment that the inventory analysis may have. This involves evaluating each life cycle activity's emissions, resource use, and other relevant factors. The impacts are often categorized into specific environmental categories, such as greenhouse gas emissions or water consumption.
- Interpretation of the Results: The evaluation is completed by analyzing the results and making sure they are supported by sufficient evidence during the interpretation step. This involves understanding the importance of the environmental effects, pointing out problem areas, and making judgments about how well the product, procedure, or service performs overall in terms of sustainability. Another aspect of interpretation is taking uncertainties and prospective improvement areas into account.

LCA evaluation is a comparatively recent method in MSW management. Most publications have been released since the 2010s, and it is not widely known abroad. To comprehend the multi-layered effects, LCA can also evaluate the effects of MSW at the stages of generation, transportation, processing, and final disposal (Luiz, 2023). Figure 5 illustrates the LCA flows of MSW. It displays the various activities that define the system boundary, such as raw material extraction, transportation, production, usage, energy consumption, recycling, and waste treatment.

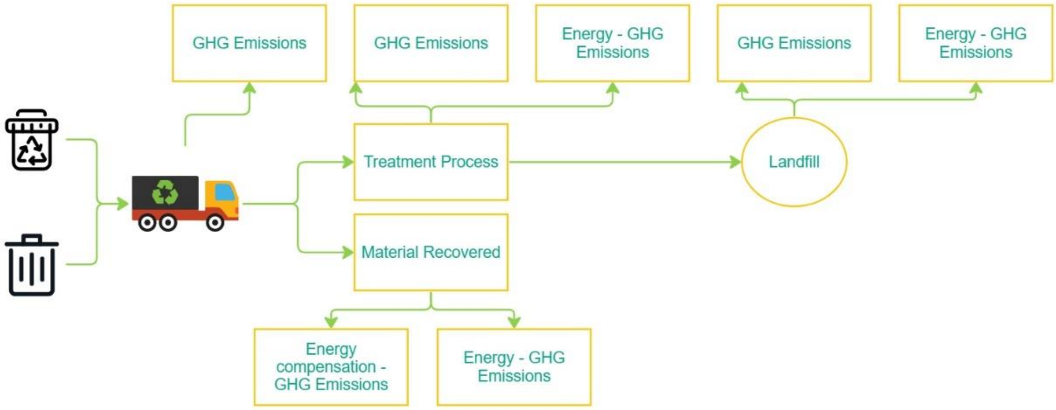
Figure 5 - Waste Management System Boundary



Source: Peiris, 2023

Urban solid waste management impacts the environment, particularly on atmospheric gas balance. Considering that every municipality manages its waste, it is possible to say that this management can influence and cause changes on a worldwide scale, depending on the management options chosen. In general, Figure 6 depicts the emissions at each system stage.

Figure 6 - MSW GHG emissions of each stage of the system



Source: Author,2024

The Environmental Protection Agency (EPA, 2017) states the possible benefits associated with lowering GHG emissions through the use of each technology:

Recycling involves minimizing the extraction of raw materials to create new products, preserving natural resources, and decreasing the energy required for production. IT is an alternative to landfilling since some solid waste involves redirecting it back to the industry as raw material, reducing expenditures on resource extraction, transportation, and processing, leading to a significant decrease in GHG emissions.

Composting, the treatment of organic waste through decomposition, enhances energy efficiency and brings various benefits. Applying the resulting organic compost improves soil quality, reducing the need for synthetic fertilizers and decreasing soil erosion and herbicide use. Other advantages include improved energy efficiency through reduced water consumption, increased soil productivity, and heightened microbial activity, resulting in higher-quality soil. Therefore, a substantial reduction in GHG emissions is anticipated throughout the process, showcasing lower emissions in subsequent stages of compost utilization in agriculture and a reduced reliance on fertilizers and pesticides.

Anaerobic Digestion: Like composting, the controlled anaerobic digestion of organic municipal solid waste in appropriately sized reactors under regulated temperature and humidity enables energy recovery. This process involves capturing and converting the methane gas into electrical or thermal energy.

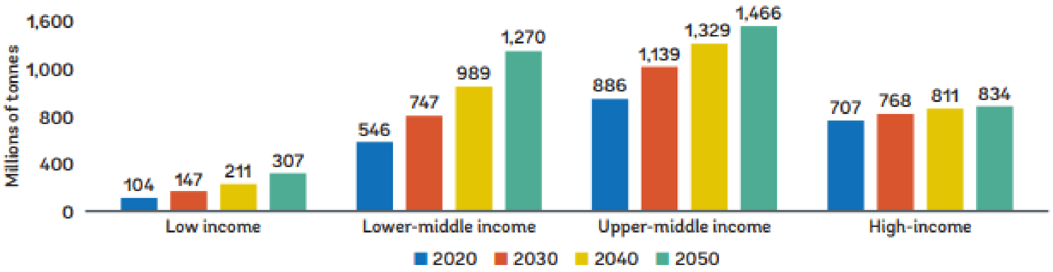
Incineration: contrary to common belief, converting waste into thermal energy through incineration leads to reduced GHG emissions. From an energy standpoint, the conventional disposal of waste in a landfill wastes the entire potential for energy generation from the waste, allowing it to decompose gradually over time and emit GHG and other environmental impacts. Conversely, generating energy from this waste replaces other energy generation sources, such as thermal power plants.

Aside from causing disposal-related impacts like liquid and gaseous effluents, landfilling waste concludes the material cycle, which should otherwise be transformed into other materials or harnessed for energy generation.

2.6. Solid Waste Management: The Global Debate – North and South Hemisphere

With industrial development and global population growth, consumption has become one of the main drivers of the global economy. However, with this economic development, various environmental problems have arisen, including a considerable increase in solid waste. This issue stems from a capitalist-economic culture that encourages an exacerbated need for consumption, becoming a matter of utmost importance with global dimensions. According to the World Bank (2021), the exponential productivity growth in developed countries indicates that the demand for goods, even though already satisfied by the previous production level, continues to increase. The same situation that has occurred in developed countries has been observed in developing countries, as almost every process of economic growth is supported by a policy of productivity versus consumption. In Figure 7, it is possible to realize the projection of waste generation of countries per income, noticing that all groups are projected to increase their generation by 2050.

Figure 7 - Projected Total Waste Generation by Income Group



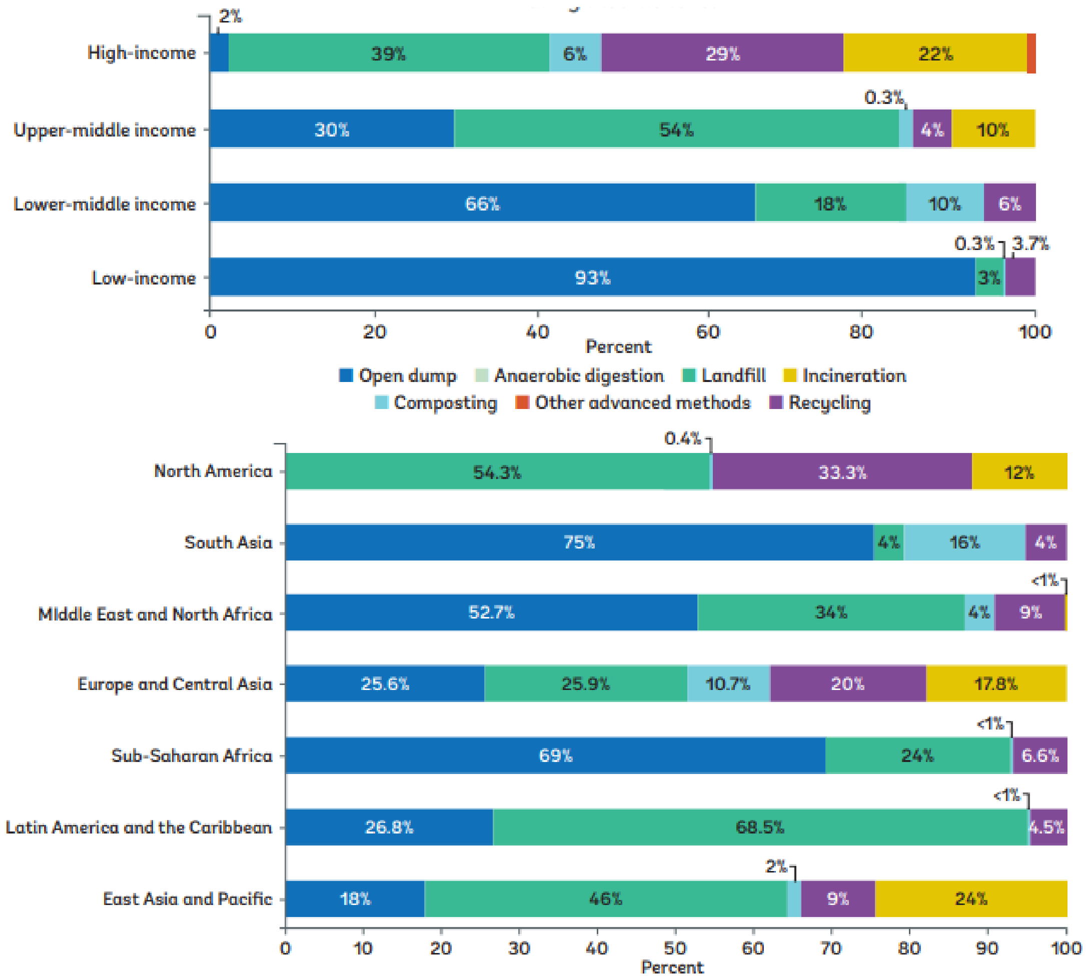
Source: World Bank, 2021

Waste management practices and challenges vary significantly between countries, cities, and regions due to differences in political regimes, policies, geography, and waste issues. On one hand, the European Union (EU) emphasizes the waste hierarchy, aiming to minimize waste, promote recycling, and utilize unavoidable waste as a resource. Conversely, in Global South cities, waste collection is a critical issue that is not explicitly addressed in the waste hierarchy. However, it serves as a prerequisite for effectively treating and disposing of waste. The presence of uncollected waste in many cities of the South can be primarily attributed to the shortcomings of waste collection systems (Onyanta, 2016).

Recycling plays a crucial role in waste reduction, and European cities have made significant investments in infrastructure and public participation schemes, leading to higher recycling rates. However, according to Onyanta (2016), recycling rates in the South vary, with some low- and middle-income cities achieving high rates, while overall rates remain low and predominantly informal. Participation in recycling is influenced by factors such as awareness, information availability, efficient collection systems, and infrastructure.
In addition to recycling, waste reduction can also be accomplished through incineration. However, incineration in some countries that do not prevent the discharge of dioxin and other pollutants is currently discouraged due to its potential for contamination, pollution and its high associated costs. Conversely, in the Global South, incineration is not widely adopted, primarily due to the significant expenses involved and the high moisture and organic content found in municipal solid wastes, rather than primarily due to environmental concerns.

Sanitary landfilling is the last resort in the waste hierarchy but poses contamination and climate change risks. Several countries in the North have implemented bans and taxes to limit landfill usage, while progress in developing countries is mixed, with open dumping being more prevalent. Energy recovery through incineration and landfill gas extraction is gaining attention, especially in European cities, contributing to renewable energy production and climate mitigation (Onyanta, 2016). However, in many cities in the South, energy scarcity remains a critical issue, with limited waste-to-energy projects and reliance on traditional energy sources. Composting practices are rare despite the high organic content of the waste stream. Figure 8 illustrates a distinct correlation between the methods adopted for municipal solid waste (MSW) management, the geographical divisions of the North and South Hemispheres, and its income.

Figure 8 - Disposal method by income and region



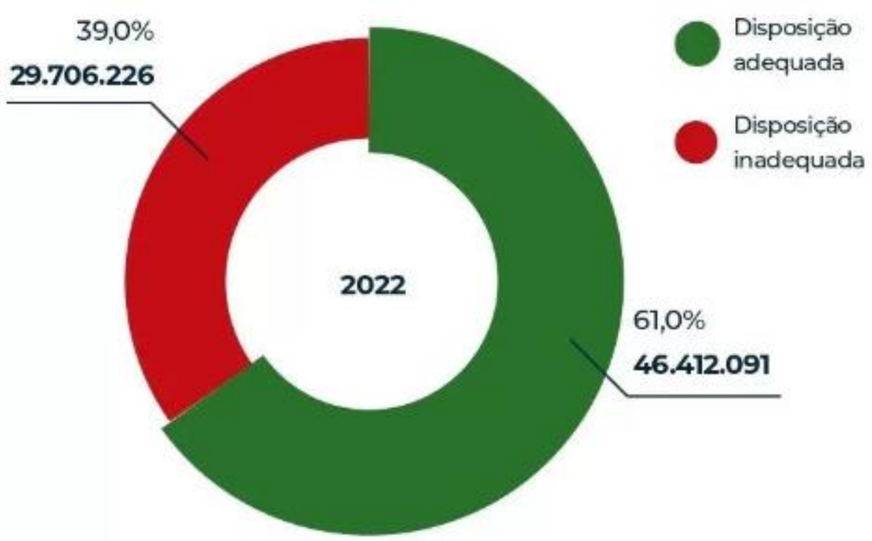
Source: What a waste, World Bank, 2018

2.7.Brazil and Finland

The contrast between Brazil and Finland reveals distinct nuances in their socio-economic and environmental realities. On the one hand, Brazil is marked by a rich cultural diversity and social challenges, facing the complexity of an emerging economy and vast climatic contrasts. On the other hand, Finland stands out for its social homogeneity and an advanced economy centered on innovation and technology. Waste management in this context reflects cultural and social differences and the unique approaches adopted by each country to balance economic development with environmental sustainability. This disparity is evident in waste management strategies and policies, where Brazil seeks inclusive solutions, while Finland prioritizes technological efficiency and minimizing environmental impact.

Brazil, the largest country in Latin America, with a population of 214,488,053 (IBGE, 2023) and an expansive territory spanning 8,515,767 km2, faces significant challenges in waste management. Unfortunately, only 61% of the MSW (see Figure 9) collected in 2021 was appropriately disposed of in sanitary landfills, while 39% ended up in controlled landfills or open dumps, totaling 76.118.317 tons (ABRELPE, 2022). The collection of recyclable material, with limited initiatives in place, currently covers less than half of the national territory, and the percentage is 4%. Abrelpe reports that the annual MSW generation per capita is roughly 381 kg, less than the approximately 440 kg generally observed in higher-income nations.

Figure 9 - Brazil MSW disposal



Source: Abrelpe, 2022

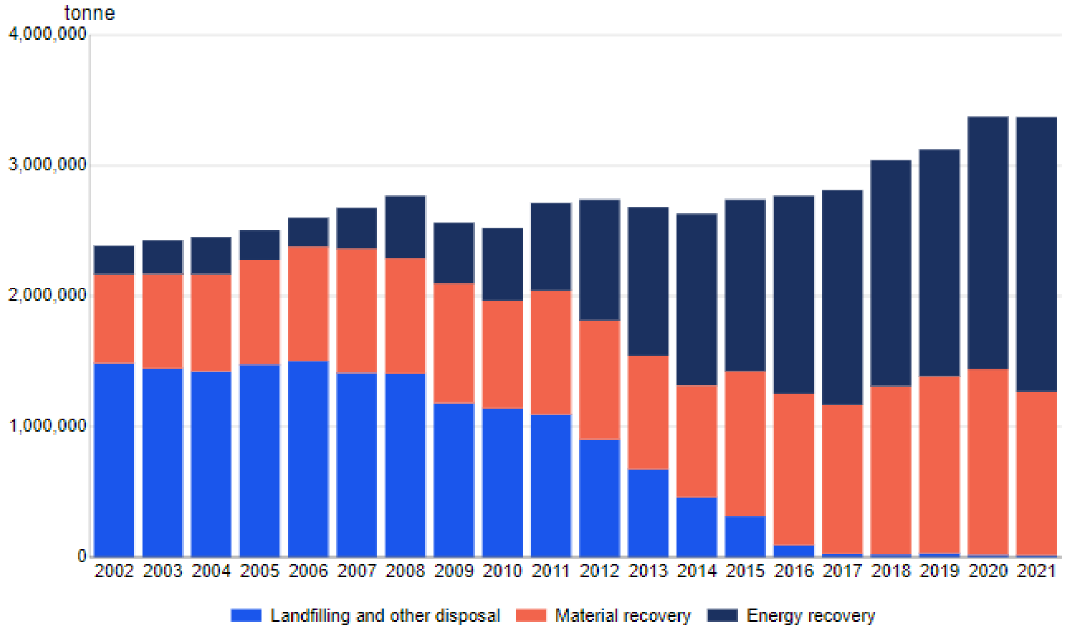
According to Alfaia (2017), Federal Law No. 12.305, which established the National Policy on Solid Waste (NPSW) in August 2010, must be seen as a turning point in Brazil's waste management history. As a matter of comparison, legislation and programs related to waste management were established in the 1970s in more developed countries.

This law's objectives were to prevent environmental and public health harm by reducing, reusing, recycling, treating, and properly disposing of MSW, including energy recovery technologies. According to this law, MSW could not be disposed of in open dumps, and by 2014, all states and localities should have closed their open dumps. However, since the NPSW was introduced, the situation regarding MSW in Brazil has not changed, and many of it still ends up in improper places.

After more than twelve years of waiting, Decree No. 11.043 was published on April 13, 2022, instituting the National Solid Waste Plan. It is an essential instrument of the NPSW, as it offers a way to achieve the objectives and materialize the policy via guidelines, strategies, actions, and targets to improve solid waste management in the country. Over 20 years, the projection is that waste recovery will increase to around 50%, in addition to the closure of all open dumps. Therefore, half of the waste generated will go to landfill and be reused through composting, biodigestion, recycling, and energy recovery.

Meanwhile, Finland has the lowest average population density of any EU member state, with 5.2 million people living there per km−2. Finland started to industrialize in the latter part of the 1800s. The post-World War II accelerated MSW generation due to urbanization and rapid GDP expansion. An estimated 629 kg of municipal waste per capita was generated in 2021, equating to approximately 3.3 million tonnes of waste. Nowadays, Finland occupies the fifth position of countries with the best MSW. According to Hupponen (2023), in 2009, 18% of municipal waste was sent to energy recovery, 36% to material recovery, and 46% to landfills. According to Figure 10 from Statistics Finland (2022), just 1% of MSW was sent to landfills in 2019, 56% went toward energy recovery, and 44% went toward material recovery (including composting and digestion). As a result, in 2020, Finland's waste sector produced 63% less greenhouse gas emissions than it did in 1990.

Figure 10 - Municipal waste by treatment method from 2002 to 2021



Source: Statistics Finland, 2022

Finland does not hold this position fortuitously. For the past three decades, it has been a nation actively addressing and prioritizing investments in solid waste management. The following paragraphs will briefly summarize the country's evolution in terms of MSW management.

As a result of Finland's 1995 EU membership, national and EU waste laws influenced Finnish waste policy. Since the EU landfill directive (1999/31/EC) went into effect, waste management has been amended in many EU nations. Reducing the amount of biodegradable waste dumped in landfills was the directive's primary goal. The Finnish policy on biodegradable waste was approved in December 2004 as mandated by the regulation. The necessary investments cost €400 million per year until 2016.

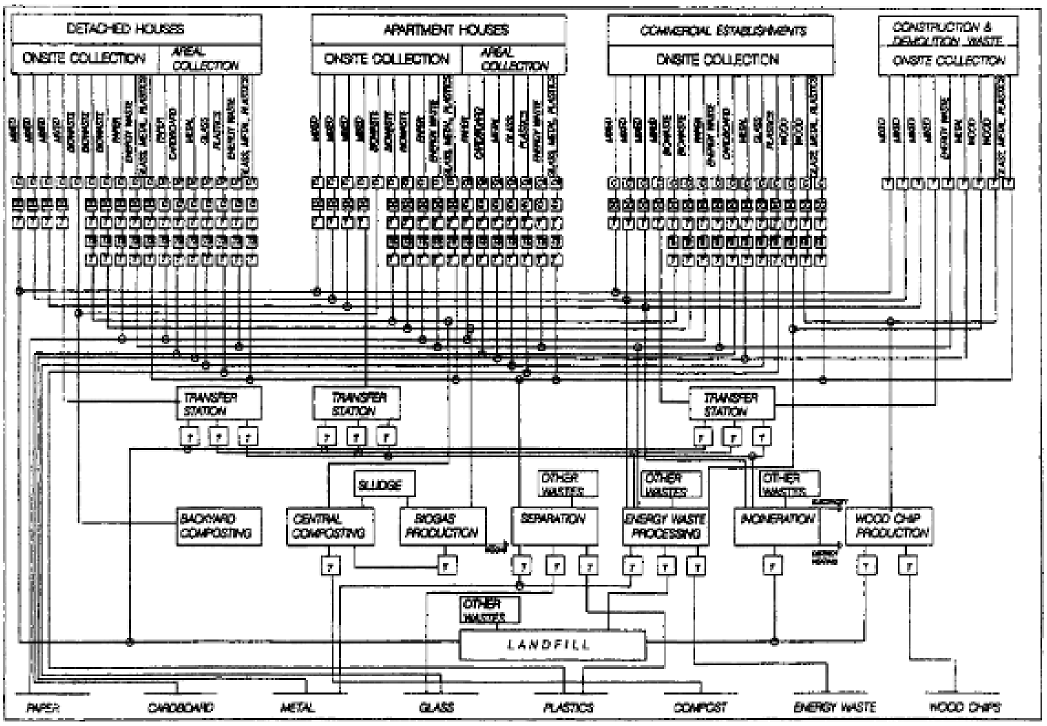
However, prior to joining the EU, Finland launched the Waste Act of Finland (1072/1993), and it was recognized as the first National Waste Management Plan and the first movement regarding this subject (Sokka, 2007). Tanskanen (1998) states that MSWM in Finland had historically been centered on many little landfills owned by individual municipalities. About 500 landfills received 70% (or 1.5 million tons) of the total mass of municipal solid waste in 1994. The majority of these landfills did not match the requirements of the anticipated EU directive.

The above plan established the following primary objectives for MSWM in terms of waste minimization for Finland:

- By 2000, the total amount of waste should not increase; by the end of 2005, it should be 15% less than experts estimated.
- Towards 2000, the recovery rate should be at least 50%; by the end of 2005, it should go above 70% (Tanskanen, 1998).
- The amount of waste dumped in landfills by 2005 should not exceed 30% (=0.6 million tons) per the new recovery rate standards. It was also projected that there would only be 100 to 200 sizable landfills in Finland in a few years.
-

Tanskanen, in his paper, *Waste streams, costs and emissions in municipal solid waste management: a case study from Finland,* released in 1998, made some predictions based on The Waste Act of Finland and The Swedish Mimes/Wastemodel—figure 11 highlights how Finland was advanced in the 1990s, when Finnish research designed MSW flow.

Figure 11 - Flow chart of the Finnish Mimes/Waste version (C=containers, CC>--collection, T=transportation, OT=own transportation by waste producers, TS=transfer station)



Source: Tanskanen, 1998

Almost thirty years later, after analyzing all Finnish policies, it is possible to say he was right. Below are listed some predictions:

- It appears that source separation initiatives and inter-municipal cooperation will enable the attainment of the recovery rate targets outlined in the National Waste Management Plan.
- The nature of MSWM in Finland will change as a result. An increase in waste flow pathways, functional components, and interdependencies on the waste management systems results from source separation, which splits the waste mass into distinct waste streams. Composting and electricity production—two waste management techniques—will proliferate.
- Cooperation among communities, on the other hand, will result in larger waste volumes and longer system transfer distances. Thus, waste management systems will get larger and more sophisticated.

CHAPTER 3: Methodology

In the first phase of the methodology (Figure 12), data regarding the current waste management system in Pouso Alegre, Brazil, will be collected through official document . This process will identify key emission sources and gaps in the region's waste management system. In addition, strategies from Lahti will be assessed, considering various factors such as infrastructure, technologies, policies, and community engagement. The objective is to highlight transferable and adaptable elements that can be used to enhance the sustainability of waste management practices in Pouso Alegre.

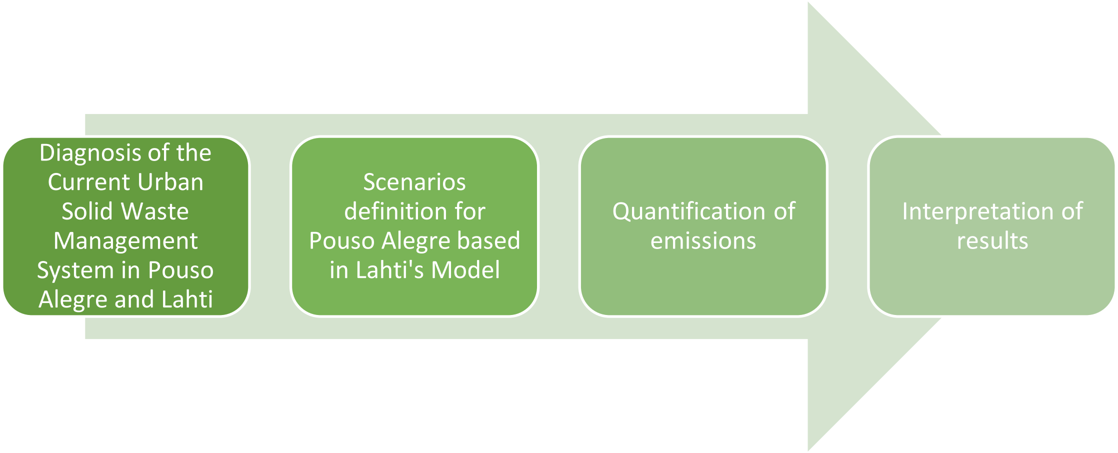
The second phase will focus on proposing prospective scenarios for Pouso Alegre. These scenarios will be based on a gradual evolution until they reach the waste management practices observed in Lahti. Strategies such as, selective waste collection implementation, investments in recycling technologies, and promotion of composting, will be included.

In the third phase of the methodology, an assessment of GHG emissions related to solid waste management will be carried out using the SWM GHG Calculator – Life Cycle Assessment Approach created by the IFEU – Institut of Energie- und Umweltforschung Heidelberg gGmbH on behalf of The German Agency for International Cooperation (GIZ).

Using the tool, users can estimate selected emissions as a baseline and compare the results to a number of scenarios provided. These scenarios are intended to assist cities in identifying climate-friendly waste management solutions and alternatives. Using LCA principles, the tool accounts for both projected and current waste-related emissions. As a result, the tool is tailored for predicting net emissions considering all stages of the waste management life cycle, potential emissions avoidance/savings (for instance, through resource recovery from waste), and indirect GHG (IFEU, 2023). After entering the input data of waste production for Pouso Alegre in the year 2021, the software tool will provide GHG emissions data for the treatment and final destination of various scenarios, allowing for a detailed comparison of emissions from the proposed alternatives.

Finally, a comprehensive interpretation of the three pillars of sustainability, as well as the environmental, economic, and social implications associated with each scenario, will be made, providing a foundation for future strategies.

