TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Civil Engineering and Architecture

LIFE CYCLE ASSESSMENT OF MUNICIPAL SOLID WASTE TREATMENT OPTIONS IN BARCELONA CITY

OLMEJÄÄTMETE KÄITLUSALTERNATIIVIDE OLELUSRINGI HINDAMINE BARCELONA LINNAS

MASTER THESIS

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Tallinn 2022

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Department of Civil Engineering and Architecture

THESIS TASK

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Study programme, EABM, Environmental Engineering and Management

Main speciality: Environmental Engineering and Management

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Thesis topic:

English: Life cycle assessment of municipal solid waste treatment options in Barcelona city.

Estonian: Olmejäätmete käitlusalternatiivide olelusringi hindamine Barcelona linnas

Thesis main objectives:

1. To assess the environmental impacts generated by the current treatment and disposal practices of municipal solid waste.
2. To provide a midpoint comparative of the environmental impacts between the current practises and several hypothetical scenarios.
4. To provide a clear statement and recommend improvements in municipal solid waste treatment options for Barcelona city.

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Theoretical Review	16.04.2022
2.	Methodology	2.05.2022
3.	Results, conclusions, and recommendations	22.05.2022

Language: English

Deadline for submission of thesis: 23rd May 2022

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LIST OF ABBREVIATIONS AND SYMBOLS

NH_3	Ammonia
CO_2	Carbon Dioxide
CO	Carbon Monoxide
DPF	Diesel Particulate Filters
EU	European Union
FU	Functional Unit
ISO	International Organization for Standardisation
LD	Landfill Directive
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
MBT	Mechanical-Biological Treatment
CH_4	Methane
MSW	Municipal Solid Waste
NOx	Nitrogen Oxides
PPWD	Packaging and Packaging Waste Directive
POPs	Persistent Organic Compounds
RDF	Refuse-Derived Fuel
VOCs	Volatile Organic Compounds
WFD	Waste Framework Directive

GLOSSARY

Biowaste fraction: organic fraction of municipal waste mainly consisting of food scraps (vegetables, fruit, shells, peels, meat, fish, flour, etc.) and vegetable waste (gardening and pruning), susceptible to biological degradation.

Ecopark: waste facility responsible for treating two fractions of the municipal solid waste, the organic matter from the selective collection of the MSW and the waste fraction. This type of facility usually involves mechanical-biological treatment. Different recyclable materials are extracted (glass, paper, plastic, metals), energy in the form of heat or electricity, compost, and bio-stabilised material.

Energy recovery facility: facility where waste is incinerated. The treatment reduces the volume of waste through combustion and allows the energy of the process to be harnessed to generate heat and electricity.

Glass fraction: fraction of municipal waste made up of glass containers (bottles, jars, etc.).

Light packaging: fraction of municipal waste consisting of packaging with the common characteristic of having a low weight/volume ratio. It consists mainly of plastic bottles, plastic film, cans and bricks or cardboard for drinks.

Mechanical-biological treatment: pre-treatment waste facility which combines mechanical waste sorting with biological treatment. The end products obtained from the overall MBT plant are recyclable materials, biogas, compost, bio-stabilised material, refuse-derived fuel (RDF) and waste fraction.

Paper and cardboard fraction: municipal waste fraction made up of paper and cardboards, including newspapers, white and printed paper, coloured paper, cardboard boxes, wrappers, etc.

Sanitary landfilling: controlled disposal of waste that consists of dumping waste in conditions of environmental safety, so it cannot be a source of pollution for the environment.

Sorting plant: facility where the fraction of light packaging is separated from the five-fraction model by materials (glass, paper and cardboard, light packaging, biowaste and waste fraction). The aim is to deliver a homogeneous material to recyclers so that they can make new products from it.