Figure 12 - Methodology Steps



Source: Author, 2024

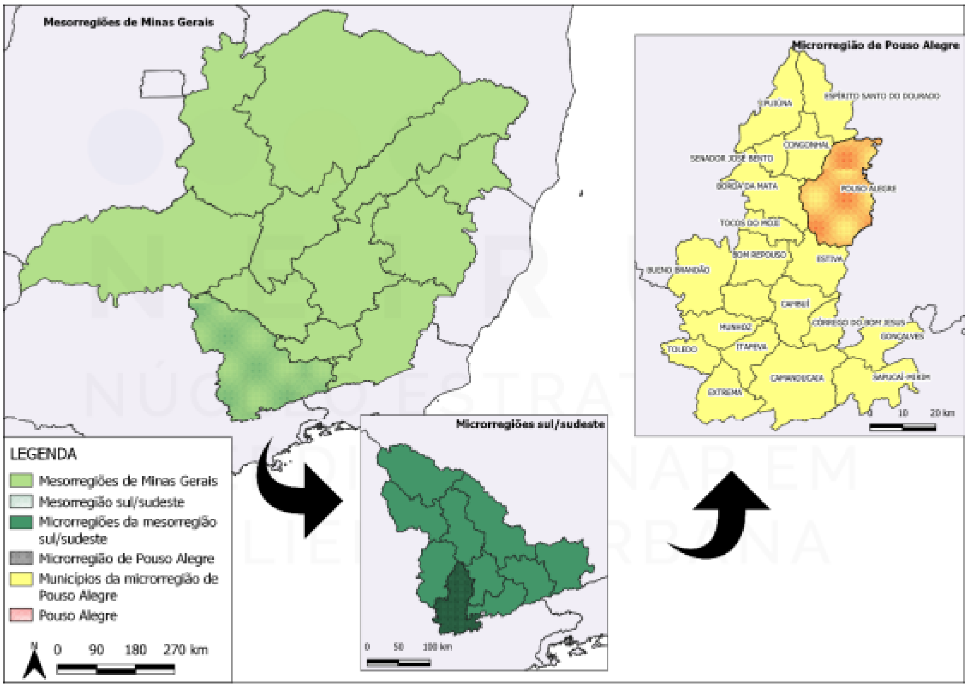
3.1.Diagnosis of the Current Urban Solid Waste Management System in Pouso Alegre and Lahti

The specific cities were chosen for two reasons: firstly, Lahti, in Finland, won the European Green Capital award in 2021 and is an example of a city to be followed, mainly because it has primarily targets: become a carbon-neutral city by 2025, zero-waste circular economy city by 2050, and it will cut down greenhouse gas emissions by 80% compared to the level of 1990 by 2025. Secondly, the similar range population of both cities, Pouso Alegre is a city in a developing country like Brazil, similar in size to Lahti (120,700), with a population of 152,212. The MSW characteristics of these two urban centers will be presented below.

3.1.1. Pouso Alegre

The municipality of Pouso Alegre is located in the south of Minas Gerais, Brazil (Figure 13). It has a total area of 542.8 km² and an estimated population of 152,212 (IBGE, 2022). Its economy is primarily based on agribusiness, mainly coffee, bananas, strawberries, and milk, and it is the most significant contributor to the state's agricultural GDP. The Municipal Department of Infrastructure, Works, and Public Services is responsible for the city's infrastructure, including urban cleaning and the collection of solid household waste.

Figure 13 - Pouso Alegre location

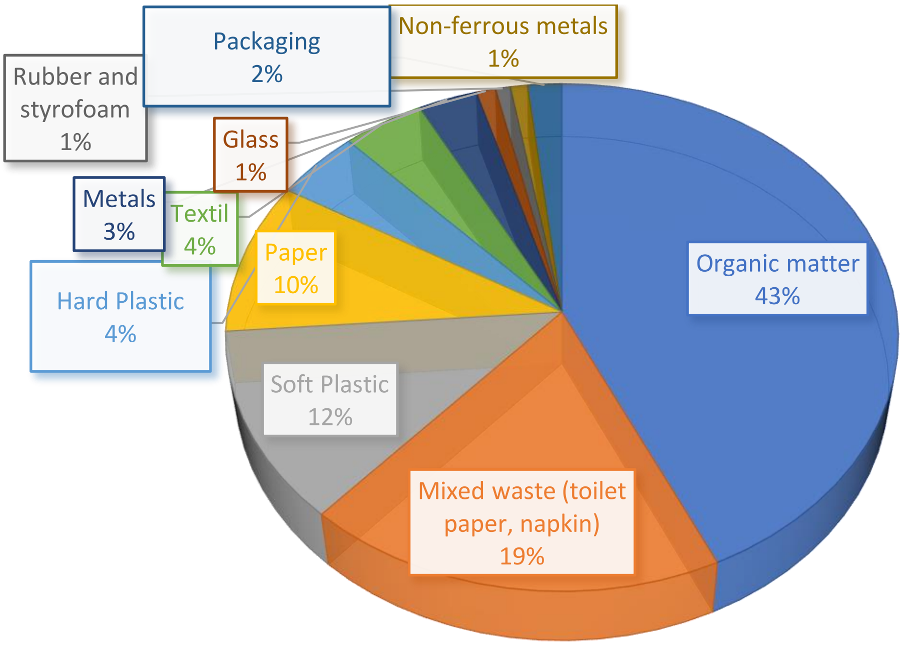


Source: Author, 2024

According to the Pouso Alegre City Hall, the municipality's citizens generate an average of 111 tons of waste daily. According to information from the City Hall, 40.874,46 tons of waste were collected in 2021 by all responsible agents in the municipality. Thus, the per capita generation of the population served by the collection service is 0.73 kg/inhab/day.

With the data on MSW generation in 2021 in the municipality of Pouso Alegre, the waste was categorized using as a basis the waste characterization published by the Municipality through the Municipal Plan for Integrated Solid Waste Management Plan of 2021 (PMGIRS), see Figure 14, which carried out a gravimetric sampling of the waste collected in all regions of the municipality, obtaining the composition of MSW in percentage terms.

Figure 14 - Gravimetric composition of solid urban waste in the municipality of Pouso Alegre 2021



Source: PMGIRS, 2021

Figure 15 shows that most of the waste collected is organic matter (43%). This waste is mainly made up of leftover food and the remains of pruned plants. Mixed waste paper from toilets and napkins compose 18.53%. Soft plastic, bags, and other packaging account for 12.02%, and paper and cardboard for 9.72% of the total. The figures presented point to a high potential for recycling the waste collected in the municipality of Pouso Alegre, as less than 23.62% of what is collected is considered waste and should go to the environmentally appropriate final disposal. The remaining waste can be recycled, reducing landfill costs, providing a more environmentally appropriate final destination, and generating income for families who collect recyclables (PMGIRS, 2021).

1.1.1.1. Household Waste Sorting

Packaging is placing solid waste inside suitable, lined containers that guarantee their watertightness in regular hygienic conditions, with a view to their subsequent storage or collection. In general, household and commercial waste in Pouso Alegre is packaged in plastic bags and disposed of in rural and urban garbage cans, and, notably, many neighborhoods do not dispose of waste cans properly. As a result, much waste is disposed of irregularly outside dumpsters and without plastic bags (PMGIRS, 2021). The municipality also reported problems with the maintenance of public waste garbage cans. Many of them are damaged, and others are set on fire, as shown in Figure 15, which contributes to the high number of positive responses to the lack of public garbage cans.

Figure 15 - Waste bin in Pouso Alegre municipality


Source: PIGIRS, 2021

1.1.1.2. Collection

The Municipal Department of Infrastructure, Works, and Services collects waste. The municipality contracts the company VINA Equipamentos e Construções LTDA to carry out conventional collection, urban cleaning, and pruning services. All urban and rural neighborhoods are served weekly with door-to-door collections or, in the case of more remote neighborhoods, by rural waste collection points. According to information obtained from the Works Department, the total team involved in the daily conventional collection is made up of: - 13 drivers; - 43 collectors; - 02 supervisors; - 01 compactor truck for hard-to-reach areas; - 10 compactor trucks for urban areas; - 01 reserve compactor truck. The waste collection service runs from Monday to Saturday, from 7:00 a.m. to 18:00. In Figure 16, it is possible to observe how waste collection works in Pouso Alegre (PMGIRS, 2021).

Figure 16 - Team working on a daily conventional collection in Pouso Alegre

Source: PIGIRS, 2021

1.1.1.3. Transport

According to PMGIRS (2021), the MSW trucks cover an average of 523 kilometers per collection day. After collection in the neighborhoods, the compactors take all the household and comercial waste to the municipal sanitary landfill. The recyclable and large-volume waste collected is transported by cage or tipper trucks to its destination.

1.1.1.4. Treatment

Currently, the municipality supports the Pouso Alegre Recyclable Material Collectors Association (ACAMPA), an organization of recyclable material collectors that carries out Selective Collection in the municipality. This service collects materials that can be reused, such as cardboard, plastics, metals, and glass, which are sorted, classified, and sold to institutions responsible for the correct destination of the waste. They are sold to industries in Pouso Alegre, Varginha, Elói Mendes, and Poços de Caldas, according to the type of material the buyers request. (PMGIRS, 2021). According to SNIS (2022), 500 tons of recyclable material were collected in selective collection in 2022. The total amount of recyclable material recovered in the same year was 468,5 tons, or 93,7% (see Table 2).

Table 2 - Materials recycled from Pouso Alegre

Recycle Materials	% Tons Recovered	Tons Recovered
Plastic	23.3	107.755
Paper	40.5	189.7425
Metals	13.5	63.2475
Non-ferrous metals	5.9	27.6415
Glass	16.9	79.1765
Total	100	468.563

Source: PMGIRS, 2021

1.1.1.5. Disposal

The final disposal service for household and commercial waste in the municipality of Pouso Alegre is outsourced and is the responsibility of the company LARA Central de Tratamento de Resíduos LTDA. All the MSW generated by the municipality is sent to the Pouso Alegre Landfill (see Figure 17). Most of the waste coming from Pouso Alegre arrives compacted and cannot be sorted (PMGIRS, 2021).

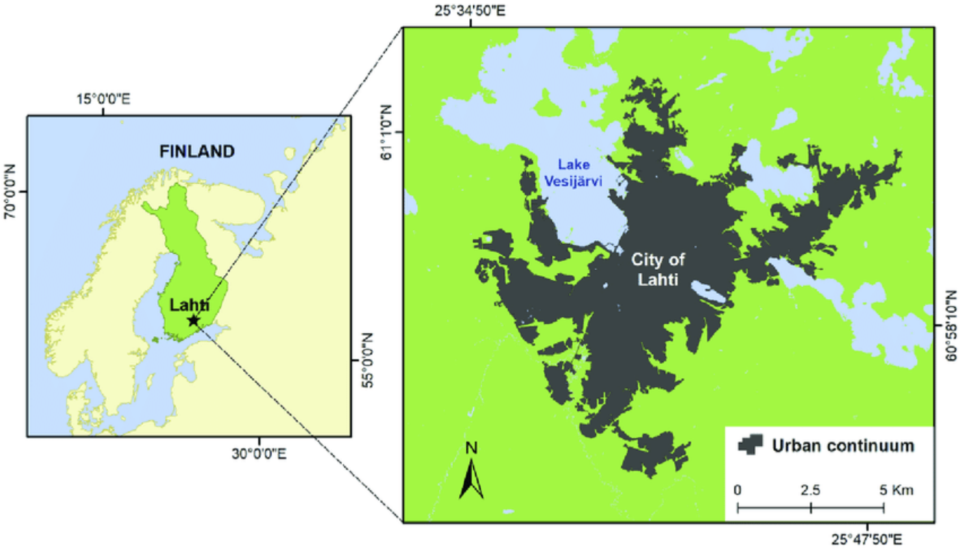
Figure 17 - Waterproofed landfill areas for receiving waste in Pouso Alegre

Source: PIGIRS, 2021

3.1.2. Lahti

Lahti, Finland, is located in the southern part of the country, about 100 kilometers north of the capital, Helsinki. With a population of approximately 120,700 people (Statistics Finland, 2024), it is one of the largest cities in Finland, covering 517.21 square kilometers. Lahti is renowned for its environmental consciousness and commitment to sustainability, evident in its urban planning and policies (Figure 18).

Figure 18 - Lahti location



Source: MacGregor-Fors et al, 2021.

Salpakierto Ltd, often referred to simply as Salpakierto, is a limited liability company responsible for municipal waste management services in the Lahti region of Finland and eight other municipalities. The municipalities served by Salpakierto, which include Asikkala, Heinola, Hollola, Kärkölä, Lahti, Myrskylä, Orimattila, Pukkila, and Padasjoki, collectively have around 196,000 residents and approximately 13,000 companies. Established in 1993, Salpakierto is jointly owned by nine municipalities, including Lahti, and operates with the intention of managing waste in an environmentally responsible manner. Its services encompass various aspects of waste management, such as waste reception, transportation, processing, and recycling (Salpakierko, 2024).

According to the company, in 2023, 8,300 tons of energy waste were collected in Lahti, 30,000 tons of mixed waste, and 9,000 tons of organic matter, summarizing 47.300 tons of waste per year and 134 tons per day. Thus, the per capita generation of the population served by the collection service is 111 kg/inhab/day. In Table 3, it is possible to analyze the amount of recycled materials Lahti is recovering yearly. 1217,86 tons of recyclables household packaging waste (plastic, metal, glass, and cartons) are collected by Rinki Company.

Table 3- Household Packaging Materials recycled from Lahti

Recycle Materials	% Tons Recovered	Tons Recovered
Cardboard (Paper)	49.30	600.36
Glass	15.84	192.87
Metal	12.17	148.29
Plastic	22.69	276.34
Total	100.00	1217.86

Source: Rinki Company, 2024

Lahti has set an ambitious goal of achieving a 90% recycling rate by 2030, aiming to improve upon the current rate of 51.7% significantly. Moreover, at the beginning of July 1, 2024, new waste legislation in Lahti, Heinola, Hollola, and Nastola village centers will mandate the sorting of biowaste in urban properties with at least 10.000 inhabitants. However, exemptions will be granted to properties already composting biowaste. Residents are encouraged to compost food waste voluntarily, while detached houses can opt into the biowaste collection system through Salpakierto’s customer service. Lahti's commitment to achieving a 90% recycling rate is evident in their sorting process. At the sorting plant, plastic waste collected from homes is separated from other types of energy waste, showcasing their dedication to efficient recycling practices.

Within the Salpakierto operating area, approximately 51.7% of municipal waste flows were successfully recycled, representing a slight increase compared to the previous year. Notably, energy waste comprised about 47.8% of the municipal waste, highlighting the city's commitment to utilizing waste for energy production. Moreover, only a minimal 0.5% of waste was deemed unsuitable for recycling or energy conversion, emphasizing Lahti's dedication to minimizing landfill disposal (Salpakierko, 2024).

1.1.3.1. Household Waste Sorting

In Finland, municipalities typically provide residents with separate bins or containers for different types of waste, facilitating easy and efficient sorting at the source. Common categories for household waste sorting in Finland include biowaste, mixed waste, paper and cardboard, glass, metals and plastics, and hazardous waste (see Figure 19).

Figure 19 - Household Waste Sorting

Source: Author, 2024

Salpakierto has introduced a new waste bin for sale to residents aimed at facilitating the collection of recyclables. Priced at 15 euros per month (Salpakierko, 2024), this bin offers inhabitants a convenient solution for sorting and disposing of recyclable materials, see Figure 20.

Figure 20 - Salpakierto's new waste bin


Source: Salpakierto, 2024

1.1.3.2. Transport

For the municipality transport and collection needs, approximately 12-15 trucks operate daily, varying depending on the route. Additionally, collection companies dispatch trucks in their area, primarily for mixed and energy waste. Most of these trucks operate in two shifts, effectively doubling the number of drivers compared to the number of trucks (Salpakierto, 2024).

1.1.3.3. Treatment

Salpakierto operates a comprehensive waste treatment facility comprising a biogas plant, composting plant, sorting plant, and recycling areas named Kujala Waste Centre (see Figure 21). The biogas plant employs dry fermentation to produce raw biogas from biowaste, garden waste, and wastewater sludge. Composting products from the plant are utilized in agriculture and manufacturing growing media. The facility has an annual capacity of approximately 82,000 tonnes, yielding 50 GWh of biogas and 22,000 tonnes of compost, achieving a recycling rate of 98%. Notably, the biogas produced is equivalent to the fuel consumption of 4,500 cars annually.

Figure 21 - Salpakierto Kujala Waste Centre Plant

Source: Salpakierto, 2024

The sorting plant LATE processes mixing, construction, and industrial waste, separating recyclable materials like plastics and metals for further processing. Recyclable waste is stored in tarmacked areas before being transported for processing into new raw materials.

Sewage and wastewater from the facility are directed to Lahti Aqua Ltd's wastewater treatment facility. Additionally, Salpakierko operates facilities for transforming wood waste and plastic or fiber-containing waste into solid recovered fuel (SRF) for power plants and upgrades raw biogas into transport fuel for Gasum's natural gas network. These processes underscore Salpakierto's commitment to sustainable waste management and resource recovery (Salpakierto, 2024).

Launched in 2012, Lahti Energy's Kymijärvi II power plant is a pioneering technological treatment facility, the world's first gasification plant to utilize waste-based solid recovered fuel (SRF) and waste wood for electricity and district heat production. The plant processes SRF made from plastic, wood, and paper waste from industrial, commercial, and household sectors. With a capacity of up to 250,000 tonnes of SRF and waste wood annually, Kymijärvi II generates 280-300 GWh of electricity and 680-700 GWh of heat, substantially reducing carbon dioxide emissions compared to coal. The plant employs a sophisticated gasification method where SRF is converted into "eco-gas" that rivals natural gas in purity, thanks to advanced cooling and filtration technologies that mitigate impurities.

1.1.3.4. Disposal

The closed landfill at Kujala was officially decommissioned in 2007, spanning an area of 24 hectares. Decomposing waste within the landfill generates biogas, primarily composed of methane and carbon dioxide, with trace amounts of sulfur compounds. Since 2002, landfill gas collection has been implemented at Kujala, effectively mitigating odors in the local environment and reducing greenhouse gas emissions. The landfill has gas collection wells, channels, and drainpipes to transfer wastewater for treatment. Although decommissioned, the landfill will undergo ongoing maintenance and monitoring for at least 30 years to ensure environmental safety and regulatory compliance (Green Capital, 2021).

3.2.Scenarios definition for Pouso Alegre based on Lahti's Model

Four waste management scenarios were considered in this study. They were formulated by proposing a combination of different treatments and disposal methods: recycling, composting, anaerobic digestion, landfill, and incineration. All scenario schemes were built gradually by applying new technologies and increasing the quantities in each of them. The last scenario is based on Lahti's ultimate waste management strategy, with outstanding results, which was one criterion that helped the city to be elected as European Green Capital in 2021. It is essential to highlight that since the calculator used in this study does not consider the gasification process, the incineration process will be used as an alternative to Waste to Energy technological treatment. The developed scenarios are shown in Table 4. The criteria used to build them were as follows:

- 1) **Business as Usual (BAU):** In this scenario, over 98.72% of waste is sent to landfills, while only 1.27% (468 tons) undergoes recycling at waste treatment facilities. This allocation is primarily due to existing infrastructure limitations and logistical constraints, which favor landfill disposal over recycling. BAU serves as a baseline for evaluating the potential environmental benefits of proposed technologies.
- 2) **Optimized Recycling from Selective Waste Collection:** Under this scenario, 88% of rejects, organic matter, and some recyclables are directed to landfills. Meanwhile, 8% of solid waste undergoes treatment, and 4% of organic matter is composted. This optimization reflects a strategic approach to maximize recycling from selective waste collection efforts while also addressing the disposal of non-recyclable waste.
- 3) **Enhanced Waste Recovery and Treatment:** In the third scenario, 15% of recyclable materials are reclaimed through waste treatment, 3% of organic waste undergoes anaerobic digestion, and 7% is composted. The remaining 75% is still directed to landfills. This scenario prioritizes the recovery and treatment of recyclable and organic waste, aiming to minimize landfill disposal while maximizing resource utilization.
- 4) **Lahti's Waste Management Model:** In the fourth scenario, inspired by Lahti's successful methodology, this strategy aims to recover 90% of waste, with 47.8% used for energy production and only 0.5% ending up in landfills. Accordingly, 51.7% of waste goes to recycling. 23% undergoes recycling via waste treatment, 14.65% is composted, and 14.05% is subjected to anaerobic digestion. This model emphasizes resource recovery and energy generation, aligning with sustainability objectives outlined in the Lahti Green European Capital Framework (Lahti Green Capital, 2021).

Treatment	Pouso Alegre Scenario	Second Scenario	Third Scenario	Lahti Ideal Scenario
Landfill	98.72%	88%	75%	0.5%
Waste Treatment Unit (Recycling)	1.27%	8%	15%	23%
Composting	0%	4%	7%	14.65%
Anaerobic Digestion	0%	0%	3%	14.05%

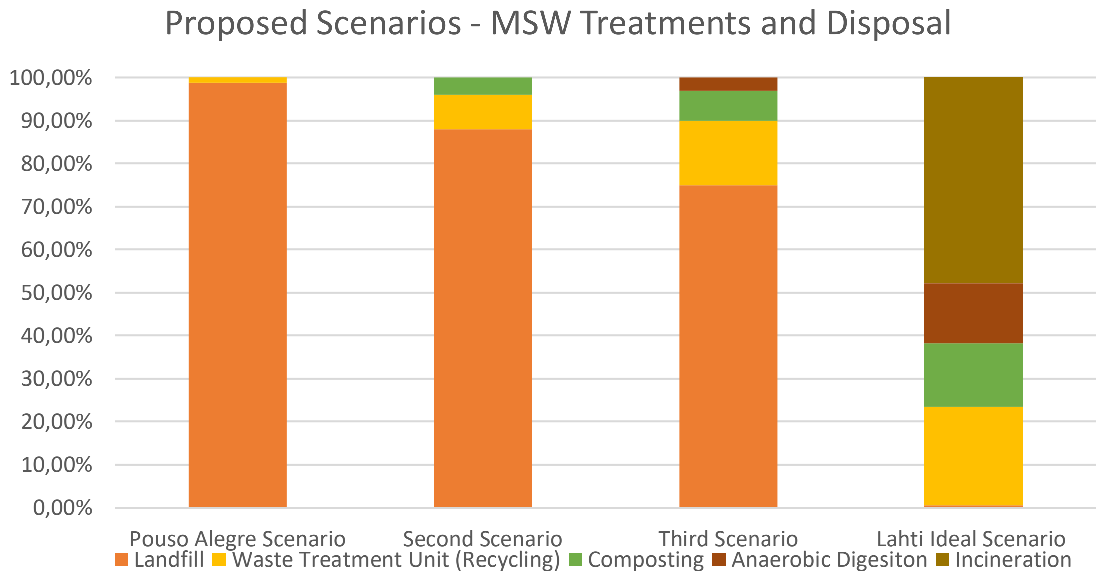
Table 4 - MSW treatment and ultimate disposal alternatives are distributed across the baseline and suggested scenarios.

Incineration	0%	0%	0%	47.8%

Source: Author, 2024

Using the options of recycling, composting, anaerobic digestion, and incineration, Figure 22 illustrates the progressive decrease in waste delivered to landfills, which goes from 97% in the BAU scenario to 3% in scenario 4.

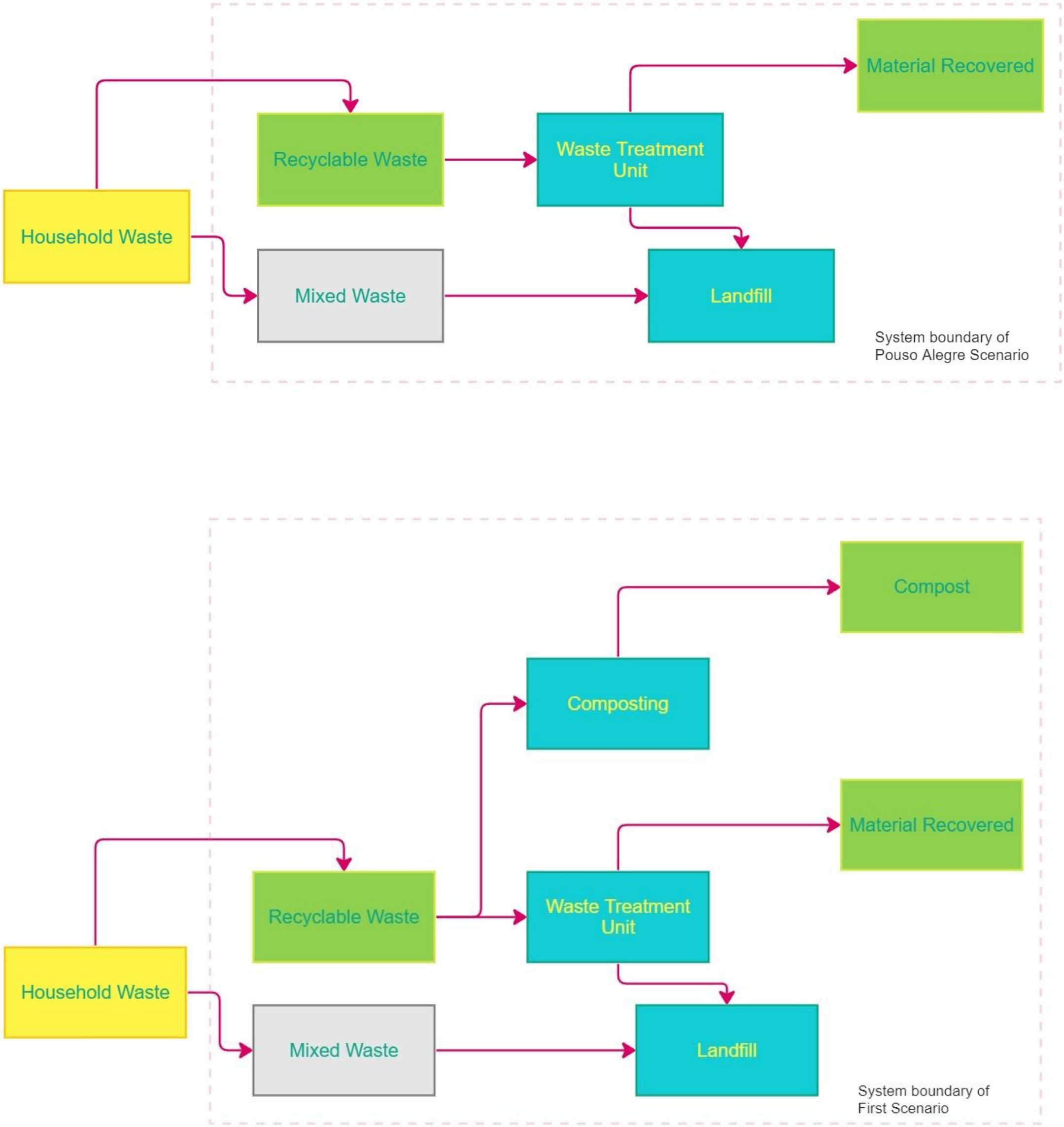
Figure 22 - Proposed Scenarios - MSW Treatments and Disposal

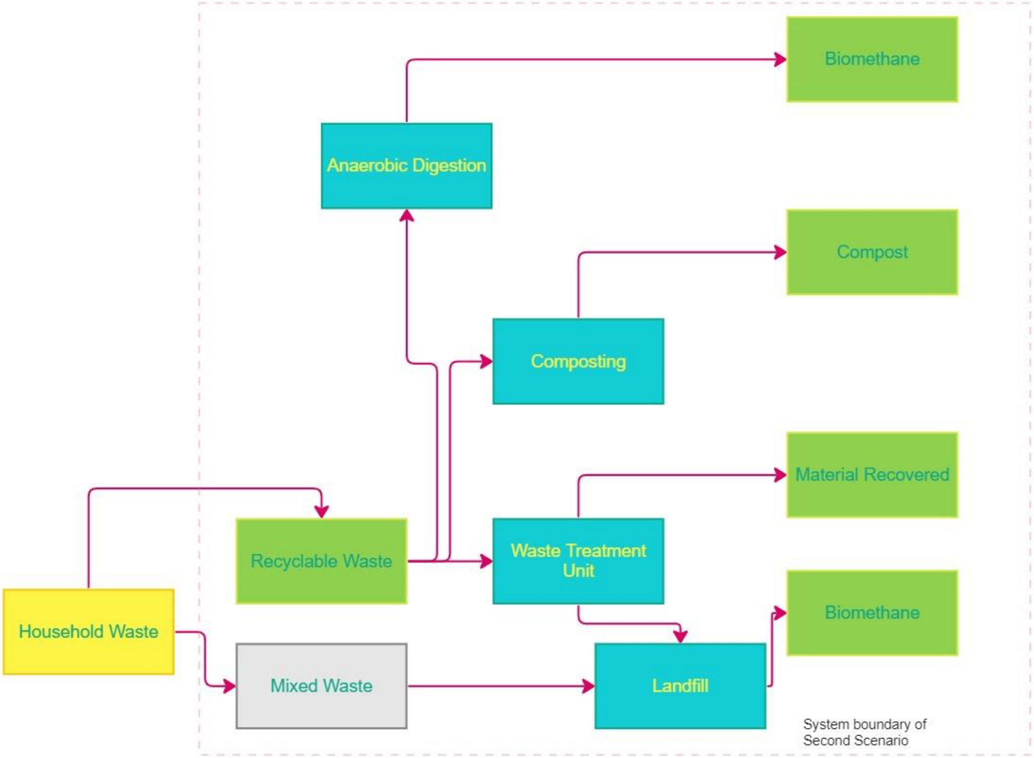


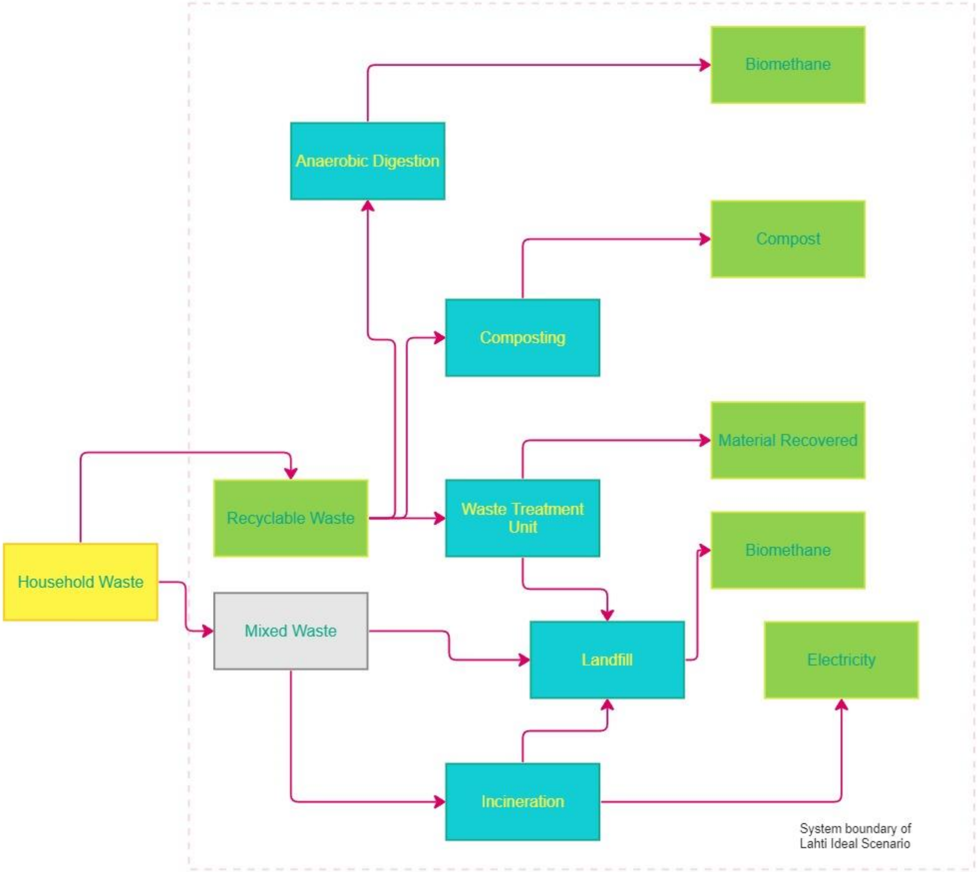
Source: Author, 2024

Regarding waste management, LCAs usually begin with solid waste generation, counting emissions from when the material is disposed of at the curb or waste collection receptacle. The system boundary for each scenario is shown in Figure 23 below.

Figure 23 - Scenarios system boundary







Source: Author, 2024

3.3. Quantification of emissions

After defining the scenarios, it is essential to understand how GHGs will be calculated.

3.3.1. Analysis of GHG emissions through LCA simulation tool

1.3.1.1. Tool

The GHG Calculator employed in this research was carefully designed to conform to globally accepted standards and practices, particularly those established by the IPCC. The Ifeu-Institut adapted this original tool for use in Brazil, commissioned by the ProteGEEr project and sponsored with funds from the International Climate Initiative (IKI) of the German Ministry for the Environment, Nature Conservation, and Nuclear Safety.

Initially launched in 2009, the SWM-GHG Calculator is a pivotal resource empowering decision-makers in developing countries and emerging economies. Its primary aim is to clarify the GHG implications of SWM practices and facilitate comprehension of the GHG mitigation potential associated with various waste management alternatives. An additional goal of the tool is to provide a seamless user experience. To this end, it was meticulously crafted as an Excel-based solution, ensuring simplicity in navigation and operation.

In 2023, the tool underwent several significant adjustments to enhance its accuracy and relevance. Notably, the characterization factors for the Global Warming Potential (GWP) were updated to incorporate the latest values from the 6th Assessment Report of the IPCC (IPCC, 2021). Additionally, the default values from the IPCC 2006 were revised following the refinements provided by the IPCC in 2019. These updates ensure that the tool reflects the most current scientific understanding and methodologies, enhancing its effectiveness in assessing GHG emissions associated with SWM practices. In addition, it considers the mass balance of GHG in terms of carbon dioxide equivalent emissions expressed in tons for each proposed scenario, encompassing emissions from the exploitation of natural resources, emissions caused by manufacturing products, transportation of the products, transportation, energy consumption, and carbon synthesis in the final disposal processes.

For each scenario, the general equation for emissions is as follows:
Net GHG Emission = Gross GHG Emissions - Avoided GHG Emissions

Nevertheless, it is essential to note that the tool primarily offers indicative data and facilitates a preliminary evaluation of the climate impact associated with various waste management strategies. As such, it falls short of constituting a comprehensive LCA or as a substitute for an Environmental Impact Assessment (EIA).

1.3.1.2. Data process

In order to initiate the modeling process, some factors must be entered. These variables essentially consist of the attributes of the Pouso Alegre waste management system that is being studied and the suggested treatments. Examples of these variables include the amount of waste per capita in the total population.

The software also requires values to be entered by class of material, with waste collected by amount divided into ten (10) materials (see Table 5). Given that the software establishes these ten categories, adjusting the gravimetric composition of Pouso Alegre's waste was necessary to suit the calculator. One crucial adjustment was establishing the amount of green waste within organic waste. According to research by Liu (2023), green waste generation ranges from 1 to 336 kg/cap/year, with a global population-weighted average of 47 kg/cap/year. Maldives, Puerto Rico, and Denmark rank in the top three, with GW generation of 336, 246, and 240 kg/cap/year, respectively. Western Europe and the United States have a higher per capita GW, whereas the value is lower in Asia and South America.

Considering the data below, GW generation in Brazil will be considered 47 kg/cap/year. Bringing this to the Pouso Alegre scenario, which has 43.05% organic matter, the amount in tons considered will be 6.9 tons per year. In addition, the Brazilian Association of Sanitary and Environmental Engineering considers that 0.21 kg/inhab/day of green waste is generated, leading to 6.9 tons for the municipality of Pouso Alegre.

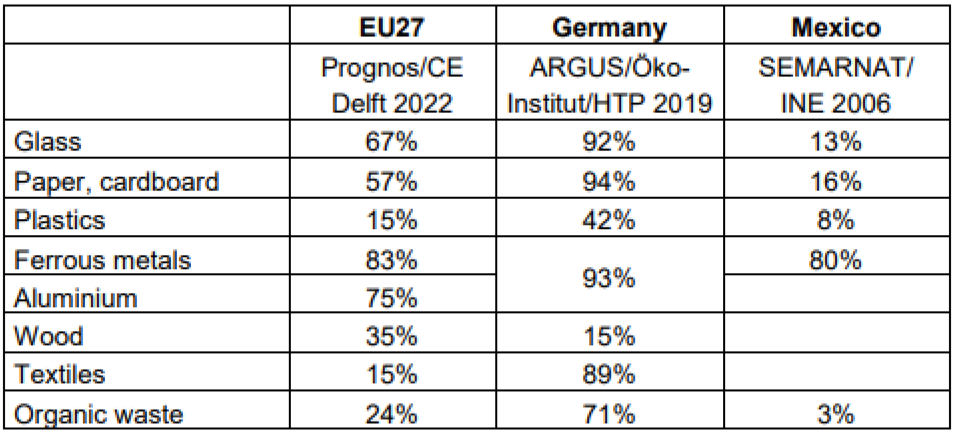
Table 5 - Waste Composition and volumes of Pouso Alegre

Waste Compostion	Percentage	Volume (tons)
Organic matter (food waste)	26.00%	10628
Organic matter (green waste)	17.00%	6949
Mixed waste (toilet paper, napkin)	18.00%	7538
Plastic	16.20%	6540
Paper	12.2%	4905
Textil	4.29%	1635
Metals	3.16%	1226
Glass	1.02%	409
Rubber and styrofoam	1.00%	409
Non-ferrous metals	0.90%	318

Source: Author, 2024

Regarding modeling data, it is essential to introduce some concepts such as, recycling rate, which is the secondary raw material or product produced through recycling and employed in production processes. Recycling rates differ from nation to nation, and it is impossible to give default options. High recycling rates are typically found in nations with integrated waste management systems. The recycling rates for waste fractions in the EU27 are displayed in Table X. According to the previously provided explanation, the recycling rates for Germany and the EU27 relate to the quantity of secondary raw materials generated from material that was collected separately (SWM-GHG Calculator, 2023).

Table 6 - Recycling rates in the EU27, Germany, and Mexico



	EU27	Germany	Mexico
	Prognos/CE Delft 2022	ARGUS/Öko-Institut/HTP 2019	SEMARNAT/ INE 2006
Glass	67%	92%	13%
Paper, cardboard	57%	94%	16%
Plastics	15%	42%	8%
Ferrous metals	83%	93%	80%
Aluminium	75%		
Wood	35%	15%	
Textiles	15%	89%	
Organic waste	24%	71%	3%

Source: Ifeu Calculator, 2023

In order to stipulate the material recycling rates for the scenarios proposed in this research, the current recycling rate in Pouso Alegre was taken into account for the BAU scenario. The second and third scenarios were drawn up following the idea of improving recycling rates, considering the rates in Mexico and Europe. Finally, for the ideal scenario, the recycling rate for Lahti was considered, which was 51.7% in 2023. Table 7 below shows the recycling rates for each scenario.

Table 7 - Recycling rate for each scenario

Recycling Rate	**1%**	12%	25%	51.7%
Tons	468	5024	10407	21149

Source: Author, 2024

As can be seen, the tons have increased along with recycling rates. The relationship between the different material types and the proportion of each type that is recycled in each scenario is displayed in Table 8.

Table 8 - Percentage and tons of recyclable materials in each scenario

Recycling Materials	Pouso Alegre Scenario (Tons)	Pouso Alegre Scenario (Percentage)	First Scenario (Tons)	First Scenario (Percentage)	Second Scenario (Tons)	Second Scenario (Percentage)	Lahti Ideal Scenario (Tons)	Lahti Ideal Scenario (Percentage)
Organic waste (food waste)	0	0%	1062	21%	2656	26%	6802	32%
Organic waste (green waste)	0	0%	694	14%	1737	17%	4864	23%
Paper	186	40%	1814	36%	3090	30%	4414	27%
Plastic	107	23%	654	13%	1308	13%	2943	18%
Glass	81	17%	143	3%	265	3%	368	2%
Metals	66	14%	490	10%	858	8%	1103	7%
Non ferrous metals	25	5%	163	3%	490	5%	654	4%
Total	468	100%	5024	100%	10407	100%	21149	100%

Source: Author, 2024

As composting and anaerobic digestion only allow for treatments of the organic matter fraction, the proportion of organic waste transported for these treatments, composting, and anaerobic digestion must respect the percentage of the waste's gravimetric composition.

The percentages defined above in each scenario were considered for solid waste disposal. In addition, some disposal parameters were defined for the landfill. For example, the BAU and first scenarios did not consider the possibility of collecting methane gas. On the other hand, the third and fourth considered collection with maximum efficiency and the possibility of electricity generation and biomethane production, respectively.

Taking Lahti as a model for energy production via incineration and considering Brazil's energy matrix, the net efficiency of energy generation from waste incineration treatment was chosen to be electrical. In Table 9 below, it is possible to verify these data.

Table 9 - Summary table of the reported variables

Characteristic	**Variable Input Data**
Percentage of biogas from anaerobic digestion for biomethane production - All Scenarios implicated	100%
Treatment and type of use of collected landfill gas - Pouso Alegre Scenario - No treatment, ventilation only	100%
Treatment and type of use of collected landfill gas - First Scenario - No treatment, ventilation only	100%
Treatment and type of use of collected landfill gas - Second Scenario - Electricity production	100%
Treatment and type of use of collected landfill gas - Lahti Ideal Scenario - Biomethane production	100%
Net efficiency of energy use through waste incineration - Electricity - standard value	15%

Source: Author, 2024

3.4. Interpretation of Results

Using the Ifeu calculator, modeling was conducted after creating the scenarios and organizing the data appropriately. The tool was employed to determine the GHG emissions of each scenario in terms of tons of CO2 equivalent (TCO2eq). The results presented in this section reflect the potential GHG emissions statistics based on the four scenarios analyzed. However, these figures should not be taken as precise due to the model's assumptions and the actual waste management conditions in both cities.

For the calculations, essential structures and cycles were taken into account, such as (Guia Brasil, 2022):

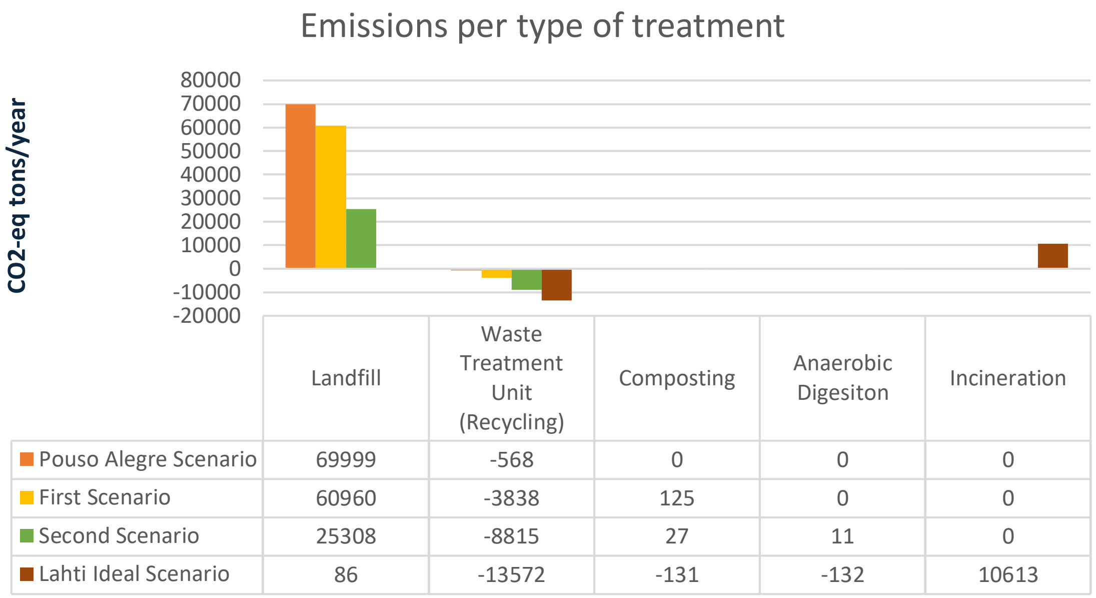
- The structure of the recycling system concerning the type of material in the waste stream, the applied recycling technology, the quality of the secondary material, and its beneficial use, which could replace the primary material;
- Structure of primary material production that meets the same beneficial use as the secondary material provided by the recycling system;
- Energy consumption and GHG associated with various product life cycle stages. Including energy-intensive processes such as extracting and processing raw materials, manufacturing products, managing end-of-life products, and transporting materials and products between life-cycle stages.
- The structure of disposal, landfill methane gas capture, and waste-to-energy technologies that reduces the volume of waste sent to landfills and generate renewable energy, displacing emissions from fossil fuel-based energy sources.

Right after calculations, a comparison was made between the scenarios, representing which configuration is the most beneficial in reducing GHG emissions and which of the benefits of each treatment alternative contribute most to reducing these emissions. It is important to note that variations in positive emissions, such as raw material exploitation, manufacturing, and carbon sequestration, and negative emissions, such as recycling, composting, combustion, and anaerobic digestion, occur according to the alternatives chosen in each scenario. However, each type of MSW has a different life cycle, so there are consequences when technology changes.

The outcomes have been divided into the following sub-items: emissions by sort of treatment, emissions by type of waste, and comparison of emissions across scenarios.

In Figure 24, a comparison is made regarding the emissions generated by each type of treatment for the proposed scenarios. The emission values for each treatment type indicate the emissions expected under each alternative for the respective proposed scenario. Notably, the highest emission values are attributed to waste recycling, followed by emissions from landfilling. While the emission values for composting, anaerobic digestion, and incineration treatments are comparatively lower, a significant reduction is observed due to the diversion from landfilling.

Figure 24 - Net Emissions per type of treatment



	Landfill	Waste Treatment Unit (Recycling)	Composting	Anaerobic Digesiton	Incineration
🟧 Pouso Alegre Scenario	69999	-568	0	0	0
🟨 First Scenario	60960	-3838	125	0	0
🟩 Second Scenario	25308	-8815	27	11	0
🟫 Lahti Ideal Scenario	86	-13572	-131	-132	10613

Source: Author, 2024

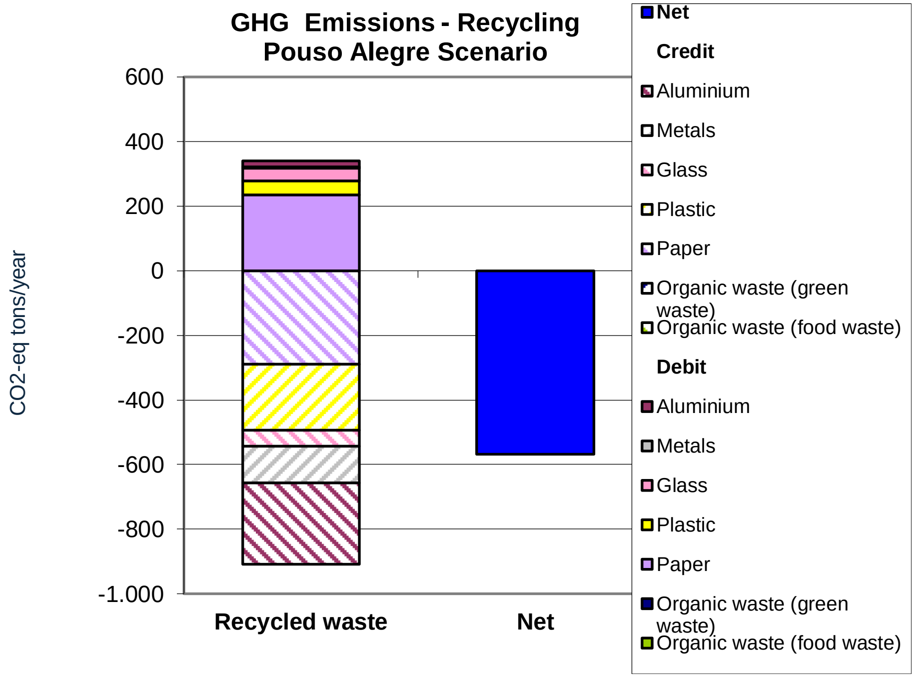
The findings showed the hotspots of GHG emissions:(Gautam, 2021), (Luiz, 2022):
- Energy consumption, particularly from the use of fossil fuels, and emissions linked to the extraction, production, transportation, utilization, and final disposal of MSW;
- Energy consumption during the process of waste collection and transportation due to combustion of fuel, mainly CO2 and small amounts of N2O and CH4;
- Emissions not tied to energy, such as the release of CO2 when limestone (CaCO3) utilized in steel production is transformed into lime (CaO) or the generation of perfluorocarbons (PFCs) during the aluminum smelting process, among others;
- CH4 emissions resulting from the breakdown of organic materials in landfills;
- CO2 and N2O emissions produced during the combustion of MSW;

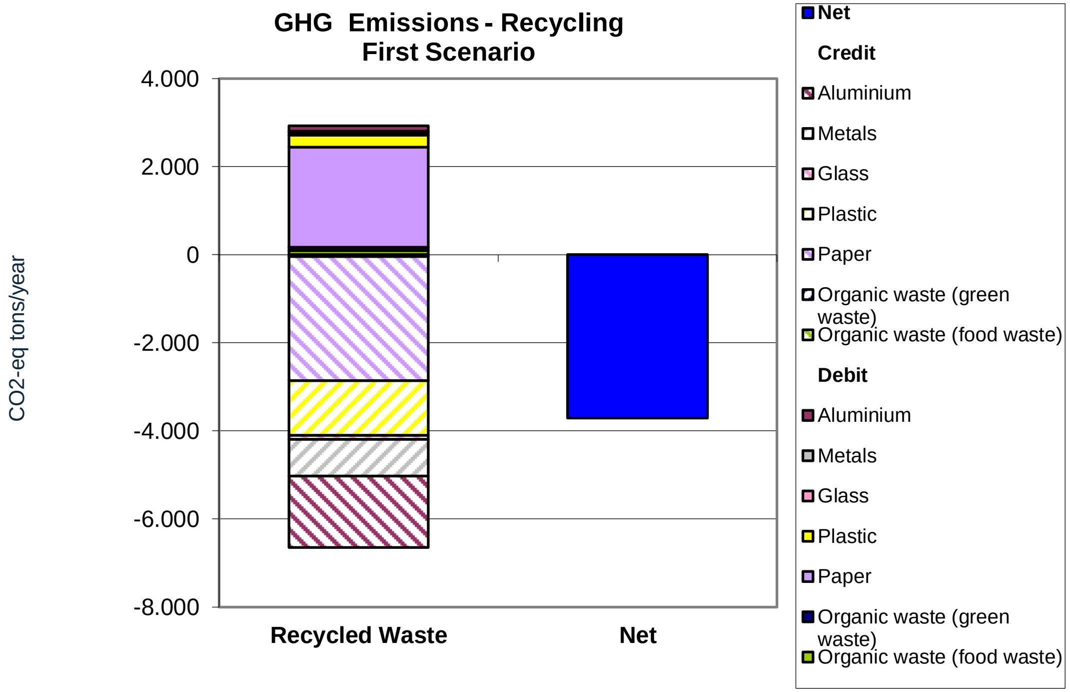
In addition, showed as well potential sources of GHGs reductions:
- Segregating and recycling waste substituting raw materials in manufacturing, thereby reducing energy consumption and minimizing GHG emissions during subsequent management processes.
- Reduction and reuse of GHG at the end of the waste life cycle, such as CH4 produced by anaerobic digestion and CH4 transformed into CO2 in landfill gas burners

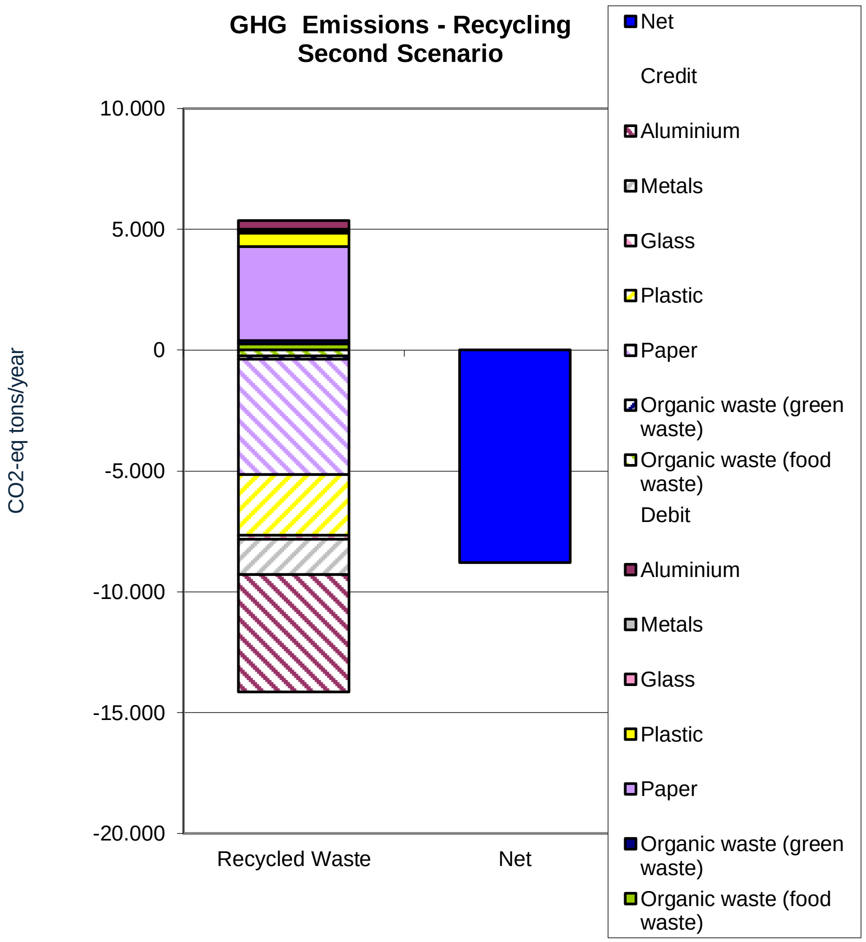
Table 10 and Figure 25 illustrate the aggregate emissions per waste type across each scenario, from the waste exhibiting the most substantial reduction, paper, to the least impactful, organic matter (green waste).