Waste fraction: residual fraction of municipal waste consisting of waste that does not currently have a material valorisation methodology such as sanitary textiles (diapers, compresses, sticks cleaning the ears, wet towels, etc.), the remains of the house cleaning (dust vacuum cleaner, vacuum cleaner bag) or cigarette butts or ash from cigarettes or fireplaces among others. It also includes waste from cleaning tasks on public roads, recreational areas and beaches.

1. INTRODUCTION

1.1. Background and problem statement

Municipal solid waste (MSW) has experienced a worldwide increase during the last centuries due to the exponential enlargement of the population with the simultaneous development of the social economy and the enhancement of the living standards (Karak, Bhagat and Bhattacharyya, 2012). On average, the European Union (EU) generated 505 kilograms of municipal waste per capita in 2020, from which 50% was treated through unsustainable practices understood as landfilling or incineration (Eurostat, 2021).

In Spain, the municipal waste generation was slightly below the European mean, producing 455 kilograms per capita in 2020 (Eurostat, 2021). However, the MSW generation in Spain is not uniform throughout the whole territory due to demographic differences or specific regional economic activities, among other factors. For instance, Barcelona is the second most populated city in the Iberian Peninsula and the tenth in the European Union (EU), which presented slightly different waste generation patterns. Precisely, Barcelona city produced 511 kilograms per capita in 2020, surpassing the EU and Spanish production by 1% and 12% respectively (Statistical Institute of Catalonia, 2022).

Furthermore, municipal waste solely accounts for approximately 10% of the total waste generated in Europe, however, its generation and subsequent collection and treatment entail a high complexity (Eurostat, 2021). Due to its composition and complex character, MSW has a potential adverse impact on human health and the environment if inappropriate management tasks take place. Precisely, the public sector often dedicates more than one-third of its financial expenditure to management and treatment labours in order to reduce and control pollution (OECD, 2015).

In fact, throughout the last decades, governments and institutions have made significant efforts and commitments regarding the implementation of better practices related to waste management, along with the intent of switching towards a circular economy approach. The formulation of the Waste Framework Directive (WFD) in 2008 or the Landfill Directive (LD) in 1999, besides the establishment of waste targets present throughout various EU legislation, set a clear statement of the European strategy and its commitment to a more sustainable approach by promoting prevention, re-use and recycling activities over incineration or landfilling. As a matter of fact, the landfill rate has decreased by 58% since 1995, partially attributed to the implementation of European legislation (Eurostat, 2021).

1.2. Aim and objective

This thesis aims to conduct a comparative life cycle assessment (LCA) of various treatment techniques implemented to the municipal solid waste in Barcelona city.

In particular, the research will address the following specific objectives:

- To assess the environmental impacts generated by the current treatment and disposal practices of municipal solid waste.
- To provide a midpoint comparative assessment of the environmental impacts between the current practises and several hypothetical scenarios.
- To provide a clear statement and recommend improvements in municipal solid waste treatment options for Barcelona city.

2. THEORETICAL OVERVIEW

2.1. Legal framework

According to the Waste Framework Directive (2008/98/EC), waste is defined as "any substance or object which the holder discards or intends or is required to be discarded". Subsequently, municipal waste is described as waste generated in households and resemblant waste in nature and composition generated in offices, public institutions and small commercial activities (OECD, 2015).

On the other hand, the legislation prevailing in Barcelona city provides a more detailed description of the municipal waste concept. According to Article 3 of the Spanish Legislative Decree 1/2009 of July 21, municipal waste is waste generated in private households, shops, offices and services, and waste that is not considered special waste and that by its nature or composition resembles domestic waste. Additionally, this waste typology includes waste from cleaning tasks on public roads, green areas, recreational areas and beaches; dead pets; abandoned furniture, utensils and vehicles; waste and demolition from minor works and home repairs.

Even though the legislation in force in the Spanish autonomous community of Catalonia provides a greater degree of accuracy in the description of municipal waste, the EU legislation has adopted a set of waste-related legislation and circular economy targets over the past two decades, which are relevant to all EU member states including Spain. In particular, these measures aim to reduce waste generation and its impacts by shifting the municipal waste management approach from waste disposal to waste preparation for re-use and recycling.