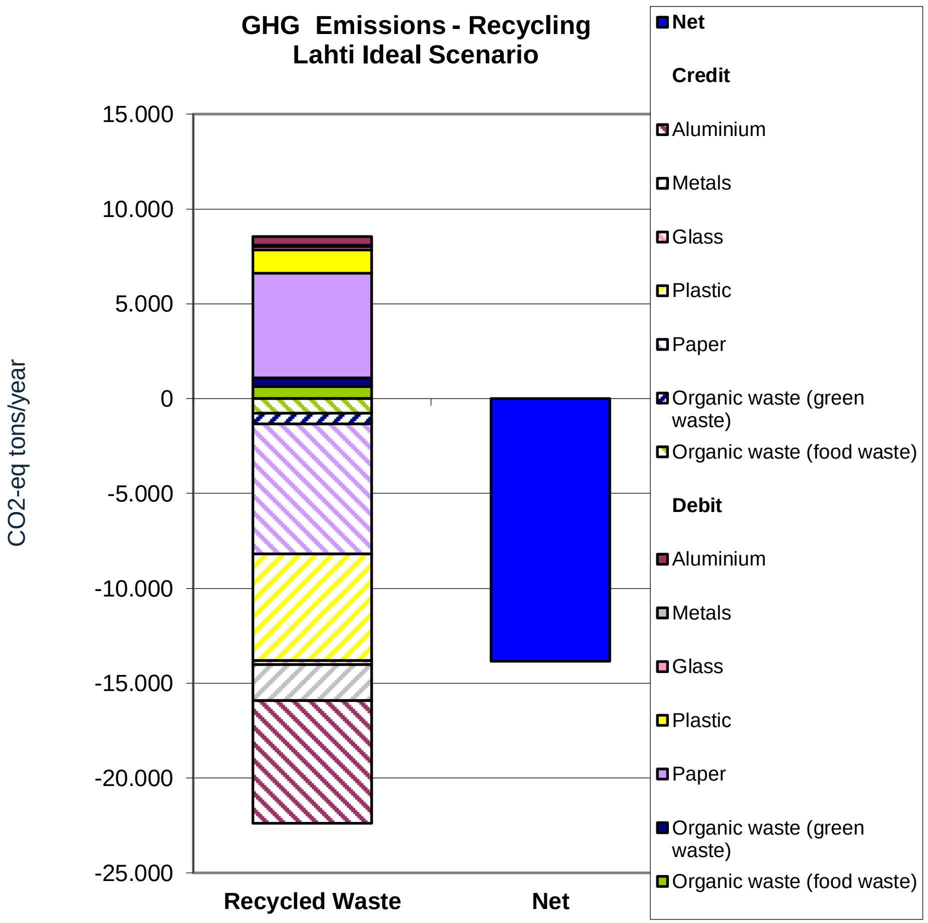
Table 10 - Recycling GHGs emissions

Recycling Emissions (CO2-eq tons/year)	**Pouso Alegre Scenario**	First Scenario	Second Scenario	Lahti Ideal Scenario
Debit				
Organic waste (food waste)	0.00	100.96	248.42	630.86
Organic waste (green waste)	0.00	66.01	162.43	451.16
Paper	234.11	2279.51	3881.32	5544.75
Plastic	44.24	268.15	536.29	1206.66
Glass	39.50	69.13	128.38	177.76
Metals	4.24	31.39	54.94	70.63
Aluminium	17.66	113.96	341.89	455.85
Credit				
Organic waste (food waste)	0.00	-25.40	-225.34	-7840.03
Organic waste (green waste)	0.00	-16.61	-147.34	-560.69
Paper	-288.54	-2809.46	-4783.67	-6833.81
Plastic	-206.09	-1249.04	-2498.08	-5620.68
Glass	-49.38	-86.41	-160.48	-222.20
Metals	-113.37	-839.76	-1469.57	-1889.45
Aluminium	-250.39	-1615.42	-4846.26	-6461.68
Net	-568.01	-3712.98	-8777.06	-13834.87


GHG Emissions - Recycling
Pouso Alegre Scenario
CO2-eq tons/year
600
400
200
0
-200
-400
-600
-800
-1.000
Recycled waste
Net
Net
Credit
Aluminium
Metals
Glass
Plastic
Paper
Organic waste (green waste)
Organic waste (food waste)
Debit
Aluminium
Metals
Glass
Plastic
Paper
Organic waste (green waste)
Organic waste (food waste)


GHG Emissions - Recycling
First Scenario
CO2-eq tons/year
4.000
2.000
0
-2.000
-4.000
-6.000
-8.000
Recycled Waste
Net
Net
Credit
Aluminium
Metals
Glass
Plastic
Paper
Organic waste (green waste)
Organic waste (food waste)
Debit
Aluminium
Metals
Glass
Plastic
Paper
Organic waste (green waste)
Organic waste (food waste)



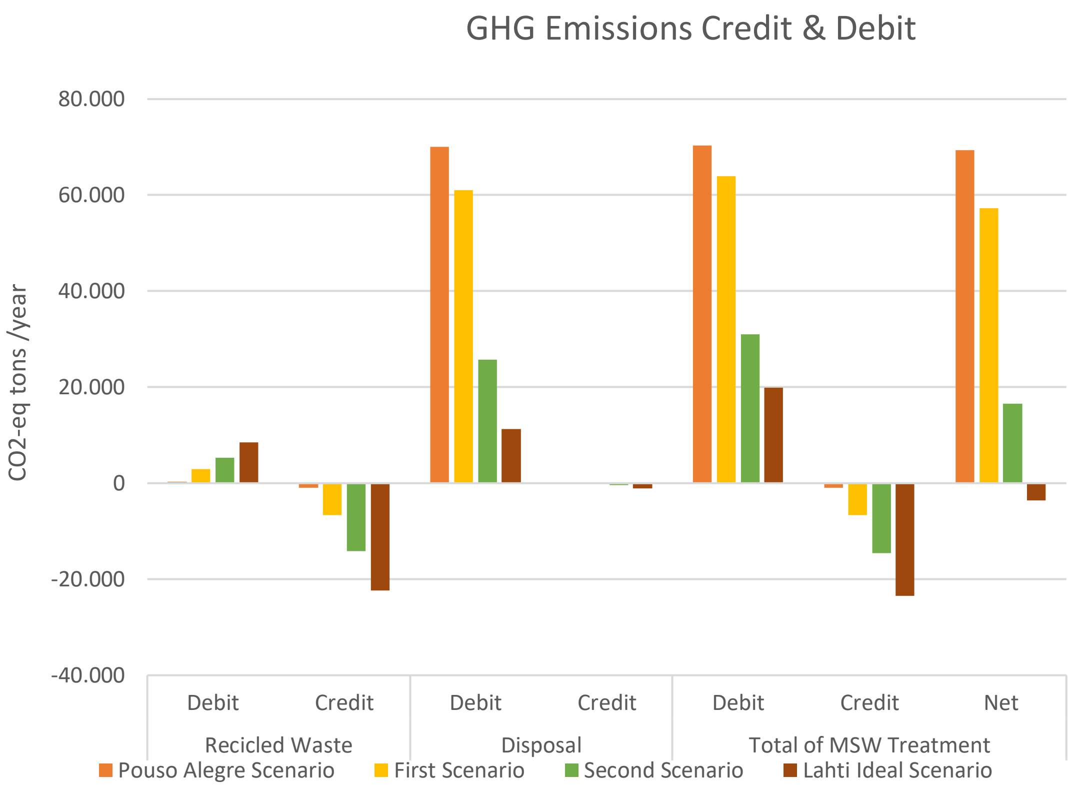


Source: Author, 2024

The comparison between GHGs emissions in waste disposal and recycling processes, as shown in Figure 25, highlights a significant disparity in emissions levels, with emissions from disposal far exceeding those from recycling. This vast difference in emissions arises primarily due to the differing nature of the two processes. In waste disposal, particularly in landfills, organic waste undergoes anaerobic decomposition, releasing methane, a potent greenhouse gas. Waste transportation to landfills and subsequent landfill management practices also contribute to methane and carbon dioxide emissions.

Conversely, emissions are comparatively lower in recycling processes due to reduced energy requirements and avoided emissions associated with extracting, processing, and manufacturing raw materials. By diverting waste from disposal to recycling, emissions are minimized, and valuable resources are conserved, making recycling a more environmentally sustainable option.

Figure 25- GHGs Emissions Credits and Debits



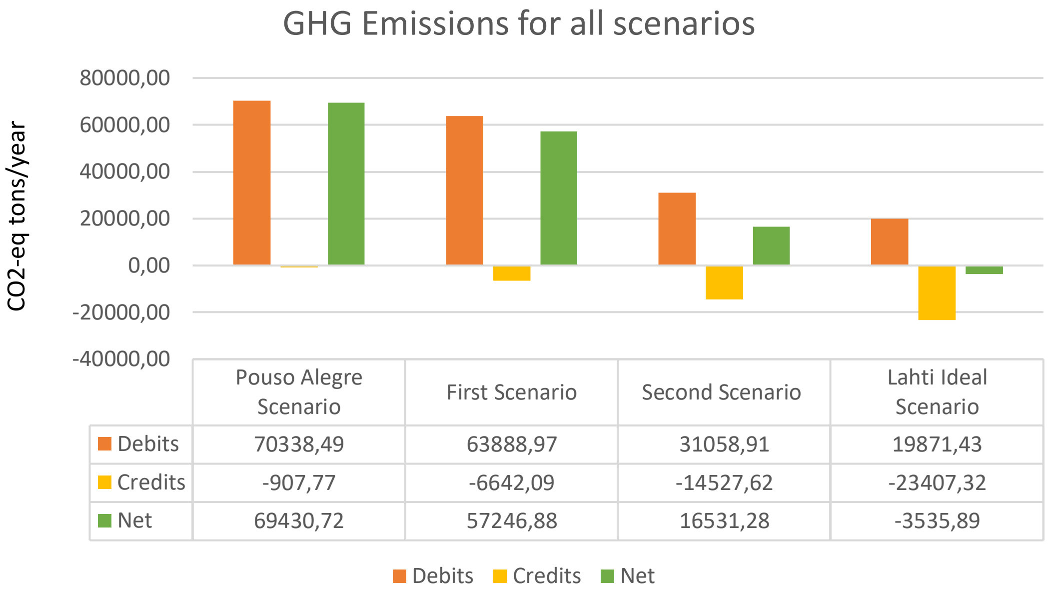
Source: Author, 2024

The findings illustrate a gradual decrease in GHGs emissions as new waste treatment alternatives are introduced to replace landfill disposal. Figure 26 compares the GHG emission values in terms of tons CO2eq between the BAU scenario and the three proposed scenarios.

The highest GHGs emissions varied between the gross and net results due to differences in GHG reduction, with Scenario 4 achieving the highest reduction (-3535,89 tons CO2-eq/year) and Scenario 1 the lowest (69430,72 tons CO2-eq/year). In Scenario 1, approximately 98% of waste treatment methods (controlled landfill) did not contribute to GHG reduction. In contrast, Scenario 4 generated electricity from 61,83% of the MSW, which was factored into the net GHGs calculations.

Lahti's ideal scenario emerges as the most efficient alternative, with a potential reduction estimated at approximately 72672,19 tons CO2-eq, followed by Second Scenario with 52899,44 tons CO2-eq.

Figure 26 - GHGs Emissions for all scenarios

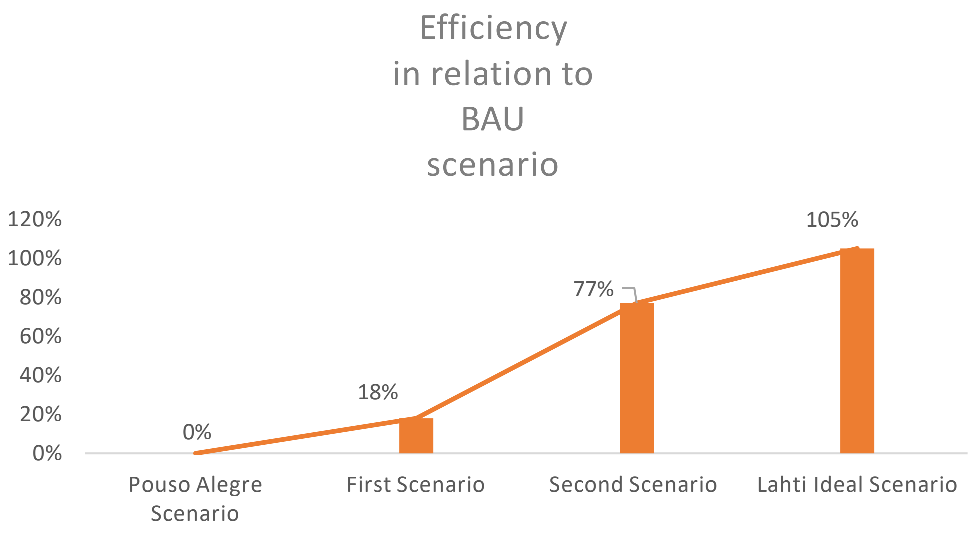


	Pouso Alegre Scenario	First Scenario	Second Scenario	Lahti Ideal Scenario
Debits	70338,49	63888,97	31058,91	19871,43
Credits	-907,77	-6642,09	-14527,62	-23407,32
Net	69430,72	57246,88	16531,28	-3535,89

Source: Author, 2024

In order to establish quantitatively the significance of each scenario compared to the BAU scenario, a comparison was made of the reduction in GHGs emissions, representing the efficiency of each scenario's implementation, below, Figure 27. As can be observed, waste management efficiency in Lahti is one hundred percent higher than that in Pouso Alegre. This result reflects how cities with similar territorial extents and populations can have vastly different GHGs emission scenarios depending on the public policies and management practices they implement.

Figure 27 - Scenarios of efficiency



Source: Author, 2024

CHAPTER 4: Discussion and Conclusion

4.1.Discussion

Some similarities were observed based on the diagnostic analysis of Pouso Alegre and Lahti municipalities. Both cities generate similar amounts of waste, around 40 thousand tons annually, with Lahti generating slightly more than 8 thousand tons. This difference is expected for cities from different countries' realities. Therefore, the daily quantity of waste generation and waste per inhabitant was higher in Lahti, with 134 daily tons, whereas Pouso Alegre had 111 daily tons.

A nation's economic development can be assessed by examining the actual composition of its MSW. Generally, a nation's consumption and, thus, waste production increases with its Gross Domestic Product (GDP). In less developed areas, there is typically less usage of packaging (paper, plastic, etc.) and more waste generated from organic materials (Alfaia, 2017). This analysis appears correct, as Lahti produces half the amount of organic matter compared to Pouso Alegre, with 9,000 tons versus 17,000 tons. However, this value may be somewhat unclear, given that Lahti's waste composition is categorized into mixed, energy, and organic waste. This categorization might imply that a significant portion of organic matter could be mixed with other types of waste.

Regarding the recycling of household packaging waste, it was observed that Lahti recycles three times more volume than Pouso Alegre, with 1,217.26 tons compared to 468.56 tons. Interestingly, the recycling percentage of each material was at a comparable level, similar in both cities, with paper being the most recovered material, followed by plastics, glass, and metal. On the one hand, Lahti has a robust household packaging recycling program, boosting advanced waste management technology, particularly at the Salpakierto plant, where a sophisticated sorting machine is employed. This machine significantly enhances the efficiency and effectiveness of the recycling process by accurately separating various materials, ensuring that a higher percentage of waste is recycled correctly. On the other hand, this diagnosis revealed that only 2% of the waste in Pouso Alegre is currently recovered, even though theoretically, almost 90% of the MSW can be sorted and recovered.

Lahti faces a scenario in which recycling targets have progressively become more demanding, resulting in collecting more recyclable materials over the years. Increased investments have been directed towards enhancing sorting techniques and utilizing secondary raw materials. This evolution in recycling practices has facilitated the reduction of reliance on fossil fuels and virgin resources. Waste is increasingly recognized as a potential resource, particularly as traditional raw material sources diminish globally (Hupponen,2023).

According to a study conducted in Canada (Kristanto, 2019), waste treatment units can reduce emissions by more than twice as much compared to anaerobic digestion despite consuming ten times more energy than anaerobic digestion, composting, or incineration. However, the reduced energy requirements for processing virgin materials offset the higher energy consumption, resulting in lower emissions. Pouso Alegre has a long way to go in developing effective waste treatment units, as it currently lacks a proper system; this will require significant investments and likely a transformation in the current governance of the city's solid waste management.

From a transportation standpoint, Lahti has leveraged its well-established separate collection system to modify the fuel used in waste collection. Instead of gas or diesel, Lahti utilizes biofuel derived from its incineration plant, reducing emissions from waste collection transportation. The heat produced by waste, which can be partially or entirely fossil-based, is now replacing fossil fuels and renewable fuels. Additionally, the electricity generated from waste is increasingly substituting renewable electricity sources. This demonstrates the importance of waste recovery, not only for waste management and GHG emissions reduction but also for rethinking energy consumption and potentially transforming the entire energy supply chain. However, it is crucial to prioritize the demand for recycled materials before utilizing waste for energy recovery. Properly sorting materials before they are destined for incineration ensures that recyclable materials are recovered first, maximizing resource efficiency.

Pouso Alegre, as a Brazilian city, benefits from an electricity generation system that predominantly relies on renewable sources such as hydroelectric power, biomass, wind, and gas, resulting in low greenhouse gas emissions. However, the transportation of collected waste still generates emissions from diesel trucks.

By proposing and developing waste management scenarios for Pouso Alegre, this thesis expects that in the future, Pouso Alegre might adopt one of the new scenarios, Scenarios 2 and 3, or even aim to achieve the Lahti Ideal Scenario. These scenarios focus on treating 10% to 70% of organic waste through anaerobic digestion and composting. Anaerobic digestion and composting are widely used biological treatment methods in developed and developing countries. Anaerobic digesters process waste in an oxygen-free environment and are best suited for wet waste, whereas composting is an aerobic process suitable for drier organic materials. Anaerobic digestion also generates biogas, which can be used as an energy source, and biosolids, which can be utilized as fertilizers, depending on their quality (Kristanto, 2019).

The remaining waste, containing less than 30% organic material, would be directed to incinerators and controlled landfill sites. This approach is designed to reduce greenhouse gas emissions from landfills significantly. Therefore, minimizing the amount of organic material sent to landfills will be crucial to achieving more sustainable waste management practices. As waste treatment technologies and systems advance, landfills are utilized less frequently, and their emissions are becoming more stable in developed countries. Conversely, with the rise of numerous large cities and the adoption of controlled landfill practices in developing countries, emissions are on the rise. The differences in landfill emissions between Scenario 1 and Scenario 4 clearly show the opposite approach from these two cities, Pouso Alegre and Lahti, 69.999 CO2 equivalent tons/year to 86 CO2 equivalent tons/year.

From a perspective focused on emissions and energy consumption, it is noticeable that incineration is widely adopted in Europe. However, the drawbacks of incinerating waste, including air pollution, high costs, challenges finding suitable locations for incinerators, and public opinion, are significant concerns. In this regard, energy solutions based on gasification and pyrolysis are attractive, and Lahti is one of the pioneer cities in this aspect. Gasification is superior to incineration in several ways. It converts waste into cleaner syngas, which can be efficiently burned, resulting in lower CO2 equivalents and fewer pollutants. Gasification also significantly reduces emissions of NOx and harmful compounds like polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs), commonly associated with incineration. Additionally, gasification produces valuable by-products and minimizes landfill use, enhancing resource recovery. Although gasification involves higher costs due to complex technology and stringent feedstock pre-treatment, its environmental benefits make it a more sustainable waste-to-energy solution than traditional incineration (Dong, 2018).

This is a crucial point of comparison between Lahti and Pouso Alegre, with Lahti being significantly ahead. As part of Europe, Lahti adheres to regulations prohibiting landfills, directly promoting waste-to-energy technologies as a waste treatment. Meanwhile, current federal legislation in Brazil still aims to eliminate irregular open dumps. The disparity between these two cities is evident in regulatory frameworks and current circumstances. The differences between countries in the Southern Hemisphere and the Northern Hemisphere are evident, and solid waste is a reflection of the economic, political, and social disparity.

With this, it is essential to highlight governance when discussing waste management. In Pouso Alegre, the municipality manages the waste collection, while a private company manages landfills. Conversely, Lahti has a Regional Waste Management Committee that creates regulations and designates responsibilities to Salpakierto, a dedicated waste management company. Another difference is that Lahti operates within a consortium-based management system. Lahti is part of Lahti Regional Waste Management, which includes Salpakierto, a publicly owned entity managed by a consortium of municipalities. On the other hand, Pouso Alegre is not part of any consortium in Minas Gerais State.

Financial constraints are revealed as a constraint to the proper management of solid waste. Providing adequate waste management services has been impeded by insufficient public-private partnerships, low economic resources, lack of continuity, and inadequate assessment of developmental projects. Developmental programs are implemented slowly, which impedes progress even more. Identifying straightforward, suitable, and cost-effective techniques for municipalities like Pouso Alegre is crucial for enhancing and effectively implementing waste management systems. These consist of centralized disposal sites, source separation systems, and incorporating all relevant parties in the planning and execution of policies. Crucial measures include merging the unorganized and formal sectors and overhauling the current recycling procedures.

In addition, it is essential to highlight the citizen's participation involved in waste management. They all contribute to forming a city's system, but frequently, this is only acknowledged as the local government's duty. In ideal circumstances, the municipality and its residents are viewed as co-responsible parties. Establishing an efficient and effective system requires having an awareness of all the stakeholders and their roles within the structure. Unfortunately, in many cities in the Southern Hemisphere, citizens believe that waste disappears when you throw it away in the garbage can bag. The vast majority of the population is unaware of, or has no interest in, how waste is disposed of and the importance of this process in preventing an increase in GHGs, pollution, and the extraction of raw materials.

Regarding types of equipment, all municipalities look for equipment, believing those would resolve the wide range of issues they encounter. However, in addition to technology solutions, a functional system must also have links to the environment, society, culture, law, institutions, and economy. These linkages must exist for the system to work. Solid waste management involves costs like any other service, although these are typically not recuperated. Resources are needed to have qualified staff, suitable infrastructure, equipment, and adequate maintenance and operation. A modernized, sustainable system requires the federal government's financial assistance, the engagement of municipal leaders in waste management matters, the involvement of service users, and the appropriate administration of funds.

4.2. Conclusion

A detailed evaluation of the effects of various technological approaches for MSW treatment on GHG emissions was facilitated using a GHG calculator based on the LCA approach across different proposed scenarios. The study also highlighted waste materials and technological treatments that have the most significant impact on reducing emissions.

Four scenarios were developed to mitigate GHG emissions from the waste management sector in Pouso Alegre, Brazil. The results showed that Scenario 4, modeled after Lahti's current situation, produced the lowest GHG emissions, treating 40,874.86 tons/year of waste from Pouso Alegre. This scenario included 5,988.33 tons/year through composting, 9,401.22 tons/year through material recovery, 5,742.92 tons/year through anaerobic digestion, 16,628 tons/year through incineration, and 99 tons/year through controlled landfills. Across all scenarios, WTUs emitted the least GHGs.

As expected, incineration produces significant GHG emissions, making it a controversial technological process. However, it also generates energy and offsets the emissions produced. It is essential to note that this study does not endorse incineration without secondary treatment, such as incineration and gasification, as done in Lahti. For organic waste treatment, anaerobic digestion emitted fewer GHGs than composting and was more suitable for food waste with high water content. However, composting might be more practical in Pouso Alegre due to the availability of human resources and the lack of need for advanced technology. Thus, both biological treatments are viable options.

Pouso Alegre waste sector generated 69431 tons/year of CO2 equivalent in 2021, of which 69999 tons/year of CO2 equivalent were produced by the decomposition of waste in landfills. Source reduction, recycling, landfill gas capture, composting, anaerobic digestion, and incineration are the primary ways Pouso Alegre solid waste management may help cut emissions. In comparison, source reduction and recycling will indirectly reduce emissions, possibly to a greater extent, by substituting the processing of virgin materials. Landfill gas capture, composting, anaerobic digestion, and incineration (gasification) will reduce emissions directly from landfills.

These analyses of the waste life cycle are essential due to the increased concern of managing solid waste on a global scale due to changing manufacturing methods, pollution, lifestyles, and urbanization. Developed nations, like Lahti Finland, have established solid legislative frameworks, efficient waste management administration, highly qualified human resources, and effective waste management technology. While wealthy nations have embraced integrative approaches and sustainable waste management technologies, developing nations, such as Pouso Alegre, Brazil, depend primarily on traditional solid waste management procedures.

An important turning point for Brazil's solid waste management is the National Solid Waste Policy. However, many issues around the collection, incorrect disposal, and waste treatment have not been resolved since 2010, the year it was approved. This illustrates how unstable the nation's current environmental laws, public policies, and environmental regulations are when it comes to their successful implementation.

Overall, waste collection in Pouso Alegre and Brazilian municipalities has a high percentage of coverage in urban areas. However, it needs to be improved in rural and sub-urban areas where the conventional collection system is ineffective. The selective collection needs to be improved and studied to become more effective, enhancing its scope and lowering costs, encouraging participation from collectors in this process, and society's involvement in separating organic and recyclable waste in their residences. Brazil has a strong business of informal waste picking, and it is an example of the need for strategies to include self-employed people in public selective collection policies. In addition to its environmental role, waste picking in Brazil is a source of employment and income for people without housing and a poorly educated population.

Regarding waste resources, such as composting and recycling, they are growing yearly in Brazil but at meager growth rates rather than what would have been expected after the implementation of the National Solid Waste Policy. The primary issues with this achievement are the recycling of items that some politicians believe are not economically viable and the management of organic materials, which are ignored while representing a significant portion of MSW production in Brazil. To complete this, in most Brazilian municipalities, the inadequate forms (dumps and controlled landfills) were expected to be closed by 2014. That waste would mainly be sent to sanitary landfills. This finding highlights the backwardness of public policies and thinking on solid waste management in Brazil, which is still focused on waste disposal, considering a technique that does not prioritize waste treatment and buries wealth from our consumption that could be reused and put into other uses.

The final but equally significant argument is the impact of environmental education on solid waste management, with Finland serving as an excellent model. Education for the circular economy in Finland begins in kindergarten, when children consider decreasing food waste and learn how to segregate waste properly, and continues through primary, secondary, and higher education. Along the process, students learn about materials, entrepreneurial activities, the definition of art, and how to apply personal skills and knowledge to drive change toward a circular economy society. But, in addition to theoretical knowledge, the Finnish people have firsthand experience with waste management daily in their houses and actively contribute to it. Furthermore, as all students know, practice is the best way to consolidate knowledge.

In conclusion, assessing the four scenarios underscores the critical importance of adhering to the waste hierarchy in MSW management. Prioritizing waste prevention and minimization at the source remains a priority. However, when waste generation is unavoidable, the subsequent focus should be on maximizing recycling and composting efforts, as these methods significantly reduce GHGs emissions and conserve resources.

The scenarios demonstrate that advanced waste treatment technologies, such as anaerobic digestion and incineration with energy recovery, are essential in managing residual waste effectively. Nonetheless, these technologies should be employed strategically, complementing rather than replacing robust recycling and composting programs. By adhering to the waste hierarchy, municipalities such as Pouso Alegre can achieve a more sustainable and environmentally responsible waste management system, reducing their carbon footprint and contributing to a circular economy. After all, in nature, nothing is lost; everything is created and transformed, and waste should follow the same principle.

4.3. Limitations and Recommendations for Future Works

Although the technological solutions and environmental advantages suggested in this work for GHG reductions, compared to other studies conducted in other nations, are in the same order of priority, following waste hierarchy principles. It is important to note that the results may vary depending on the municipality, country, and MSW composition. The municipality specificity can limit the ability to assume results across municipalities with different characteristics.

Hopefully, this work will inspire additional research and provide a framework for those in charge of controlling MSW, especially in Pouso Alegre. This work is expected to assist policy developers in connecting the MSW management strategy to its effects on greenhouse gas emissions and its consequent environmental impacts.

Along the same topic as this study, it would be interesting for future work to take a sociological approach to urban solid waste management. To gain a qualitative understanding of a developing country's obstacles when raising public awareness. Public awareness plays a crucial role in waste management for several reasons. Firstly, it helps to promote a transformation from irresponsible waste disposal to more sustainable and environmentally conscious waste practices.

People are more inclined to adopt responsible behavior when they understand the negative impacts of improper waste disposal on human health, the environment, and wildlife. In addition, it is vital to raise awareness among residents to promote the proper separation and recycling of waste. Often, people are unaware of the various types of waste and how to recycle or reuse them. Furthermore, when people have the knowledge and expertise to develop and implement policies addressing this issue, it will become more accessible. To begin with, no one will need to be convinced of its value because everyone is already aware of it. Second, half of the task will be completed because the population will contribute to reduced consumption and selected collecting. The primary focus would be on waste recovery and disposal technology.

A second study that could be done is to understand how waste management consortiums work in different nations, including the political and economic aspects apart from the GHGs calculations, and to evaluate their efficiency. In Brazil, the National Solid Waste Policy (PNRS) establishes regulations for public consortiums to expand management capacity and reduce collection, treatment, and disposal costs. Consortiums could maximize resource allocation and improve relationships among municipalities within an area, promoting regional identity. However, most Brazilian municipalities have not fully implemented this management system. It would be interesting to identify how the consortiums are working worldwide and identify patterns and possibilities for improvement with the analysis of GHG emissions.

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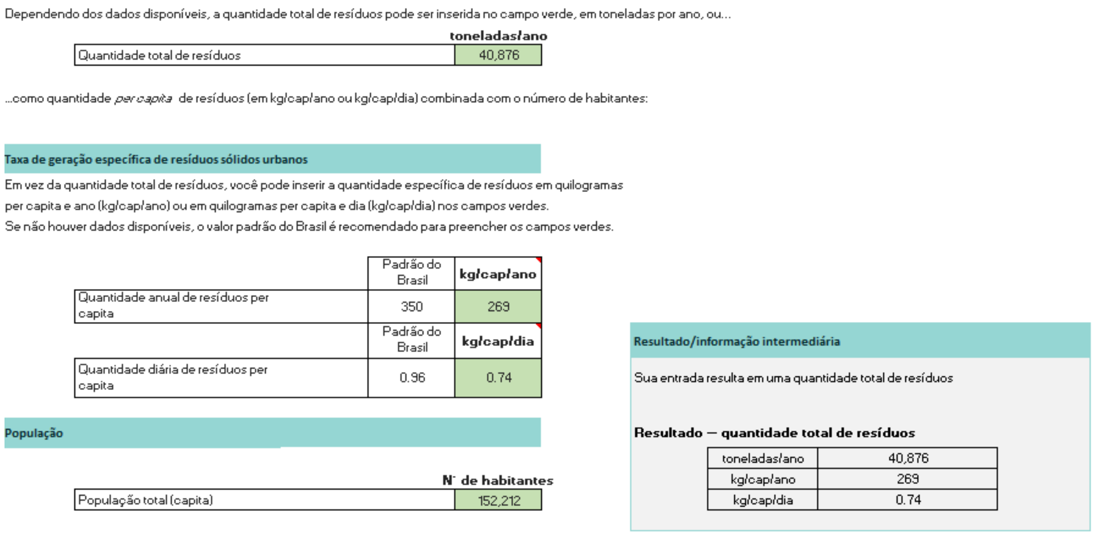
Appendix: IFEU Calculations



Dependendo dos dados disponíveis, a quantidade total de resíduos pode ser inserida no campo verde, em toneladas por ano, ou...

	toneladas/ano
Quantidade total de resíduos	40,876

...como quantidade *per capita* de resíduos (em kg/cap/ano ou kg/cap/dia) combinada com o número de habitantes:

Taxa de geração específica de resíduos sólidos urbanos

Em vez da quantidade total de resíduos, você pode inserir a quantidade específica de resíduos em quilogramas per capita e ano (kg/cap/ano) ou em quilogramas per capita e dia (kg/cap/dia) nos campos verdes.
Se não houver dados disponíveis, o valor padrão do Brasil é recomendado para preencher os campos verdes.

	Padrão do Brasil	**kg/cap/ano**
Quantidade anual de resíduos per capita	350	269
	Padrão do Brasil	**kg/cap/dia**
Quantidade diária de resíduos per capita	0.96	0.74

População

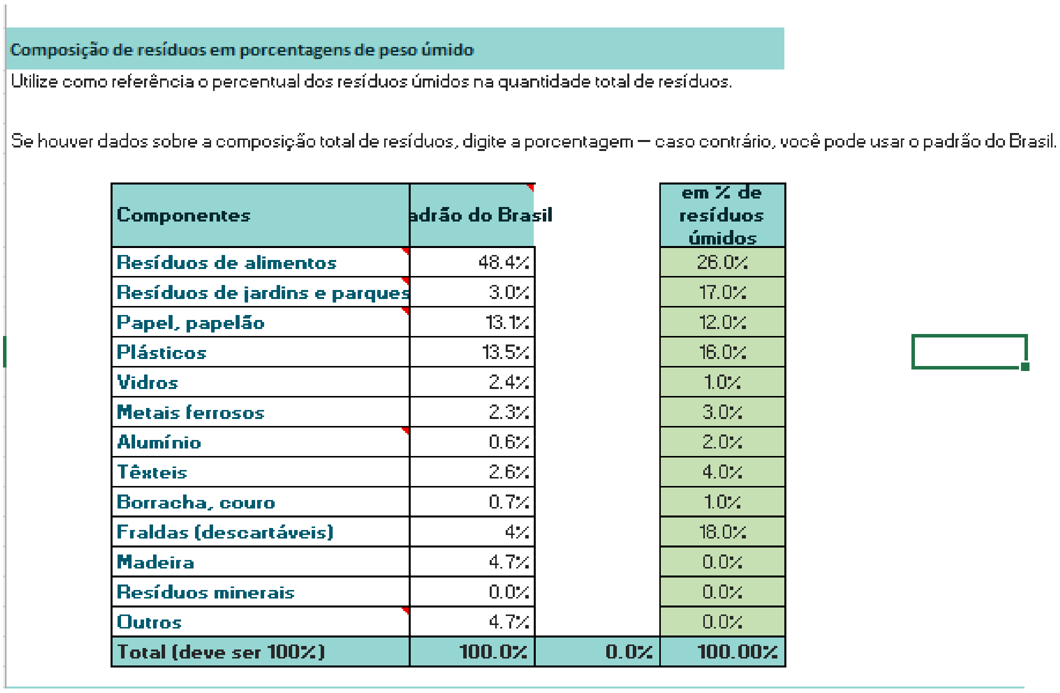
	N° de habitantes
População total (capita)	152,212

Resultado/informação intermediária

Sua entrada resulta em uma quantidade total de resíduos

Resultado — quantidade total de resíduos

toneladas/ano	40,876
kg/cap/ano	269
kg/cap/dia	0.74

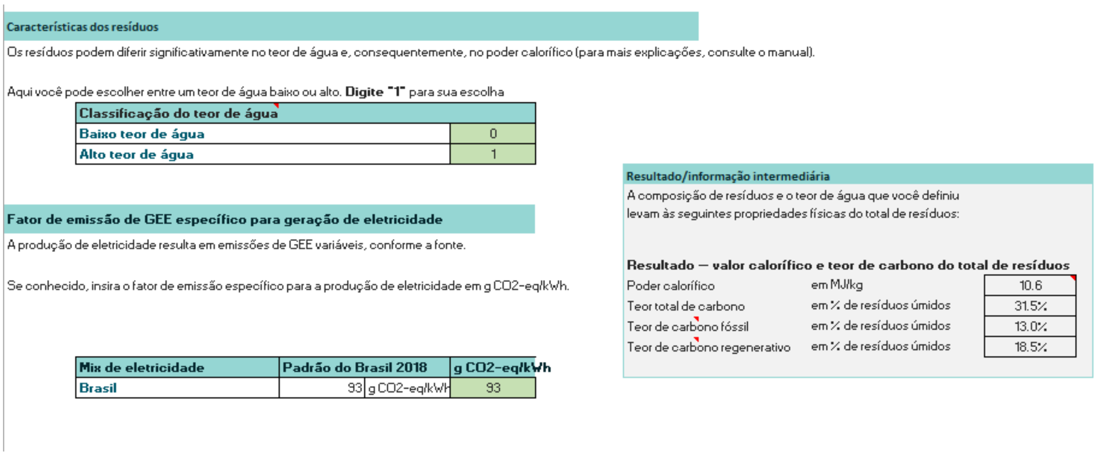


Composição de resíduos em porcentagens de peso úmido

Utilize como referência o percentual dos resíduos úmidos na quantidade total de resíduos.

Se houver dados sobre a composição total de resíduos, digite a porcentagem — caso contrário, você pode usar o padrão do Brasil.

Componentes	adrão do Brasil		em % de resíduos úmidos
Resíduos de alimentos	48.4%		26.0%
Resíduos de jardins e parques	3.0%		17.0%
Papel, papelão	13.1%		12.0%
Plásticos	13.5%		16.0%
Vidros	2.4%		1.0%
Metais ferrosos	2.3%		3.0%
Alumínio	0.6%		2.0%
Têxteis	2.6%		4.0%
Borracha, couro	0.7%		1.0%
Fraldas (descartáveis)	4%		18.0%
Madeira	4.7%		0.0%
Resíduos minerais	0.0%		0.0%
Outros	4.7%		0.0%
Total (deve ser 100%)	100.0%	0.0%	100.00%



Características dos resíduos

Os resíduos podem diferir significativamente no teor de água e, consequentemente, no poder calorífico (para mais explicações, consulte o manual).

Aqui você pode escolher entre um teor de água baixo ou alto. **Digite "1"** para sua escolha

Classificação do teor de água	
Baixo teor de água	0
Alto teor de água	1

Fator de emissão de GEE específico para geração de eletricidade

A produção de eletricidade resulta em emissões de GEE variáveis, conforme a fonte.

Se conhecido, insira o fator de emissão específico para a produção de eletricidade em g CO2-eq/kWh.

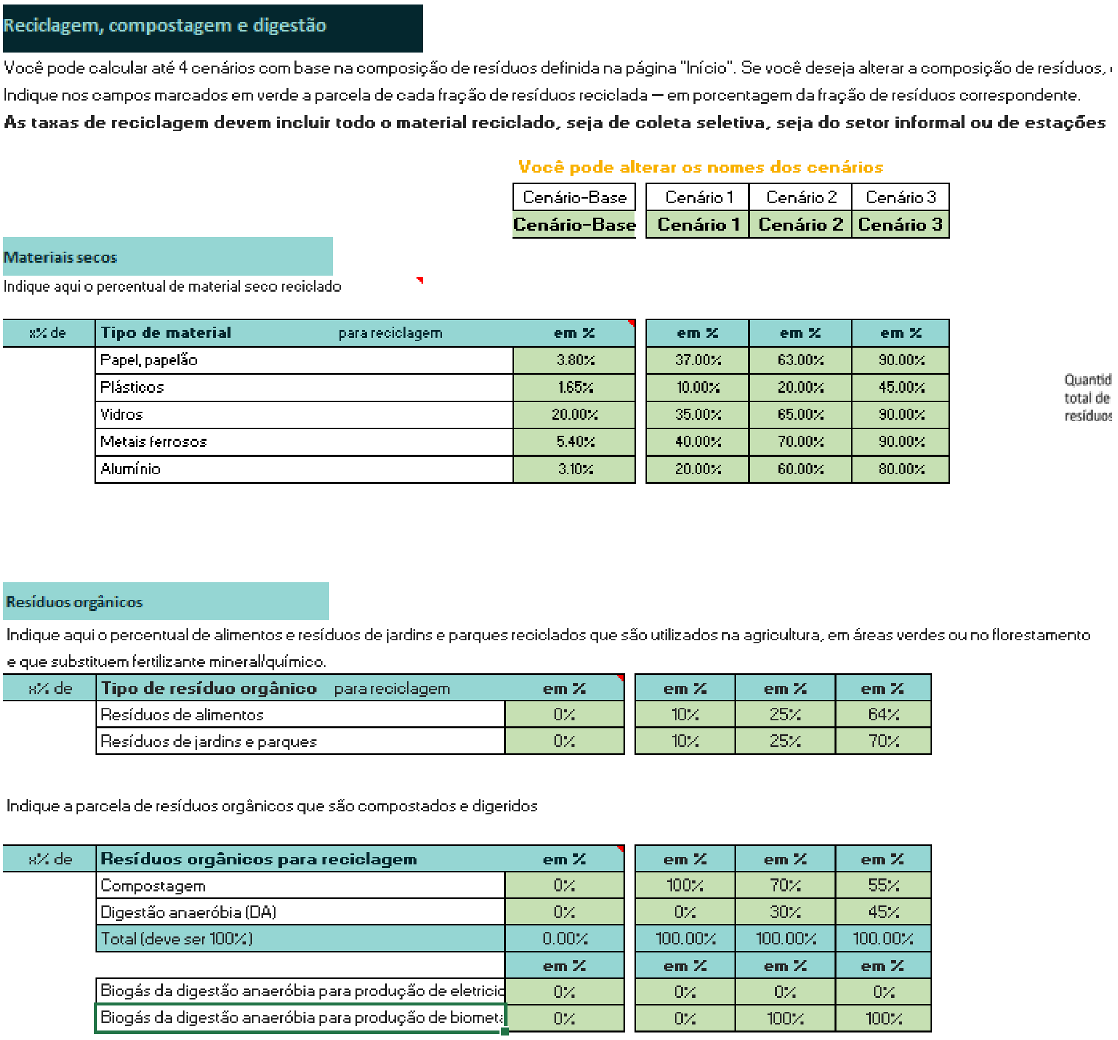
Mix de eletricidade	Padrão do Brasil 2018		g CO2-eq/kWh
Brasil	93	g CO2-eq/kWh	93

Resultado/informação intermediária

A composição de resíduos e o teor de água que você definiu levam às seguintes propriedades físicas do total de resíduos:

Resultado — valor calorífico e teor de carbono do total de resíduos		
Poder calorífico	em MJ/kg	10.6
Teor total de carbono	em % de resíduos úmidos	31.5%
Teor de carbono fóssil	em % de resíduos úmidos	13.0%
Teor de carbono regenerativo	em % de resíduos úmidos	18.5%

Recycling



Reciclagem, compostagem e digestão

Você pode calcular até 4 cenários com base na composição de resíduos definida na página "Início". Se você deseja alterar a composição de resíduos,

Indique nos campos marcados em verde a parcela de cada fração de resíduos reciclada – em porcentagem da fração de resíduos correspondente.

As taxas de reciclagem devem incluir todo o material reciclado, seja de coleta seletiva, seja do setor informal ou de estações

Você pode alterar os nomes dos cenários

Cenário-Base	Cenário 1	Cenário 2	Cenário 3
Cenário-Base	**Cenário 1**	**Cenário 2**	**Cenário 3**

Materiais secos

Indique aqui o percentual de material seco reciclado

x% de	**Tipo de material** para reciclagem	**em %**	**em %**	**em %**	**em %**
	Papel, papelão	3.80%	37.00%	63.00%	90.00%
	Plásticos	1.65%	10.00%	20.00%	45.00%
	Vidros	20.00%	35.00%	65.00%	90.00%
	Metais ferrosos	5.40%	40.00%	70.00%	90.00%
	Alumínio	3.10%	20.00%	60.00%	80.00%

Quantid
total de
resíduos

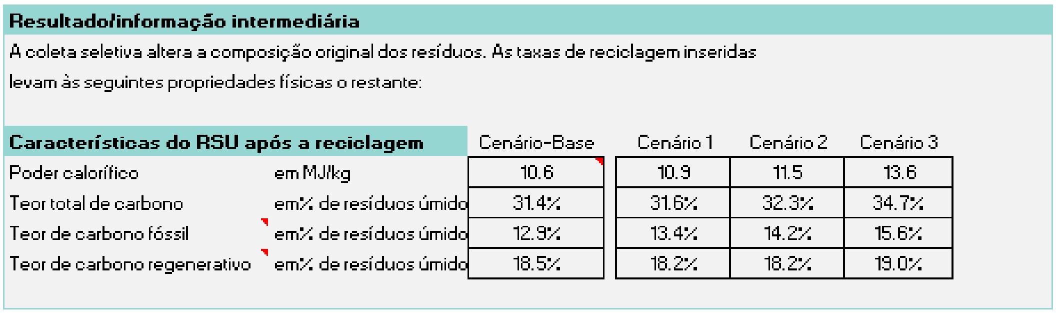
Resíduos orgânicos

Indique aqui o percentual de alimentos e resíduos de jardins e parques reciclados que são utilizados na agricultura, em áreas verdes ou no florestamento e que substituem fertilizante mineral/químico.

x% de	**Tipo de resíduo orgânico** para reciclagem	**em %**	**em %**	**em %**	**em %**
	Resíduos de alimentos	0%	10%	25%	64%
	Resíduos de jardins e parques	0%	10%	25%	70%

Indique a parcela de resíduos orgânicos que são compostados e digeridos

x% de	**Resíduos orgânicos para reciclagem**	**em %**	**em %**	**em %**	**em %**
	Compostagem	0%	100%	70%	55%
	Digestão anaeróbia (DA)	0%	0%	30%	45%
	Total (deve ser 100%)	0.00%	100.00%	100.00%	100.00%
		em %	**em %**	**em %**	**em %**
	Biogás da digestão anaeróbia para produção de eletricid	0%	0%	0%	0%
	Biogás da digestão anaeróbia para produção de biomet	0%	0%	100%	100%

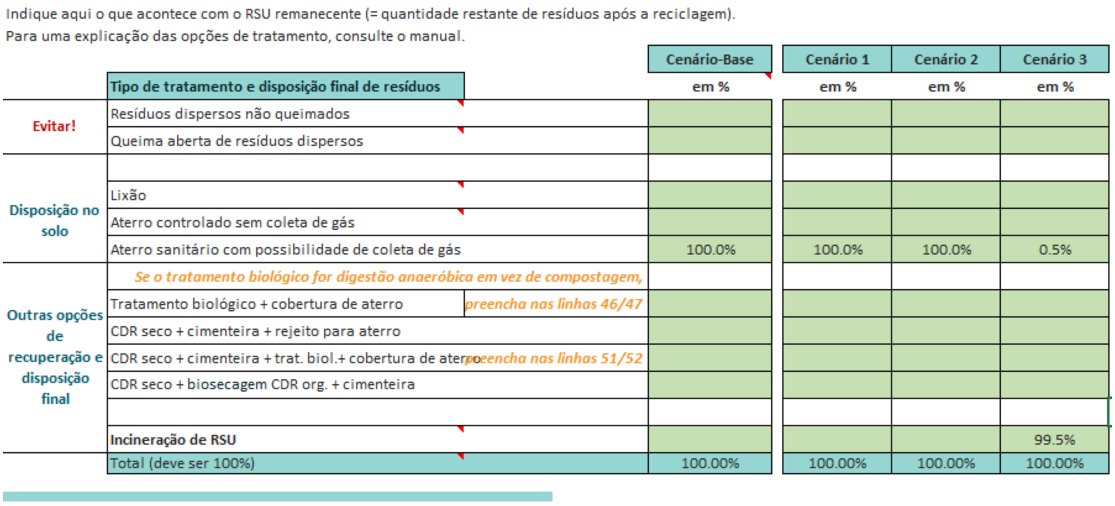


Resultado/informação intermediária

A coleta seletiva altera a composição original dos resíduos. As taxas de reciclagem inseridas levam às seguintes propriedades físicas o restante:

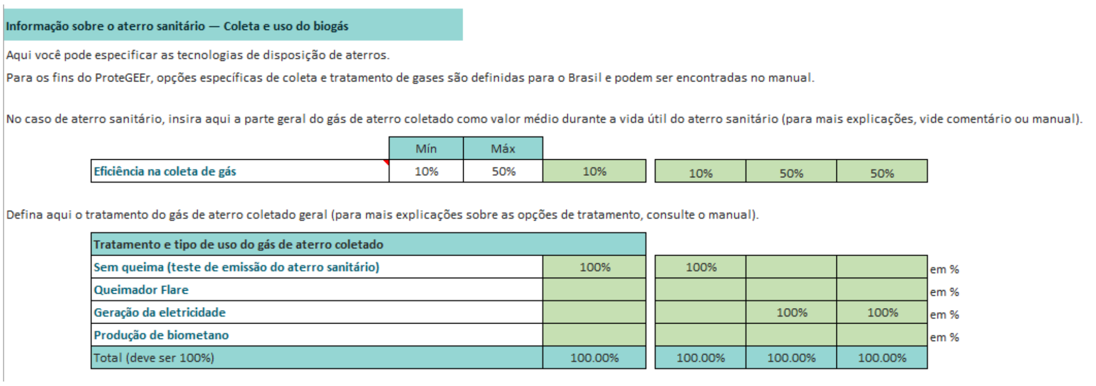
Características do RSU após a reciclagem		Cenário-Base	Cenário 1	Cenário 2	Cenário 3
Poder calorífico	em MJ/kg	10.6	10.9	11.5	13.6
Teor total de carbono	em% de resíduos úmido	31.4%	31.6%	32.3%	34.7%
Teor de carbono fóssil	em% de resíduos úmido	12.9%	13.4%	14.2%	15.6%
Teor de carbono regenerativo	em% de resíduos úmido	18.5%	18.2%	18.2%	19.0%

Disposal



Indique aqui o que acontece com o RSU remanecente (= quantidade restante de resíduos após a reciclagem).
Para uma explicação das opções de tratamento, consulte o manual.

			Cenário-Base	Cenário 1	Cenário 2	Cenário 3
	Tipo de tratamento e disposição final de resíduos		em %	em %	em %	em %
Evitar!	Resíduos dispersos não queimados					
	Queima aberta de resíduos dispersos					
Disposição no solo						
	Lixão					
	Aterro controlado sem coleta de gás					
	Aterro sanitário com possibilidade de coleta de gás		100.0%	100.0%	100.0%	0.5%
Outras opções de recuperação e disposição final	*Se o tratamento biológico for digestão anaeróbica em vez de compostagem,*					
	Tratamento biológico + cobertura de aterro	*preencha nas linhas 46/47*				
	CDR seco + cimenteira + rejeito para aterro					
	CDR seco + cimenteira + trat. biol.+ cobertura de aterro	*preencha nas linhas 51/52*				
	CDR seco + biosecagem CDR org. + cimenteira					
	Incineração de RSU					99.5%
	Total (deve ser 100%)		100.00%	100.00%	100.00%	100.00%



Informação sobre o aterro sanitário — Coleta e uso do biogás

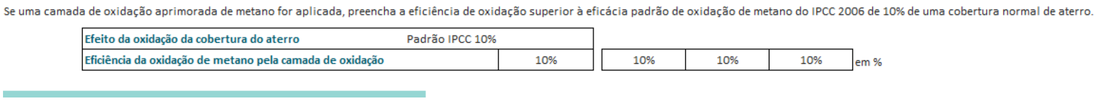
Aqui você pode especificar as tecnologias de disposição de aterros.
Para os fins do ProteGEEr, opções específicas de coleta e tratamento de gases são definidas para o Brasil e podem ser encontradas no manual.

No caso de aterro sanitário, insira aqui a parte geral do gás de aterro coletado como valor médio durante a vida útil do aterro sanitário (para mais explicações, vide comentário ou manual).

	Mín	Máx				
Eficiência na coleta de gás	10%	50%	10%	10%	50%	50%

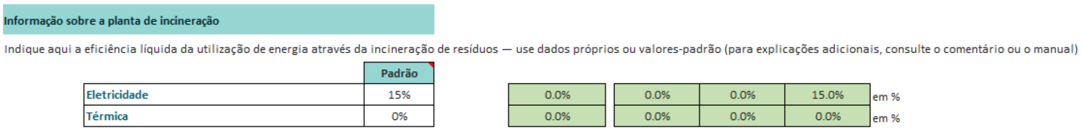
Defina aqui o tratamento do gás de aterro coletado geral (para mais explicações sobre as opções de tratamento, consulte o manual).

Tratamento e tipo de uso do gás de aterro coletado					
Sem queima (teste de emissão do aterro sanitário)	100%	100%			em %
Queimador Flare					em %
Geração da eletricidade			100%	100%	em %
Produção de biometano					em %
Total (deve ser 100%)	100.00%	100.00%	100.00%	100.00%	



Se uma camada de oxidação aprimorada de metano for aplicada, preencha a eficiência de oxidação superior à eficácia padrão de oxidação de metano do IPCC 2006 de 10% de uma cobertura normal de aterro.