In fact, the WFD is the main regulatory instrument available nowadays to change the waste management approach in the EU. Aside from establishing various definitions related to waste management, this directive introduced the waste hierarchy concept. This principle prioritises prevention as the best management option; forwarded by the preparation for re-use, recycling, other forms of recovery such as energy recovery through incineration processes; and lastly, disposal practices (Spanish Ministry of Agriculture, Food and Environment, 2013).

Figure 2.1 Waste hierarchy pyramid (Gharfalkar et al., 2015)

Within this context, three EU directives define specific and challenging municipal waste management and circular economy targets. Firstly, the LD in 1999 was formulated to prevent and reduce the adverse impacts on the environment caused by landfilling practices. In particular, this directive banned landfilling of separately collected waste fractions from 2020 and limited up to 10% the MSW disposal in landfills by 2035. Secondly, the WFD in 2008 was created to prevent and reduce the generation of waste and its impacts, with the final goal of protecting the environment and human health. Specifically, this directive established recycling targets for municipal waste, which consist of recycling at least 55%, 60% and 65% of municipal waste by 2025, 2030 and 2035 respectively. Lastly, the Packaging and Packaging Waste Directive (PPWD) in 2018 was published to promote the recycling practices of packaging waste through the implementation of recycling objectives in order to prevent and reduce this typology of waste and its potential adverse impacts on the environment. In the Table 2.1, the relevant EU targets concerning waste management and more precisely, municipal waste treatment objectives have been compiled.

Table 2.1 EU waste management targets.

	2025	2030	2035	Source
Landfilling of municipal waste	-	-	<10%	Directive 1999/31/EC on the landfill of waste
Recycling of municipal waste	55%	60%	65%	Directive 2008/98/EC on waste
Recycling of packaging	65%	70%	-	Directive 94/62/EC on packaging and packaging waste
Specific recycling targets by type of packaging material				
Recycling of plastic packaging	50%	55%	-	Directive 94/62/EC on packaging and packaging waste
Recycling of wood packaging	25%	30%	-	Directive 94/62/EC on packaging and packaging waste

	2025	2030	2035	Source
Recycling of ferrous packaging	70%	80%	-	Directive 94/62/EC on packaging and packaging waste
Recycling of aluminium packaging	50%	60%	-	Directive 94/62/EC on packaging and packaging waste
Recycling of glass packaging	70%	75%	-	Directive 94/62/EC on packaging and packaging waste
Recycling of paper and cardboard packaging	75%	85%	-	Directive 94/62/EC on packaging and packaging waste

Overall, these waste management and circular economy targets aim to turn Europe into an efficient society concerning the usage of resources by producing less waste and using the waste generated as a resource whenever possible. However, these objectives need to be accompanied by higher levels of recycling while minimising the extraction of additional resources. In this sense, the role of public administrations is crucial both in the performance of their functions of environmental protection and in the role of promoters of a more efficient, prosperous and socially inclusive economy (Spanish Ministry of Agriculture, Food and Environment, 2013).

As a result of the EU member states' commitment to these objectives, some favourable outcomes have already been observed, and they can be partially attributed to the implementation of the European waste legislation. For instance, landfill practices have decreased by 58% on average in the EU since 1995. At the same time, energy recovery processes, material recycling and composting have respectively increased by 105%, 192% and 186%. Despite the rise of more sustainable waste treatment practices, it is fundamental to acknowledge that European municipal waste generation has increased throughout this period, and higher quantities of waste require treatment (Eurostat, 2021).

2.2. MSW management in Barcelona

As stated in the Spanish Legislative Decree 1/2009 of July 21, municipal waste management involves a set of operations and tasks carried out from the generation of the waste, involving its collection, classification, transport, treatment and disposal. Precisely, due to the large volume of annual MSW generation and its strategic importance, waste management and the pertinent infrastructure need to be in place. In Barcelona, the current management model is based on the principles of proximity, sufficiency and responsibility of the producer, and the waste hierarchy principle is taken into consideration by prioritising waste prevention actions and separately fraction collection (Waste Agency of Catalonia, 2013).