Efeito da oxidação da cobertura do aterro	Padrão IPCC 10%				
Eficiência da oxidação de metano pela camada de oxidação	10%	10%	10%	10%	em %



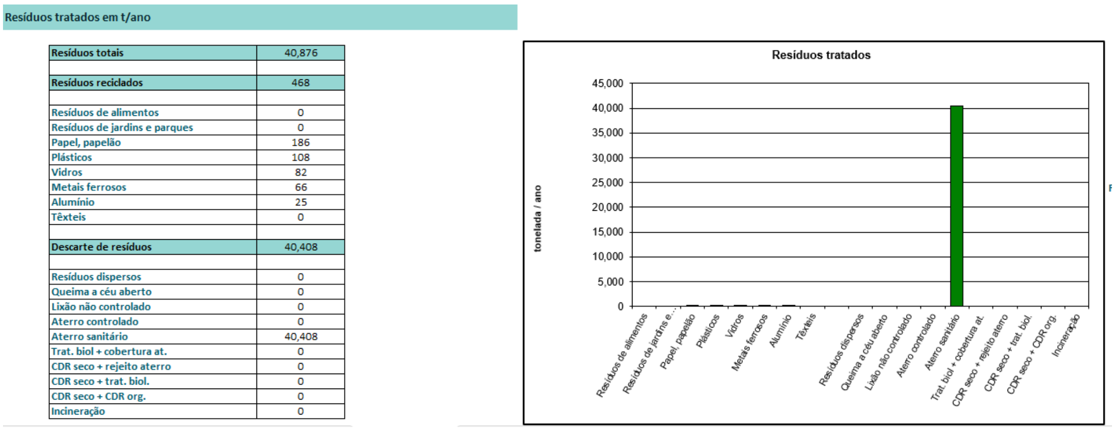
Informação sobre a planta de incineração

Indique aqui a eficiência líquida da utilização de energia através da incineração de resíduos — use dados próprios ou valores-padrão (para explicações adicionais, consulte o comentário ou o manual)

	Padrão					
Eletricidade	15%	0.0%	0.0%	0.0%	15.0%	em %
Térmica	0%	0.0%	0.0%	0.0%	0.0%	em %

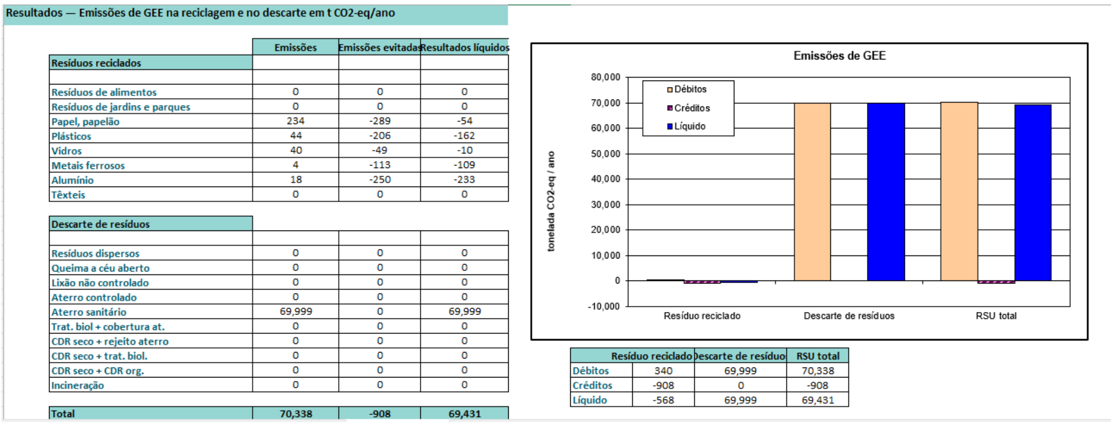
Results

BAU



Resíduos tratados em t/ano

Resíduos totais	40,876
Resíduos reciclados	468
Resíduos de alimentos	0
Resíduos de jardins e parques	0
Papel, papelão	186
Plásticos	108
Vidros	82
Metais ferrosos	66
Alumínio	25
Têxteis	0
Descarte de resíduos	40,408
Resíduos dispersos	0
Queima a céu aberto	0
Lixão não controlado	0
Aterro controlado	0
Aterro sanitário	40,408
Trat. biol + cobertura at.	0
CDR seco + rejeito aterro	0
CDR seco + trat. biol.	0
CDR seco + CDR org.	0
Incineração	0

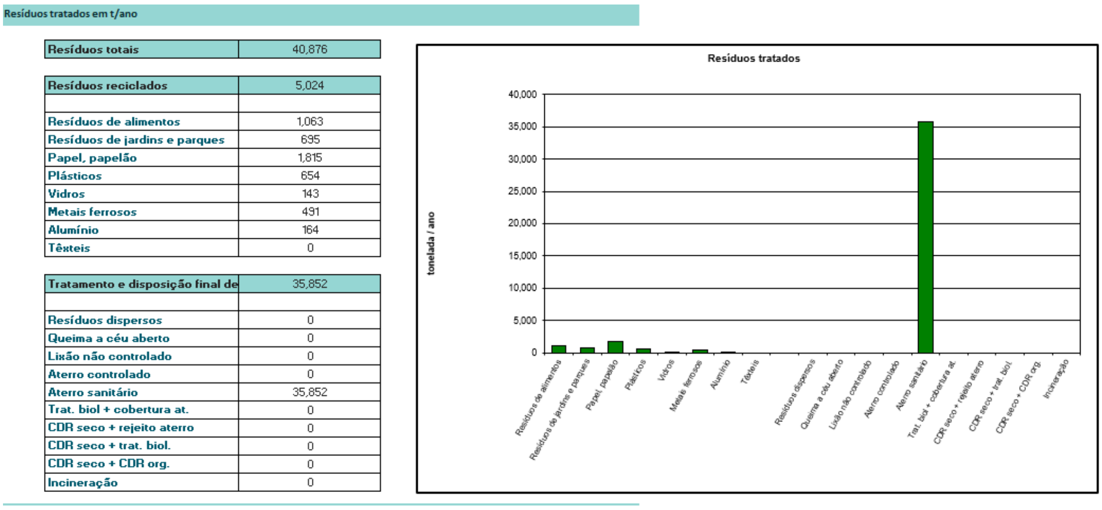


Resultados — Emissões de GEE na reciclagem e no descarte em t CO2-eq/ano

	Emissões	Emissões evitadas	Resultados líquidos
Resíduos reciclados			
Resíduos de alimentos	0	0	0
Resíduos de jardins e parques	0	0	0
Papel, papelão	234	-289	-54
Plásticos	44	-206	-162
Vidros	40	-49	-10
Metais ferrosos	4	-113	-109
Alumínio	18	-250	-233
Têxteis	0	0	0
Descarte de resíduos			
Resíduos dispersos	0	0	0
Queima a céu aberto	0	0	0
Lixão não controlado	0	0	0
Aterro controlado	0	0	0
Aterro sanitário	69,999	0	69,999
Trat. biol + cobertura at.	0	0	0
CDR seco + rejeito aterro	0	0	0
CDR seco + trat. biol.	0	0	0
CDR seco + CDR org.	0	0	0
Incineração	0	0	0
Total	**70,338**	**-908**	**69,431**

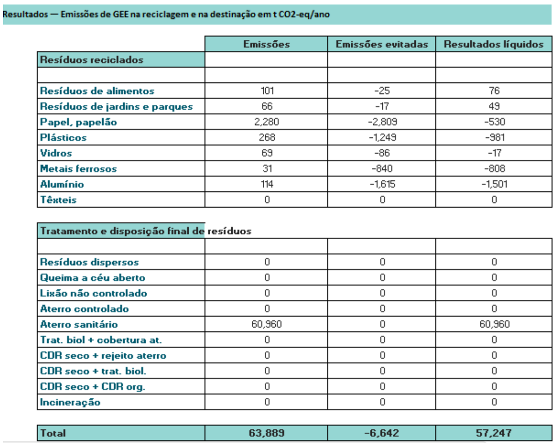
	Resíduo reciclado	escarte de resíduo	RSU total
Débitos	340	69,999	70,338
Créditos	-908	0	-908
Líquido	-568	69,999	69,431

First Cenario



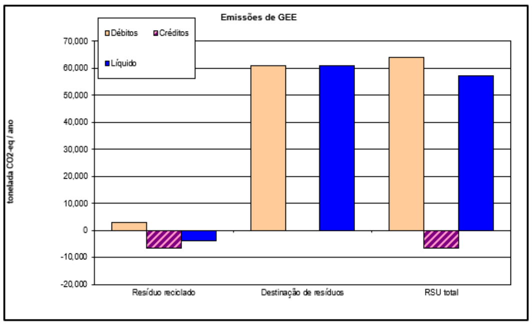
Resíduos tratados em t/ano

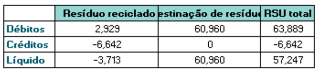
Resíduos totais	40,876
Resíduos reciclados	5,024
Resíduos de alimentos	1,063
Resíduos de jardins e parques	695
Papel, papelão	1,815
Plásticos	654
Vidros	143
Metais ferrosos	491
Alumínio	164
Têxteis	0
Tratamento e disposição final de	35,852
Resíduos dispersos	0
Queima a céu aberto	0
Lixão não controlado	0
Aterro controlado	0
Aterro sanitário	35,852
Trat. biol + cobertura at.	0
CDR seco + rejeito aterro	0
CDR seco + trat. biol.	0
CDR seco + CDR org.	0
Incineração	0



Resultados — Emissões de GEE na reciclagem e na destinação em t CO2-eq/ano

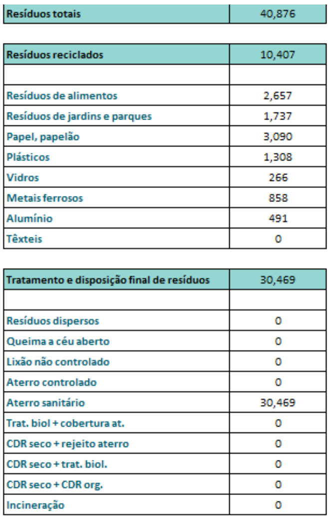
	Emissões	Emissões evitadas	Resultados líquidos
Resíduos reciclados			
Resíduos de alimentos	101	-25	76
Resíduos de jardins e parques	66	-17	49
Papel, papelão	2,280	-2,809	-530
Plásticos	268	-1,249	-981
Vidros	69	-86	-17
Metais ferrosos	31	-840	-808
Alumínio	114	-1,615	-1,501
Têxteis	0	0	0
Tratamento e disposição final de resíduos			
Resíduos dispersos	0	0	0
Queima a céu aberto	0	0	0
Lixão não controlado	0	0	0
Aterro controlado	0	0	0
Aterro sanitário	60,960	0	60,960
Trat. biol + cobertura at.	0	0	0
CDR seco + rejeito aterro	0	0	0
CDR seco + trat. biol.	0	0	0
CDR seco + CDR org.	0	0	0
Incineração	0	0	0
Total	**63,889**	**-6,642**	**57,247**



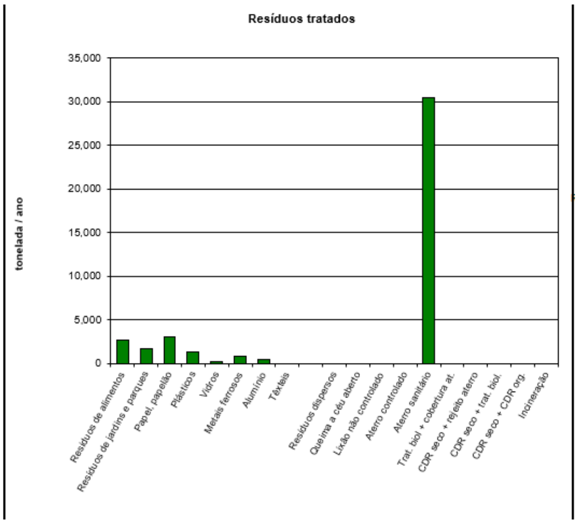


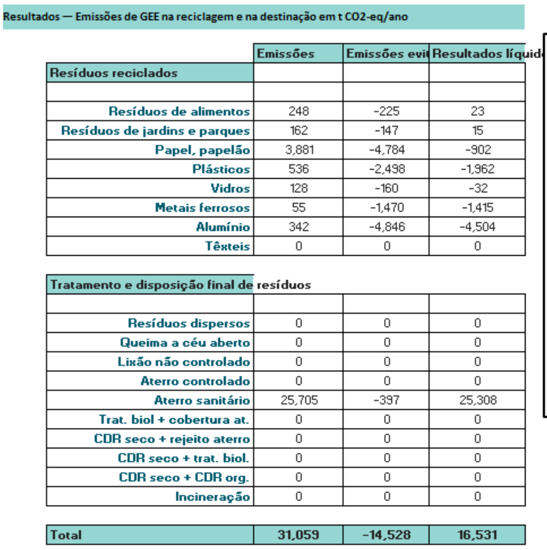
	Resíduo reciclado	estinação de resídu	RSU total
Débitos	2,929	60,960	63,889
Créditos	-6,642	0	-6,642
Líquido	-3,713	60,960	57,247

Second Scenario



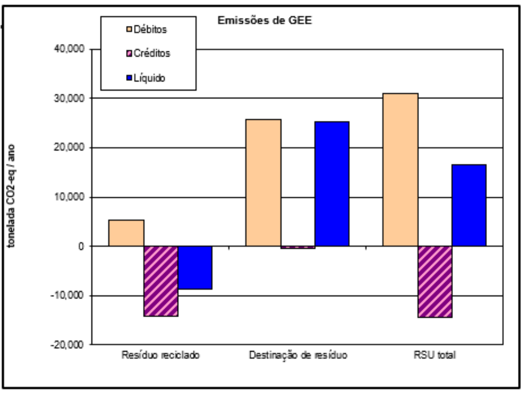
Resíduos totais	40,876
Resíduos reciclados	10,407
Resíduos de alimentos	2,657
Resíduos de jardins e parques	1,737
Papel, papelão	3,090
Plásticos	1,308
Vidros	266
Metais ferrosos	858
Alumínio	491
Têxteis	0
Tratamento e disposição final de resíduos	30,469
Resíduos dispersos	0
Queima a céu aberto	0
Lixão não controlado	0
Aterro controlado	0
Aterro sanitário	30,469
Trat. biol + cobertura at.	0
CDR seco + rejeito aterro	0
CDR seco + trat. biol.	0
CDR seco + CDR org.	0
Incineração	0





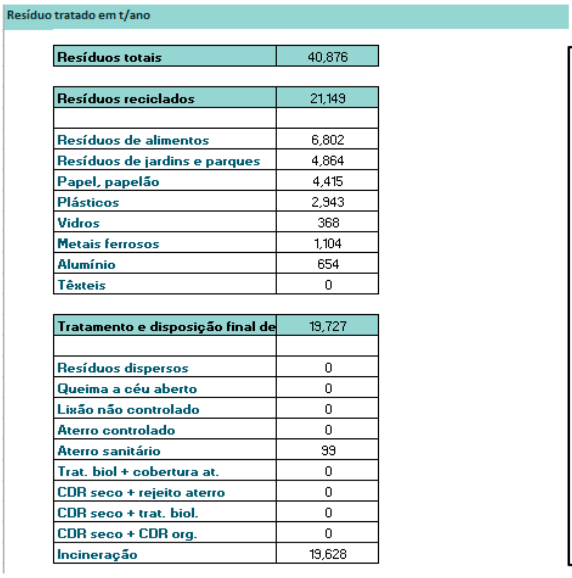
Resultados — Emissões de GEE na reciclagem e na destinação em t CO2-eq/ano

	Emissões	Emissões evit	Resultados líquid
Resíduos reciclados			
Resíduos de alimentos	248	-225	23
Resíduos de jardins e parques	162	-147	15
Papel, papelão	3,881	-4,784	-902
Plásticos	536	-2,498	-1,962
Vidros	128	-160	-32
Metais ferrosos	55	-1,470	-1,415
Alumínio	342	-4,846	-4,504
Têxteis	0	0	0
Tratamento e disposição final de resíduos			
Resíduos dispersos	0	0	0
Queima a céu aberto	0	0	0
Lixão não controlado	0	0	0
Aterro controlado	0	0	0
Aterro sanitário	25,705	-397	25,308
Trat. biol + cobertura at.	0	0	0
CDR seco + rejeito aterro	0	0	0
CDR seco + trat. biol.	0	0	0
CDR seco + CDR org.	0	0	0
Incineração	0	0	0
Total	**31,059**	**-14,528**	**16,531**



	Resíduo reciclado	stinação de resíd	RSU total
Débitos	5,354	25,705	31,059
Créditos	-14,131	-397	-14,528
Líquido	-8,777	25,308	16,531

Lahti Ideal Scenario

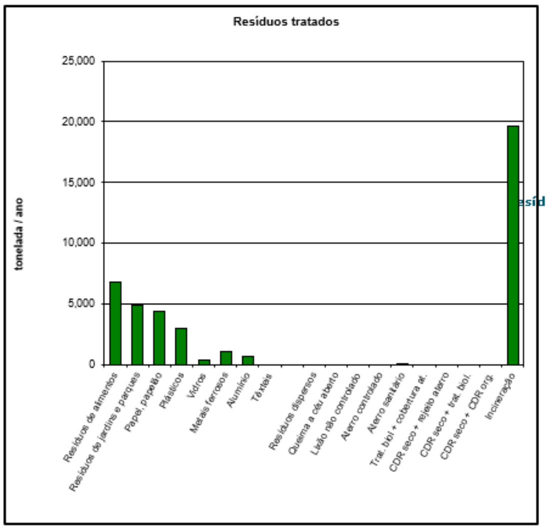


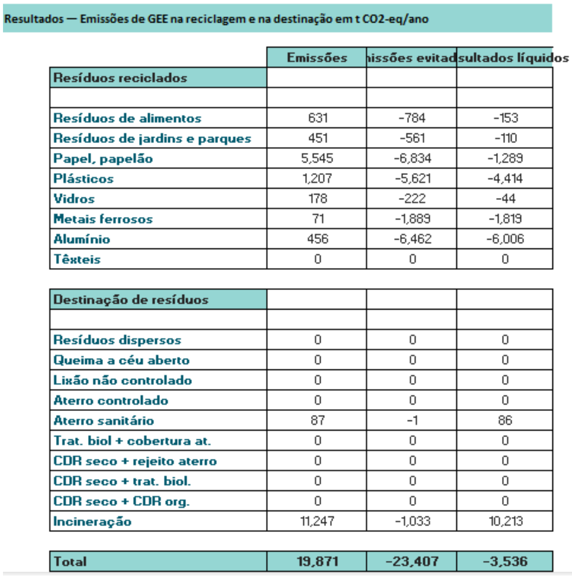
Resíduo tratado em t/ano

Resíduos totais	40,876

Resíduos reciclados	21,149
Resíduos de alimentos	6,802
Resíduos de jardins e parques	4,864
Papel, papelão	4,415
Plásticos	2,943
Vidros	368
Metais ferrosos	1,104
Alumínio	654
Têxteis	0

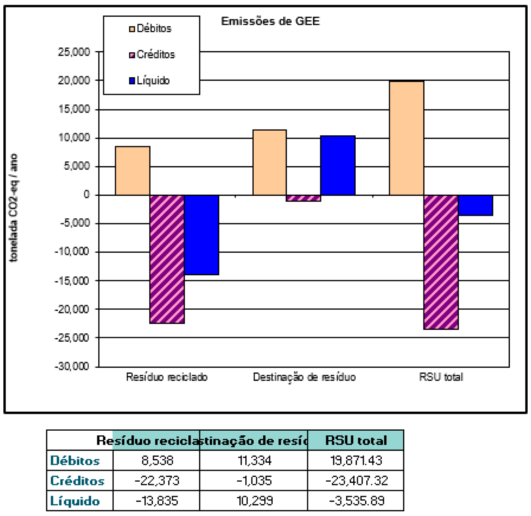
Tratamento e disposição final de	19,727
Resíduos dispersos	0
Queima a céu aberto	0
Lixão não controlado	0
Aterro controlado	0
Aterro sanitário	99
Trat. biol + cobertura at.	0
CDR seco + rejeito aterro	0
CDR seco + trat. biol.	0
CDR seco + CDR org.	0
Incineração	19,628





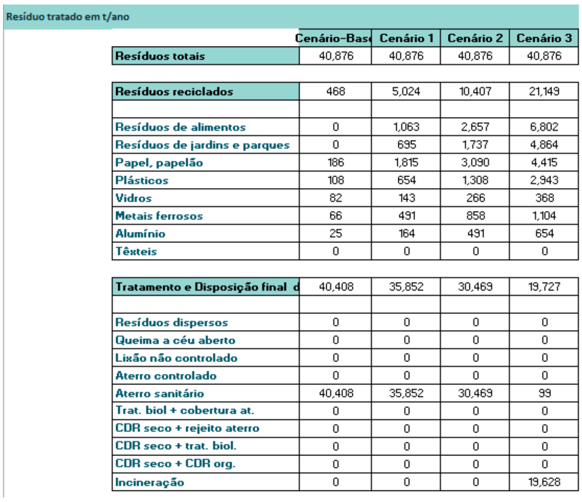
Resultados — Emissões de GEE na reciclagem e na destinação em t CO2-eq/ano

	Emissões	missões evitad	sultados líquidos
Resíduos reciclados			
Resíduos de alimentos	631	-784	-153
Resíduos de jardins e parques	451	-561	-110
Papel, papelão	5,545	-6,834	-1,289
Plásticos	1,207	-5,621	-4,414
Vidros	178	-222	-44
Metais ferrosos	71	-1,889	-1,819
Alumínio	456	-6,462	-6,006
Têxteis	0	0	0
Destinação de resíduos			
Resíduos dispersos	0	0	0
Queima a céu aberto	0	0	0
Lixão não controlado	0	0	0
Aterro controlado	0	0	0
Aterro sanitário	87	-1	86
Trat. biol + cobertura at.	0	0	0
CDR seco + rejeito aterro	0	0	0
CDR seco + trat. biol.	0	0	0
CDR seco + CDR org.	0	0	0
Incineração	11,247	-1,033	10,213
Total	**19,871**	**-23,407**	**-3,536**



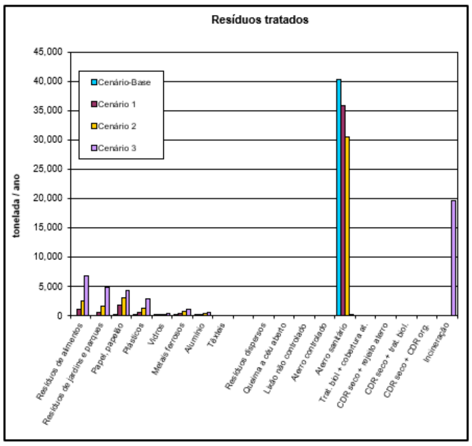
	Resíduo recicla	stinação de resíd	RSU total
Débitos	8,538	11,334	19,871.43
Créditos	-22,373	-1,035	-23,407.32
Líquido	-13,835	10,299	-3,535.89

All Results

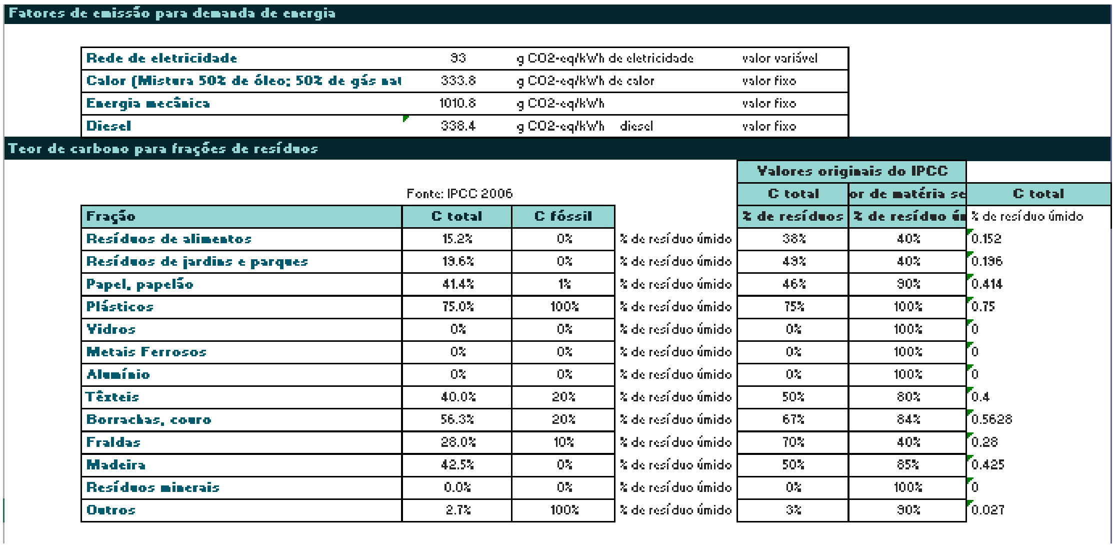


Resíduo tratado em t/ano

	Cenário-Bas	Cenário 1	Cenário 2	Cenário 3
Resíduos totais	40,876	40,876	40,876	40,876
Resíduos reciclados	468	5,024	10,407	21,149
Resíduos de alimentos	0	1,063	2,657	6,802
Resíduos de jardins e parques	0	695	1,737	4,864
Papel, papelão	186	1,815	3,090	4,415
Plásticos	108	654	1,308	2,943
Vidros	82	143	266	368
Metais ferrosos	66	491	858	1,104
Alumínio	25	164	491	654
Têxteis	0	0	0	0
Tratamento e Disposição final d	40,408	35,852	30,469	19,727
Resíduos dispersos	0	0	0	0
Queima a céu aberto	0	0	0	0
Lixão não controlado	0	0	0	0
Aterro controlado	0	0	0	0
Aterro sanitário	40,408	35,852	30,469	99
Trat. biol + cobertura at.	0	0	0	0
CDR seco + rejeito aterro	0	0	0	0
CDR seco + trat. biol.	0	0	0	0
CDR seco + CDR org.	0	0	0	0
Incineração	0	0	0	19,628



Calculations

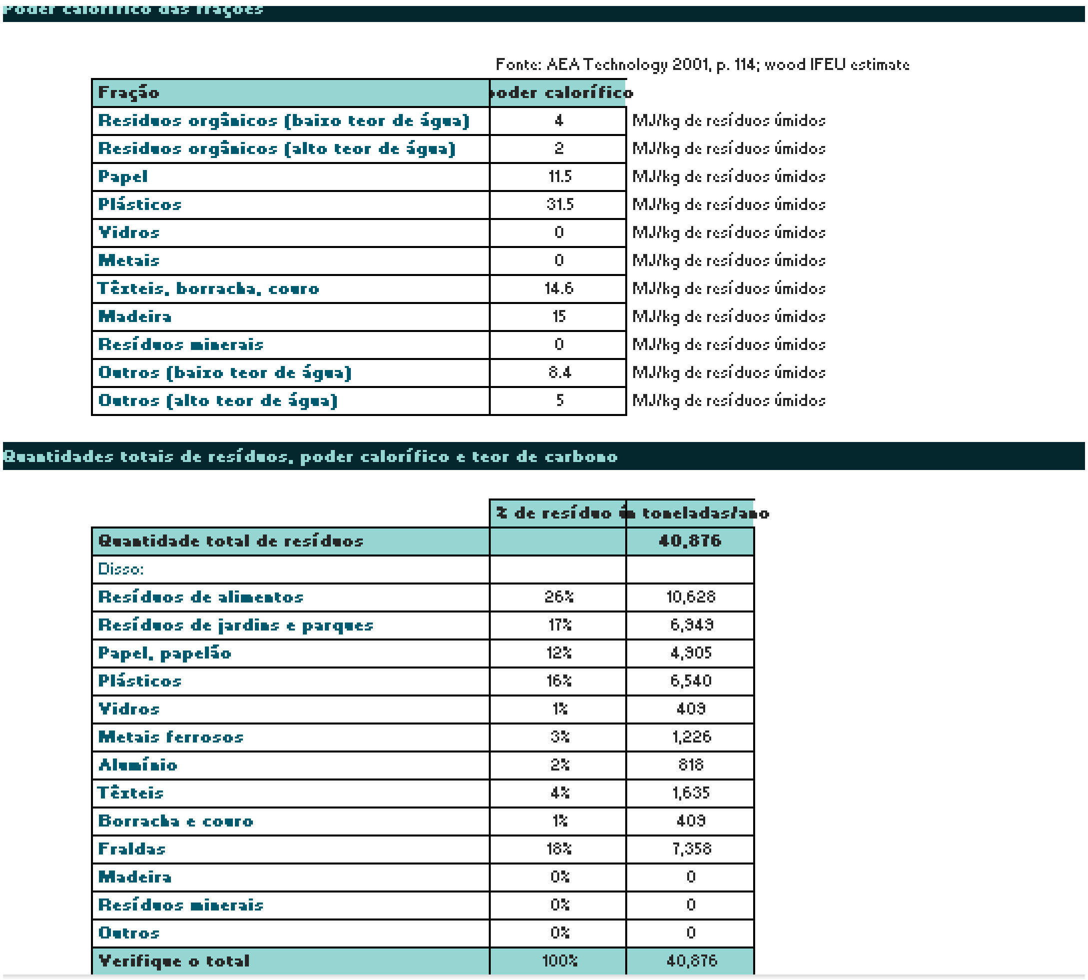


Fatores de emissão para demanda de energia

Rede de eletricidade	93	g CO2-eq/kWh de eletricidade	valor variável
Calor (Mistura 50% de óleo; 50% de gás nat	333.8	g CO2-eq/kWh de calor	valor fixo
Energia mecânica	1010.8	g CO2-eq/kWh	valor fixo
Diesel	338.4	g CO2-eq/kWh diesel	valor fixo

Teor de carbono para frações de resíduos

				Valores originais do IPCC		
	Fonte: IPCC 2006			C total	or de matéria se	C total
Fração	**C total**	**C fóssil**		**% de resíduos**	**% de resíduo ú**	% de resíduo úmido
Resíduos de alimentos	15.2%	0%	% de resíduo úmido	38%	40%	0.152
Resíduos de jardins e parques	19.6%	0%	% de resíduo úmido	49%	40%	0.196
Papel, papelão	41.4%	1%	% de resíduo úmido	46%	90%	0.414
Plásticos	75.0%	100%	% de resíduo úmido	75%	100%	0.75
Vidros	0%	0%	% de resíduo úmido	0%	100%	0
Metais Ferrosos	0%	0%	% de resíduo úmido	0%	100%	0
Alumínio	0%	0%	% de resíduo úmido	0%	100%	0
Têxteis	40.0%	20%	% de resíduo úmido	50%	80%	0.4
Borrachas, couro	56.3%	20%	% de resíduo úmido	67%	84%	0.5628
Fraldas	28.0%	10%	% de resíduo úmido	70%	40%	0.28
Madeira	42.5%	0%	% de resíduo úmido	50%	85%	0.425
Resíduos minerais	0.0%	0%	% de resíduo úmido	0%	100%	0
Outros	2.7%	100%	% de resíduo úmido	3%	90%	0.027