Moreover, based on the Spanish Law 22/2011 of July 28 related to waste and soil contamination, the waste management responsibilities lie on the autonomous communities, which simultaneously lie on the local entities or provincial councils. This hierarchy is translated as the Spanish government exercises the power of surveillance, inspection and sanction within the scope of its power; the government of the autonomous community of Catalonia is accountable for preparing regional waste prevention and management programs, the registration of information on waste-related production and management in its field of competence; and the Barcelona's council has the responsibility of providing independently or in association the MSW management services such as collection, transportation, treatment and disposal.

Focusing uniquely on the treatment and disposal processes, and more specifically on the primary destination of the municipal waste generated in Barcelona, it can be observed in the Figure 2.2 that the most frequent destination from 2016 to 2020 was mechanical-biological treatment (MBT) plants. Followed by material recycling, then energy recovery, which includes incineration of refuse-derived fuel (RDF) and incineration of waste fraction, and finally landfilling. Precisely, the observed municipal waste primary destination in Barcelona follows the hierarchy principle established by the EU's WFD.

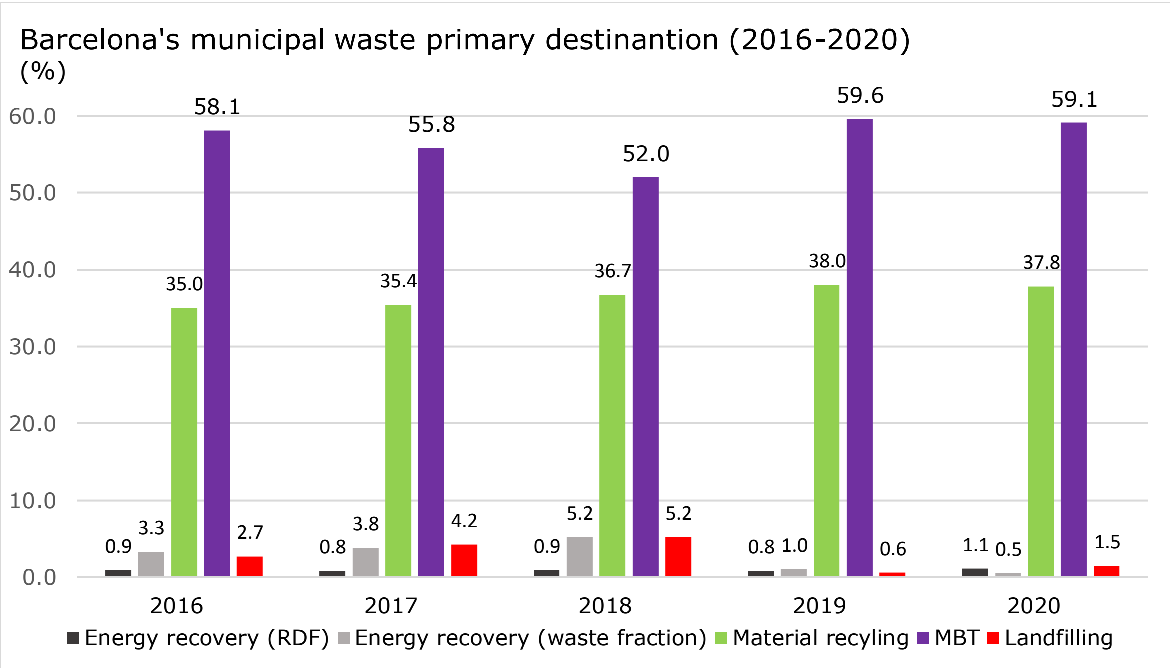

Figure 2.2 Barcelona's MSW primary destination (2016-2020) (Department of Statistics and Data Dissemination of Barcelona, 2021).