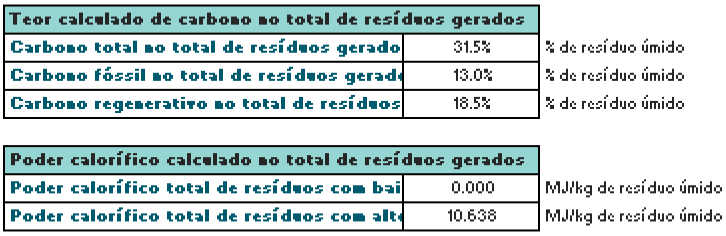
Poder calorífico das frações

Fonte: AEA Technology 2001, p. 114; wood IFEU estimate

Fração	oder calorífico	
Residuos orgânicos (baixo teor de água)	4	MJ/kg de resíduos úmidos
Residuos orgânicos (alto teor de água)	2	MJ/kg de resíduos úmidos
Papel	11.5	MJ/kg de resíduos úmidos
Plásticos	31.5	MJ/kg de resíduos úmidos
Vidros	0	MJ/kg de resíduos úmidos
Metais	0	MJ/kg de resíduos úmidos
Têxteis, borracha, couro	14.6	MJ/kg de resíduos úmidos
Madeira	15	MJ/kg de resíduos úmidos
Resíduos minerais	0	MJ/kg de resíduos úmidos
Outros (baixo teor de água)	8.4	MJ/kg de resíduos úmidos
Outros (alto teor de água)	5	MJ/kg de resíduos úmidos

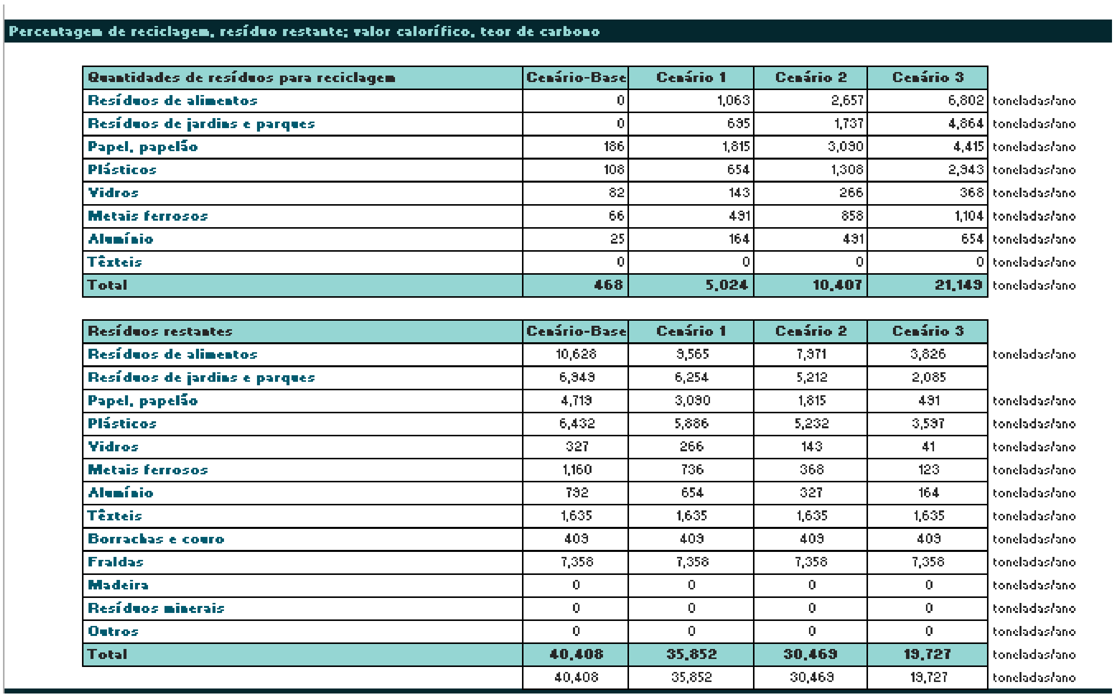
Quantidades totais de resíduos, poder calorífico e teor de carbono

	% de resíduo ú	toneladas/ano
Quantidade total de resíduos		40,876
Disso:		
Resíduos de alimentos	26%	10,628
Resíduos de jardins e parques	17%	6,949
Papel, papelão	12%	4,905
Plásticos	16%	6,540
Vidros	1%	409
Metais ferrosos	3%	1,226
Alumínio	2%	818
Têxteis	4%	1,635
Borracha e couro	1%	409
Fraldas	18%	7,358
Madeira	0%	0
Resíduos minerais	0%	0
Outros	0%	0
Verifique o total	100%	40,876



Teor calculado de carbono no total de resíduos gerados		
Carbono total no total de resíduos gerado	31.5%	% de resíduo úmido
Carbono fóssil no total de resíduos gerad	13.0%	% de resíduo úmido
Carbono regenerativo no total de resíduos	18.5%	% de resíduo úmido

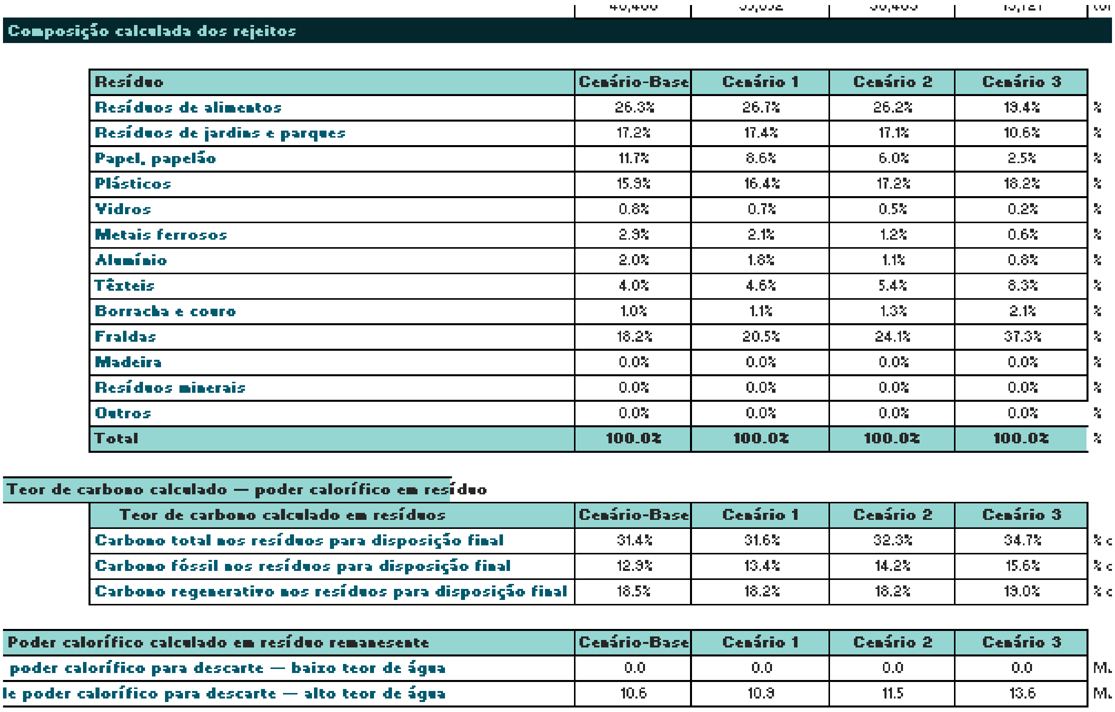
Poder calorífico calculado no total de resíduos gerados		
Poder calorífico total de resíduos com bai	0.000	MJ/kg de resíduo úmido
Poder calorífico total de resíduos com alt	10.638	MJ/kg de resíduo úmido



Percentagem de reciclagem, resíduo restante; valor calorífico, teor de carbono

Quantidades de resíduos para reciclagem	Cenário-Base	Cenário 1	Cenário 2	Cenário 3	
Resíduos de alimentos	0	1,063	2,657	6,802	toneladas/ano
Resíduos de jardins e parques	0	695	1,737	4,864	toneladas/ano
Papel, papelão	186	1,815	3,090	4,415	toneladas/ano
Plásticos	108	654	1,308	2,943	toneladas/ano
Vidros	82	143	266	368	toneladas/ano
Metais ferrosos	66	491	858	1,104	toneladas/ano
Alumínio	25	164	491	654	toneladas/ano
Têxteis	0	0	0	0	toneladas/ano
Total	**468**	**5,024**	**10,407**	**21,149**	toneladas/ano

Resíduos restantes	Cenário-Base	Cenário 1	Cenário 2	Cenário 3	
Resíduos de alimentos	10,628	9,565	7,371	3,826	toneladas/ano
Resíduos de jardins e parques	6,949	6,254	5,212	2,085	
Papel, papelão	4,719	3,090	1,815	491	toneladas/ano
Plásticos	6,432	5,886	5,232	3,597	toneladas/ano
Vidros	327	266	143	41	toneladas/ano
Metais ferrosos	1,160	736	368	123	toneladas/ano
Alumínio	792	654	327	164	toneladas/ano
Têxteis	1,635	1,635	1,635	1,635	toneladas/ano
Borrachas e couro	409	409	409	409	toneladas/ano
Fraldas	7,358	7,358	7,358	7,358	toneladas/ano
Madeira	0	0	0	0	toneladas/ano
Resíduos minerais	0	0	0	0	toneladas/ano
Outros	0	0	0	0	toneladas/ano
Total	**40,408**	**35,852**	**30,469**	**19,727**	toneladas/ano
	40,408	35,852	30,469	19,727	toneladas/ano



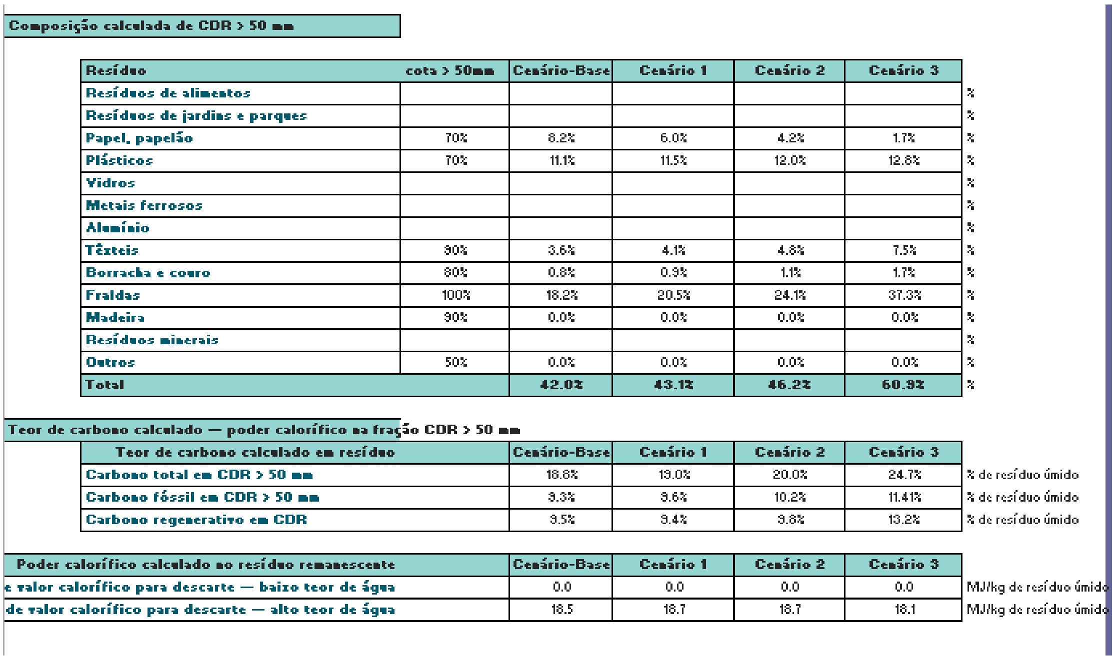
Composição calculada dos rejeitos

Resíduo	Cenário-Base	Cenário 1	Cenário 2	Cenário 3	
Resíduos de alimentos	26.3%	26.7%	26.2%	19.4%	%
Resíduos de jardins e parques	17.2%	17.4%	17.1%	10.6%	%
Papel, papelão	11.7%	8.6%	6.0%	2.5%	%
Plásticos	15.9%	16.4%	17.2%	18.2%	%
Vidros	0.8%	0.7%	0.5%	0.2%	%
Metais ferrosos	2.9%	2.1%	1.2%	0.6%	%
Alumínio	2.0%	1.8%	1.1%	0.8%	%
Têxteis	4.0%	4.6%	5.4%	8.3%	%
Borracha e couro	1.0%	1.1%	1.3%	2.1%	%
Fraldas	18.2%	20.5%	24.1%	37.3%	%
Madeira	0.0%	0.0%	0.0%	0.0%	%
Resíduos minerais	0.0%	0.0%	0.0%	0.0%	%
Outros	0.0%	0.0%	0.0%	0.0%	%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**	%

Teor de carbono calculado — poder calorífico em resíduo

Teor de carbono calculado em resíduos	Cenário-Base	Cenário 1	Cenário 2	Cenário 3	
Carbono total nos resíduos para disposição final	31.4%	31.6%	32.3%	34.7%	% c
Carbono fóssil nos resíduos para disposição final	12.9%	13.4%	14.2%	15.6%	% c
Carbono regenerativo nos resíduos para disposição final	18.5%	18.2%	18.2%	19.0%	% c

Poder calorífico calculado em resíduo remanesente	Cenário-Base	Cenário 1	Cenário 2	Cenário 3	
poder calorífico para descarte — baixo teor de água	0.0	0.0	0.0	0.0	M.
le poder calorífico para descarte — alto teor de água	10.6	10.9	11.5	13.6	M.



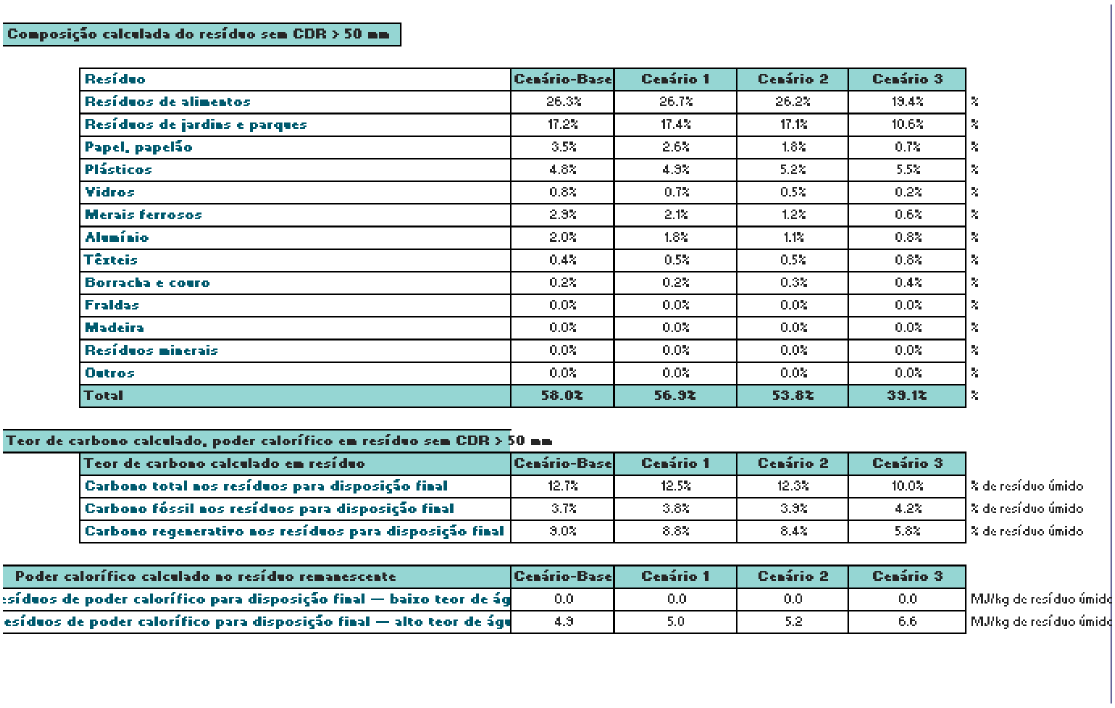
Composição calculada de CDR > 50 mm

Resíduo	cota > 50mm	Cenário-Base	Cenário 1	Cenário 2	Cenário 3	
Resíduos de alimentos						%
Resíduos de jardins e parques						%
Papel, papelão	70%	8.2%	6.0%	4.2%	1.7%	%
Plásticos	70%	11.1%	11.5%	12.0%	12.8%	%
Vidros						%
Metais ferrosos						%
Alumínio						%
Têxteis	90%	3.6%	4.1%	4.8%	7.5%	%
Borracha e couro	80%	0.8%	0.9%	1.1%	1.7%	%
Fraldas	100%	18.2%	20.5%	24.1%	37.3%	%
Madeira	90%	0.0%	0.0%	0.0%	0.0%	%
Resíduos minerais						%
Outros	50%	0.0%	0.0%	0.0%	0.0%	%
Total		**42.0%**	**43.1%**	**46.2%**	**60.9%**	%

Teor de carbono calculado — poder calorífico na fração CDR > 50 mm

Teor de carbono calculado em resíduo	Cenário-Base	Cenário 1	Cenário 2	Cenário 3	
Carbono total em CDR > 50 mm	18.8%	19.0%	20.0%	24.7%	% de resíduo úmido
Carbono fóssil em CDR > 50 mm	9.3%	9.6%	10.2%	11.41%	% de resíduo úmido
Carbono regenerativo em CDR	9.5%	9.4%	9.8%	13.2%	% de resíduo úmido

Poder calorífico calculado no resíduo remanescente	Cenário-Base	Cenário 1	Cenário 2	Cenário 3	
e valor calorífico para descarte — baixo teor de água	0.0	0.0	0.0	0.0	MJ/kg de resíduo úmido
de valor calorífico para descarte — alto teor de água	18.5	18.7	18.7	18.1	MJ/kg de resíduo úmido



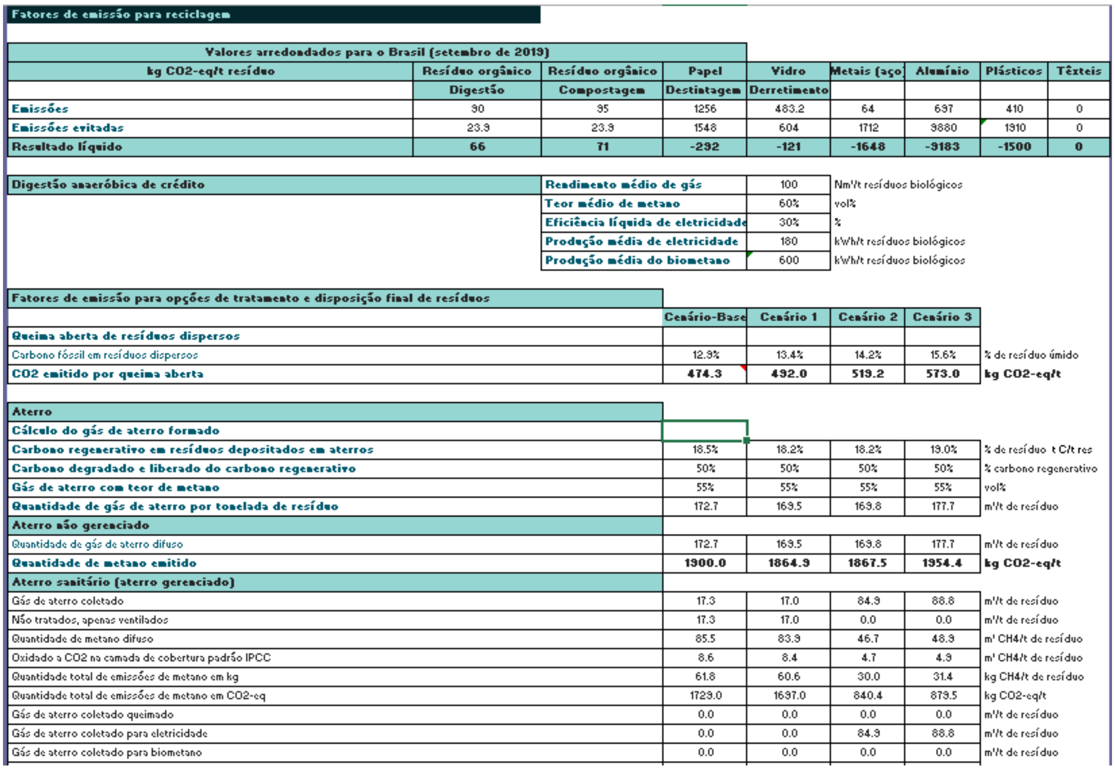
Composição calculada do resíduo sem CDR > 50 mm

Resíduo	Cenário-Base	Cenário 1	Cenário 2	Cenário 3	
Resíduos de alimentos	26.3%	26.7%	26.2%	19.4%	%
Resíduos de jardins e parques	17.2%	17.4%	17.1%	10.6%	%
Papel, papelão	3.5%	2.6%	1.8%	0.7%	%
Plásticos	4.8%	4.9%	5.2%	5.5%	%
Vidros	0.8%	0.7%	0.5%	0.2%	%
Merais ferrosos	2.9%	2.1%	1.2%	0.6%	%
Alumínio	2.0%	1.8%	1.1%	0.8%	%
Têxteis	0.4%	0.5%	0.5%	0.8%	%
Borracha e couro	0.2%	0.2%	0.3%	0.4%	%
Fraldas	0.0%	0.0%	0.0%	0.0%	%
Madeira	0.0%	0.0%	0.0%	0.0%	%
Resíduos minerais	0.0%	0.0%	0.0%	0.0%	%
Outros	0.0%	0.0%	0.0%	0.0%	%
Total	**58.0%**	**56.9%**	**53.8%**	**39.1%**	%

Teor de carbono calculado, poder calorífico em resíduo sem CDR > 50 mm

Teor de carbono calculado em resíduo	Cenário-Base	Cenário 1	Cenário 2	Cenário 3	
Carbono total nos resíduos para disposição final	12.7%	12.5%	12.3%	10.0%	% de resíduo úmido
Carbono fóssil nos resíduos para disposição final	3.7%	3.8%	3.9%	4.2%	% de resíduo úmido
Carbono regenerativo nos resíduos para disposição final	9.0%	8.8%	8.4%	5.8%	% de resíduo úmido

Poder calorífico calculado no resíduo remanescente	Cenário-Base	Cenário 1	Cenário 2	Cenário 3	
esíduos de poder calorífico para disposição final — baixo teor de ág	0.0	0.0	0.0	0.0	MJ/kg de resíduo úmido
esíduos de poder calorífico para disposição final — alto teor de ágı	4.9	5.0	5.2	6.6	MJ/kg de resíduo úmido

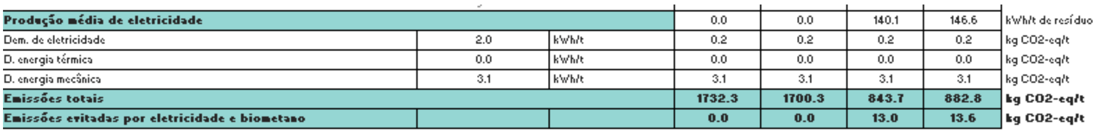


Fatores de emissão para reciclagem

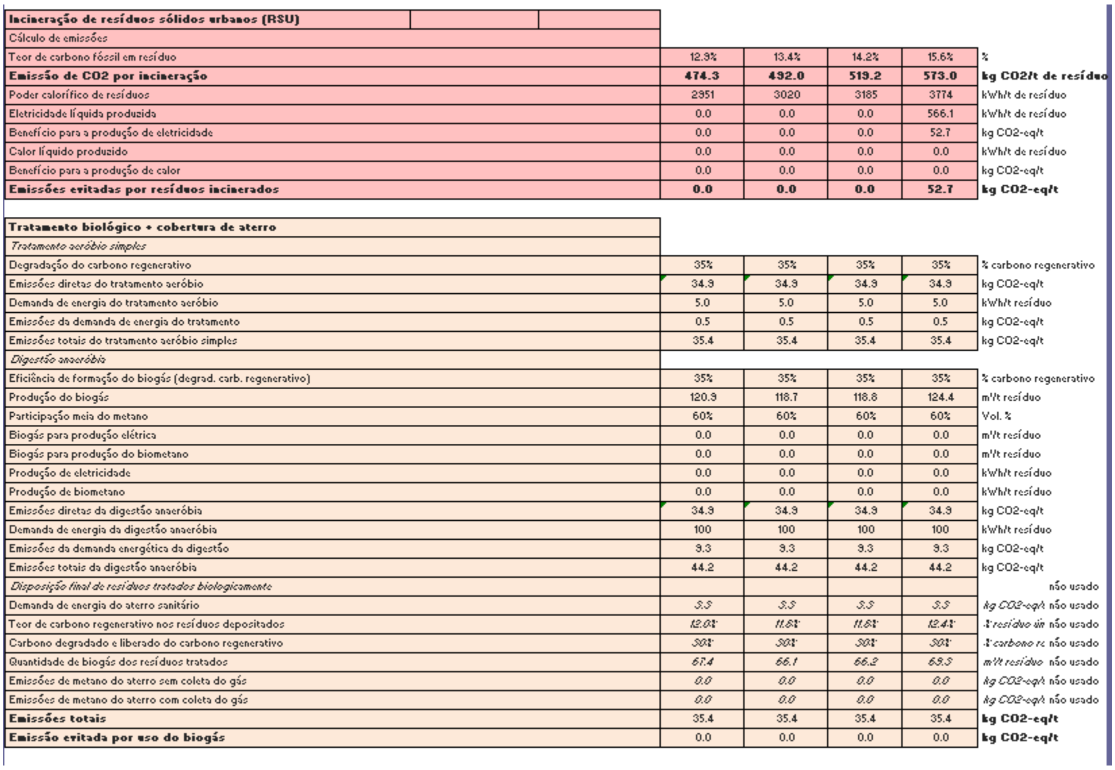
Valores arredondados para o Brasil (setembro de 2019)								
kg CO2-eq/t resíduo	**Resíduo orgânico**	**Resíduo orgânico**	**Papel**	**Vidro**	**Metais (aço)**	**Alumínio**	**Plásticos**	**Têxteis**
	Digestão	**Compostagem**	**Destintagem**	**Derretimento**				
Emissões	90	95	1256	483.2	64	697	410	0
Emissões evitadas	23.9	23.9	1548	604	1712	9880	1910	0
Resultado líquido	**66**	**71**	**-292**	**-121**	**-1648**	**-9183**	**-1500**	**0**

Digestão anaeróbica de crédito			
	Rendimento médio de gás	100	Nm^3/t resíduos biológicos
	Teor médio de metano	60%	vol%
	Eficiência líquida de eletricidade	30%	%
	Produção média de eletricidade	180	kWh/t resíduos biológicos
	Produção média do biometano	600	kWh/t resíduos biológicos

Fatores de emissão para opções de tratamento e disposição final de resíduos	**Cenário-Base**	**Cenário 1**	**Cenário 2**	**Cenário 3**	
Queima aberta de resíduos dispersos					
Carbono fóssil em resíduos dispersos	12.9%	13.4%	14.2%	15.6%	% de resíduo úmido
CO2 emitido por queima aberta	**474.3**	**492.0**	**519.2**	**573.0**	**kg CO2-eq/t**
Aterro					
Cálculo do gás de aterro formado					
Carbono regenerativo em resíduos depositados em aterros	18.5%	18.2%	18.2%	19.0%	% de resíduo t C/t res
Carbono degradado e liberado do carbono regenerativo	50%	50%	50%	50%	% carbono regenerativo
Gás de aterro com teor de metano	55%	55%	55%	55%	vol%
Quantidade de gás de aterro por tonelada de resíduo	172.7	169.5	169.8	177.7	m^3/t de resíduo
Aterro não gerenciado					
Quantidade de gás de aterro difuso	172.7	169.5	169.8	177.7	m^3/t de resíduo
Quantidade de metano emitido	**1900.0**	**1864.9**	**1867.5**	**1954.4**	**kg CO2-eq/t**
Aterro sanitário (aterro gerenciado)					
Gás de aterro coletado	17.3	17.0	84.9	88.8	m^3/t de resíduo
Não tratados, apenas ventilados	17.3	17.0	0.0	0.0	m^3/t de resíduo
Quantidade de metano difuso	85.5	83.9	46.7	48.9	m^3 CH4/t de resíduo
Oxidado a CO2 na camada de cobertura padrão IPCC	8.6	8.4	4.7	4.9	m^3 CH4/t de resíduo
Quantidade total de emissões de metano em kg	61.8	60.6	30.0	31.4	kg CH4/t de resíduo
Quantidade total de emissões de metano em CO2-eq	1729.0	1697.0	840.4	879.5	kg CO2-eq/t
Gás de aterro coletado queimado	0.0	0.0	0.0	0.0	m^3/t de resíduo
Gás de aterro coletado para eletricidade	0.0	0.0	84.9	88.8	m^3/t de resíduo
Gás de aterro coletado para biometano	0.0	0.0	0.0	0.0	m^3/t de resíduo

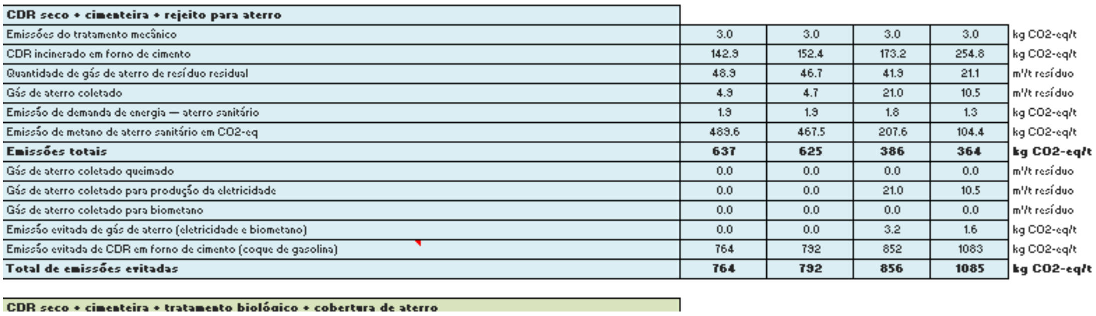


Produção média de eletricidade			0.0	0.0	140.1	146.6	kWh/t de resíduo
Dem. de eletricidade	2.0	kWh/t	0.2	0.2	0.2	0.2	kg CO2-eq/t
D. energia térmica	0.0	kWh/t	0.0	0.0	0.0	0.0	kg CO2-eq/t
D. energia mecânica	3.1	kWh/t	3.1	3.1	3.1	3.1	kg CO2-eq/t
Emissões totais			**1732.3**	**1700.3**	**843.7**	**882.8**	**kg CO2-eq/t**
Emissões evitadas por eletricidade e biometano			**0.0**	**0.0**	**13.0**	**13.6**	**kg CO2-eq/t**



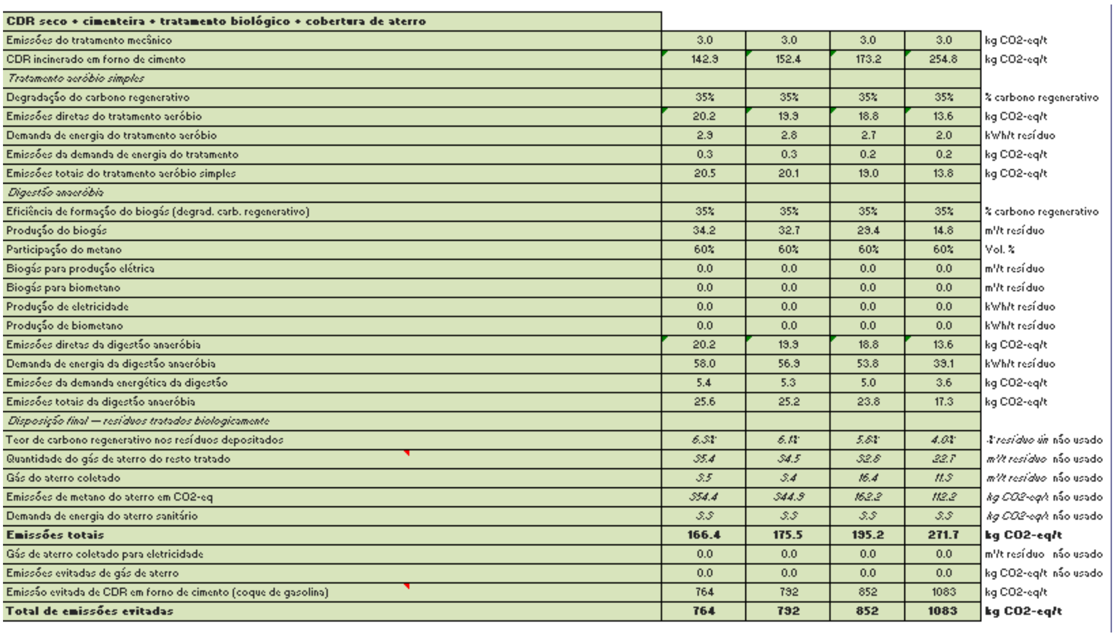
Incineração de resíduos sólidos urbanos (RSU)					
Cálculo de emissões					
Teor de carbono fóssil em resíduo	12.9%	13.4%	14.2%	15.6%	%
Emissão de CO2 por incineração	**474.3**	**492.0**	**519.2**	**573.0**	**kg CO2/t de resíduo**
Poder calorífico de resíduos	2951	3020	3185	3774	kWh/t de resíduo
Eletricidade líquida produzida	0.0	0.0	0.0	566.1	kWh/t de resíduo
Benefício para a produção de eletricidade	0.0	0.0	0.0	52.7	kg CO2-eq/t
Calor líquido produzido	0.0	0.0	0.0	0.0	kWh/t de resíduo
Benefício para a produção de calor	0.0	0.0	0.0	0.0	kg CO2-eq/t
Emissões evitadas por resíduos incinerados	**0.0**	**0.0**	**0.0**	**52.7**	**kg CO2-eq/t**

Tratamento biológico + cobertura de aterro					
Tratamento aeróbio simples					
Degradação do carbono regenerativo	35%	35%	35%	35%	% carbono regenerativo
Emissões diretas do tratamento aeróbio	34.9	34.9	34.9	34.9	kg CO2-eq/t
Demanda de energia do tratamento aeróbio	5.0	5.0	5.0	5.0	kWh/t resíduo
Emissões da demanda de energia do tratamento	0.5	0.5	0.5	0.5	kg CO2-eq/t
Emissões totais do tratamento aeróbio simples	35.4	35.4	35.4	35.4	kg CO2-eq/t
Digestão anaeróbia					
Eficiência de formação do biogás (degrad. carb. regenerativo)	35%	35%	35%	35%	% carbono regenerativo
Produção do biogás	120.9	118.7	118.8	124.4	m^3/t resíduo
Participação meia do metano	60%	60%	60%	60%	Vol. %
Biogás para produção elétrica	0.0	0.0	0.0	0.0	m^3/t resíduo
Biogás para produção do biometano	0.0	0.0	0.0	0.0	m^3/t resíduo
Produção de eletricidade	0.0	0.0	0.0	0.0	kWh/t resíduo
Produção de biometano	0.0	0.0	0.0	0.0	kWh/t resíduo
Emissões diretas da digestão anaeróbia	34.9	34.9	34.9	34.9	kg CO2-eq/t
Demanda de energia da digestão anaeróbia	100	100	100	100	kWh/t resíduo
Emissões da demanda energética da digestão	9.3	9.3	9.3	9.3	kg CO2-eq/t
Emissões totais da digestão anaeróbia	44.2	44.2	44.2	44.2	kg CO2-eq/t
Disposição final de resíduos tratados biologicamente					não usado
Demanda de energia do aterro sanitário	*3.3*	*3.3*	*3.3*	*3.3*	*kg CO2-eq/t* não usado
Teor de carbono regenerativo nos resíduos depositados	*12.0%*	*11.8%*	*11.8%*	*12.4%*	*% resíduo úm* não usado
Carbono degradado e liberado do carbono regenerativo	*50%*	*50%*	*50%*	*50%*	*% carbono re* não usado
Quantidade de biogás dos resíduos tratados	*67.4*	*66.1*	*66.2*	*69.3*	*m^3/t resíduo* não usado
Emissões de metano do aterro sem coleta do gás	*0.0*	*0.0*	*0.0*	*0.0*	*kg CO2-eq/t* não usado
Emissões de metano do aterro com coleta do gás	*0.0*	*0.0*	*0.0*	*0.0*	*kg CO2-eq/t* não usado
Emissões totais	35.4	35.4	35.4	35.4	**kg CO2-eq/t**
Emissão evitada por uso do biogás	0.0	0.0	0.0	0.0	**kg CO2-eq/t**

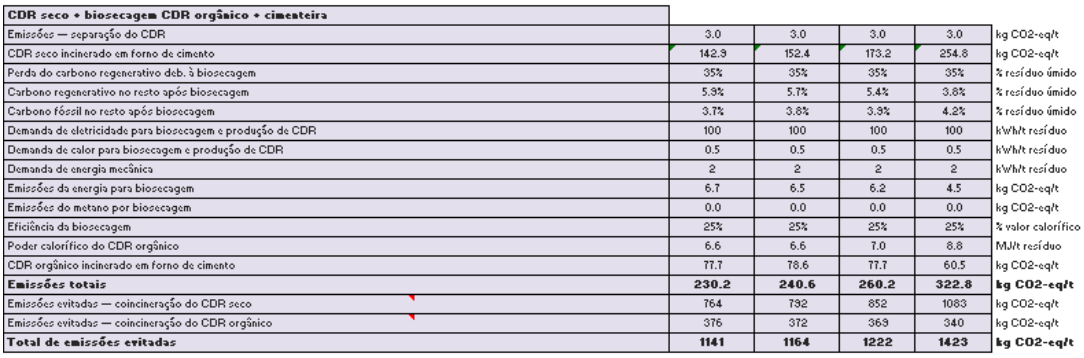


CDR seco + cimenteira + rejeito para aterro					
Emissões do tratamento mecânico	3.0	3.0	3.0	3.0	kg CO2-eq/t
CDR incinerado em forno de cimento	142.9	152.4	173.2	254.8	kg CO2-eq/t
Quantidade de gás de aterro de resíduo residual	48.9	46.7	41.9	21.1	m^3/t resíduo
Gás de aterro coletado	4.9	4.7	21.0	10.5	m^3/t resíduo
Emissão de demanda de energia — aterro sanitário	1.9	1.9	1.8	1.3	kg CO2-eq/t
Emissão de metano de aterro sanitário em CO2-eq	489.6	467.5	207.6	104.4	kg CO2-eq/t
Emissões totais	**637**	**625**	**386**	**364**	**kg CO2-eq/t**
Gás de aterro coletado queimado	0.0	0.0	0.0	0.0	m^3/t resíduo
Gás de aterro coletado para produção da eletricidade	0.0	0.0	21.0	10.5	m^3/t resíduo
Gás de aterro coletado para biometano	0.0	0.0	0.0	0.0	m^3/t resíduo
Emissão evitada de gás de aterro (eletricidade e biometano)	0.0	0.0	3.2	1.6	kg CO2-eq/t
Emissão evitada de CDR em forno de cimento (coque de gasolina)	764	792	852	1083	kg CO2-eq/t
Total de emissões evitadas	**764**	**792**	**856**	**1085**	**kg CO2-eq/t**

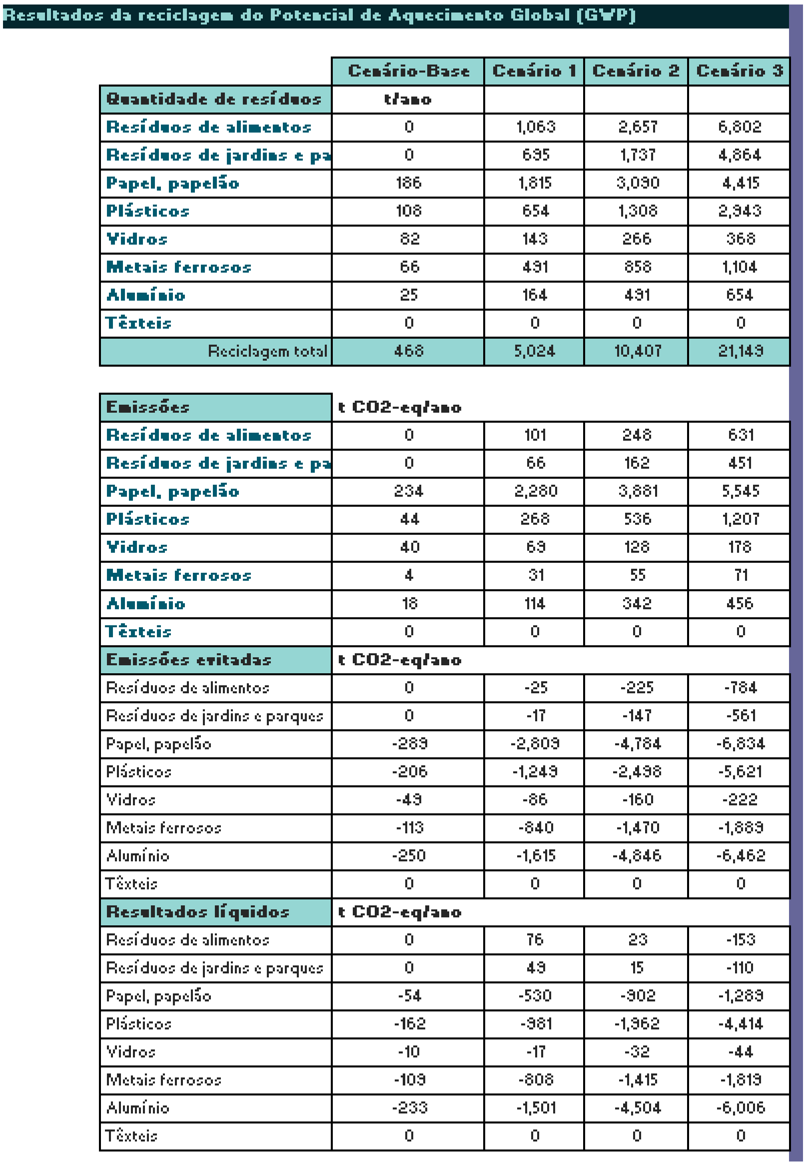
CDR seco + cimenteira + tratamento biológico + cobertura de aterro



CDR seco + cimenteira + tratamento biológico + cobertura de aterro					
Emissões do tratamento mecânico	3.0	3.0	3.0	3.0	kg CO2-eq/t
CDR incinerado em forno de cimento	142.9	152.4	173.2	254.8	kg CO2-eq/t
Tratamento aeróbio simples					
Degradação do carbono regenerativo	35%	35%	35%	35%	% carbono regenerativo
Emissões diretas do tratamento aeróbio	20.2	19.9	18.8	13.6	kg CO2-eq/t
Demanda de energia do tratamento aeróbio	2.9	2.8	2.7	2.0	kWh/t resíduo
Emissões da demanda de energia do tratamento	0.3	0.3	0.2	0.2	kg CO2-eq/t
Emissões totais do tratamento aeróbio simples	20.5	20.1	19.0	13.8	kg CO2-eq/t
Digestão anaeróbia					
Eficiência de formação do biogás (degrad. carb. regenerativo)	35%	35%	35%	35%	% carbono regenerativo
Produção do biogás	34.2	32.7	29.4	14.8	m^3/t resíduo
Participação do metano	60%	60%	60%	60%	Vol. %
Biogás para produção elétrica	0.0	0.0	0.0	0.0	m^3/t resíduo
Biogás para biometano	0.0	0.0	0.0	0.0	m^3/t resíduo
Produção de eletricidade	0.0	0.0	0.0	0.0	kWh/t resíduo
Produção de biometano	0.0	0.0	0.0	0.0	kWh/t resíduo
Emissões diretas da digestão anaeróbia	20.2	19.9	18.8	13.6	kg CO2-eq/t
Demanda de energia da digestão anaeróbia	58.0	56.9	53.8	39.1	kWh/t resíduo
Emissões da demanda energética da digestão	5.4	5.3	5.0	3.6	kg CO2-eq/t
Emissões totais da digestão anaeróbia	25.6	25.2	23.8	17.3	kg CO2-eq/t
Disposição final — resíduos tratados biologicamente					
Teor de carbono regenerativo nos resíduos depositados	*6.3%*	*6.1%*	*5.6%*	*4.0%*	*% resíduo úm* não usado
Quantidade do gás de aterro do resto tratado	*35.4*	*34.5*	*32.8*	*22.7*	*m^3/t resíduo* não usado
Gás do aterro coletado	*3.5*	*3.4*	*16.4*	*11.3*	*m^3/t resíduo* não usado
Emissões de metano do aterro em CO2-eq	*354.4*	*344.9*	*162.2*	*112.2*	*kg CO2-eq/t* não usado
Demanda de energia do aterro sanitário	*3.3*	*3.3*	*3.3*	*3.3*	*kg CO2-eq/t* não usado
Emissões totais	**166.4**	**175.5**	**195.2**	**271.7**	**kg CO2-eq/t**
Gás de aterro coletado para eletricidade	0.0	0.0	0.0	0.0	m^3/t resíduo não usado
Emissões evitadas de gás de aterro	0.0	0.0	0.0	0.0	kg CO2-eq/t não usado
Emissão evitada de CDR em forno de cimento (coque de gasolina)	764	792	852	1083	kg CO2-eq/t
Total de emissões evitadas	**764**	**792**	**852**	**1083**	**kg CO2-eq/t**

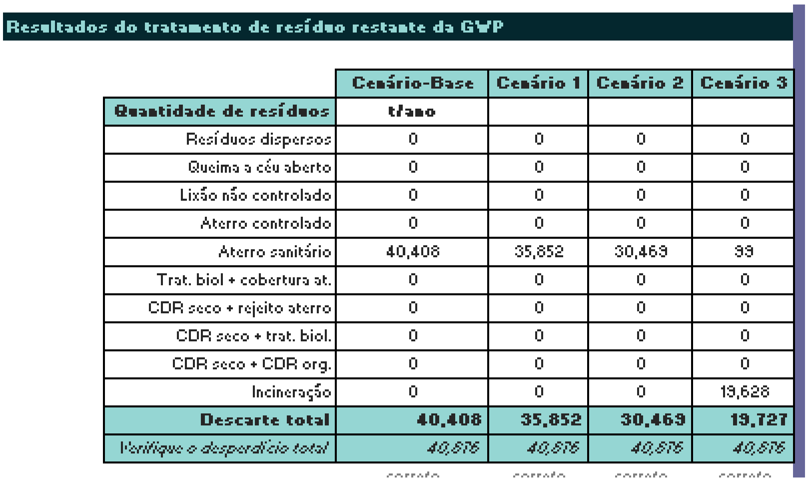


CDR seco + biosecagem CDR orgânico + cimenteira					
Emissões — separação do CDR	3.0	3.0	3.0	3.0	kg CO2-eq/t
CDR seco incinerado em forno de cimento	142.9	152.4	173.2	254.8	kg CO2-eq/t
Perda do carbono regenerativo deb. à biosecagem	35%	35%	35%	35%	% resíduo úmido
Carbono regenerativo no resto após biosecagem	5.9%	5.7%	5.4%	3.8%	% resíduo úmido
Carbono fóssil no resto após biosecagem	3.7%	3.8%	3.9%	4.2%	% resíduo úmido
Demanda de eletricidade para biosecagem e produção de CDR	100	100	100	100	kWh/t resíduo
Demanda de calor para biosecagem e produção de CDR	0.5	0.5	0.5	0.5	kWh/t resíduo
Demanda de energia mecânica	2	2	2	2	kWh/t resíduo
Emissões da energia para biosecagem	6.7	6.5	6.2	4.5	kg CO2-eq/t
Emissões do metano por biosecagem	0.0	0.0	0.0	0.0	kg CO2-eq/t
Eficiência da biosecagem	25%	25%	25%	25%	% valor calorífico
Poder calorífico do CDR orgânico	6.6	6.6	7.0	8.8	MJ/t resíduo
CDR orgânico incinerado em forno de cimento	77.7	78.6	77.7	60.5	kg CO2-eq/t
Emissões totais	**230.2**	**240.6**	**260.2**	**322.8**	**kg CO2-eq/t**
Emissões evitadas — coincineração do CDR seco	764	792	852	1083	kg CO2-eq/t
Emissões evitadas — coincineração do CDR orgânico	376	372	369	340	kg CO2-eq/t
Total de emissões evitadas	**1141**	**1164**	**1222**	**1423**	**kg CO2-eq/t**



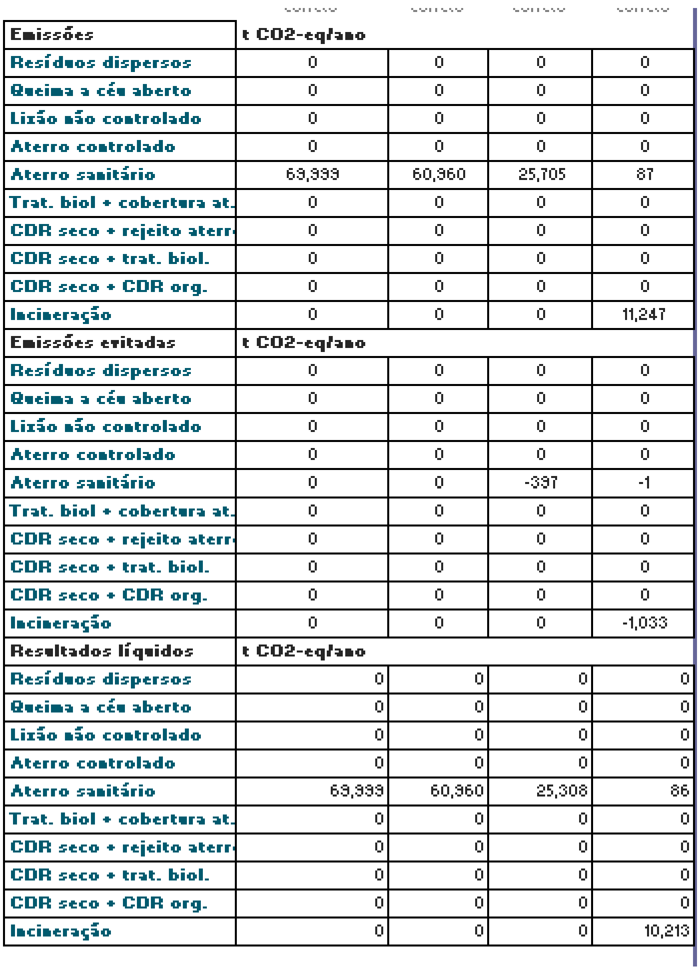
Resultados da reciclagem do Potencial de Aquecimento Global (GWP)

	Cenário-Base	Cenário 1	Cenário 2	Cenário 3
Quantidade de resíduos	t/ano			
Resíduos de alimentos	0	1,063	2,657	6,802
Resíduos de jardins e pa	0	695	1,737	4,864
Papel, papelão	186	1,815	3,090	4,415
Plásticos	108	654	1,308	2,943
Vidros	82	143	266	368
Metais ferrosos	66	491	858	1,104
Alumínio	25	164	491	654
Têxteis	0	0	0	0
Reciclagem total	468	5,024	10,407	21,149
Emissões	t CO2-eq/ano			
Resíduos de alimentos	0	101	248	631
Resíduos de jardins e pa	0	66	162	451
Papel, papelão	234	2,280	3,881	5,545
Plásticos	44	268	536	1,207
Vidros	40	69	128	178
Metais ferrosos	4	31	55	71
Alumínio	18	114	342	456
Têxteis	0	0	0	0
Emissões evitadas	t CO2-eq/ano			
Resíduos de alimentos	0	-25	-225	-784
Resíduos de jardins e parques	0	-17	-147	-561
Papel, papelão	-289	-2,809	-4,784	-6,834
Plásticos	-206	-1,249	-2,498	-5,621
Vidros	-49	-86	-160	-222
Metais ferrosos	-113	-840	-1,470	-1,889
Alumínio	-250	-1,615	-4,846	-6,462
Têxteis	0	0	0	0
Resultados líquidos	t CO2-eq/ano			
Resíduos de alimentos	0	76	23	-153
Resíduos de jardins e parques	0	49	15	-110
Papel, papelão	-54	-530	-902	-1,289
Plásticos	-162	-981	-1,962	-4,414
Vidros	-10	-17	-32	-44
Metais ferrosos	-109	-808	-1,415	-1,819
Alumínio	-233	-1,501	-4,504	-6,006
Têxteis	0	0	0	0



Resultados do tratamento de resíduo restante da GWP

	Cenário-Base	Cenário 1	Cenário 2	Cenário 3
Quantidade de resíduos	t/ano			
Resíduos dispersos	0	0	0	0
Queima a céu aberto	0	0	0	0
Lixão não controlado	0	0	0	0
Aterro controlado	0	0	0	0
Aterro sanitário	40,408	35,852	30,469	99
Trat. biol + cobertura at.	0	0	0	0
CDR seco + rejeito aterro	0	0	0	0
CDR seco + trat. biol.	0	0	0	0
CDR seco + CDR org.	0	0	0	0
Incineração	0	0	0	19,628
Descarte total	**40,408**	**35,852**	**30,469**	**19,727**
Verifique o desperdício total	*40,876*	*40,876*	*40,876*	*40,876*
	correto	correto	correto	correto



Emissões	**t CO2-eq/ano**			
Resíduos dispersos	0	0	0	0
Queima a céu aberto	0	0	0	0
Lixão não controlado	0	0	0	0
Aterro controlado	0	0	0	0
Aterro sanitário	69,999	60,960	25,705	87
Trat. biol + cobertura at.	0	0	0	0
CDR seco + rejeito aterr	0	0	0	0
CDR seco + trat. biol.	0	0	0	0
CDR seco + CDR org.	0	0	0	0
Incineração	0	0	0	11,247
Emissões evitadas	**t CO2-eq/ano**			
Resíduos dispersos	0	0	0	0
Queima a céu aberto	0	0	0	0
Lixão não controlado	0	0	0	0
Aterro controlado	0	0	0	0
Aterro sanitário	0	0	-397	-1
Trat. biol + cobertura at.	0	0	0	0
CDR seco + rejeito aterr	0	0	0	0
CDR seco + trat. biol.	0	0	0	0
CDR seco + CDR org.	0	0	0	0
Incineração	0	0	0	-1,033
Resultados líquidos	**t CO2-eq/ano**			
Resíduos dispersos	0	0	0	0
Queima a céu aberto	0	0	0	0
Lixão não controlado	0	0	0	0
Aterro controlado	0	0	0	0
Aterro sanitário	69,999	60,960	25,308	86
Trat. biol + cobertura at.	0	0	0	0
CDR seco + rejeito aterr	0	0	0	0
CDR seco + trat. biol.	0	0	0	0
CDR seco + CDR org.	0	0	0	0
Incineração	0	0	0	10,213