Nonetheless, the previously illustrated figure can lead to misinterpretation of the waste's final destination since the waste input in MBT plans can afterwards end up in landfills, energy recovery or other recycling processes. For instance, from the biowaste fraction separately collected in Barcelona city, 18% constitutes waste fraction which afterwards 58% is landfilled and 42% is incinerated (Metropolitan Area of Barcelona, 2018).

2.2.1 Recycling

According to the Spanish Law 22/2011 of July 28 related to waste and soil contamination, recycling is defined as any recovery process through which waste materials are turned into re-usable products or materials for previous or other purposes. The overall recycling concept includes material recycling and biowaste transformation into compost or bio-stabilised material. However, it does not include energy recovery or transformation of waste into materials for incineration or landfill processes such as RDF. Precisely, this definition of recycling process does not contemplate anaerobic digestion practices with biogas production as a recycling process, meaning that anaerobic digestion with biogas production and incineration with energy recover are position at the same level in the waste hierarchy pyramid.

The separation and collection of MSW is the first step in waste management, and it is a crucial stage for recycling purposes. It should be emphasised that the correct sorting is a fundamental aspect for recycling since the misclassification of different MSW fractions can lead to mutual contamination of the components and subsequent loss of quality. Currently, the municipal waste collected in Barcelona has the following composition:

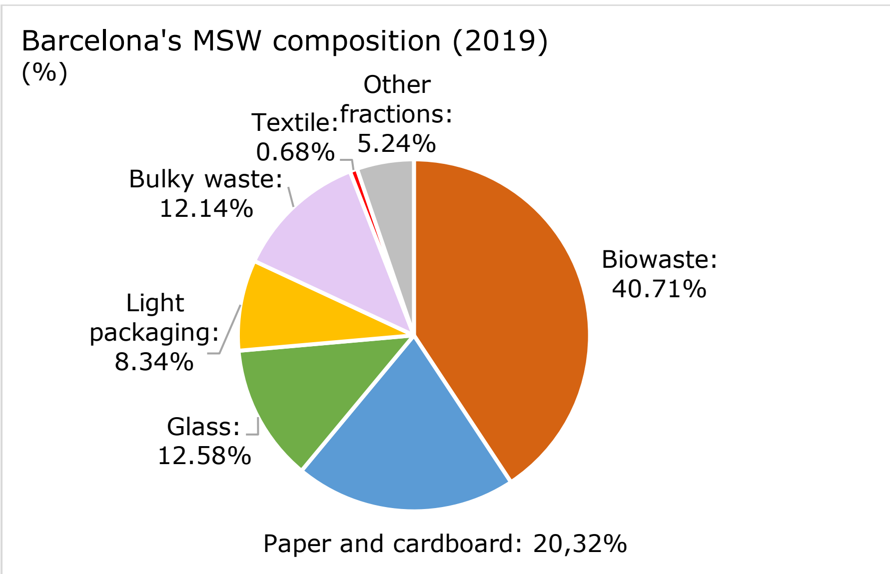

Figure 2.3 MSW composition in Barcelona (2019) (City Council of Barcelona, 2020).

MSW is being collected partially separated, partially as mixed MSW and partially as other municipal waste of special characteristics through specific collection points. The separated fractions are collected in the different neighbourhoods with colour coded bins, brown for biowaste, yellow for light packaging, green for glass and blue for paper and cardboard.

Figure 2.4 MSW collection bins in Barcelona (Metropolitan Area of Barcelona, 2021).

Additionally, a supplementary grey bin collects municipal waste that nowadays does not have a valorisation methodology available, such as sanitary textiles (diapers or wipes), cigarette buts, and household cleaning dust. It has been estimated that this fraction, also known as the waste fraction, should account for 17% of the total municipal waste, but currently it represents approximately 53%. The wrong segregation of waste causes the contrast between these two facts, and these days the waste fraction consists of 25% of biowaste, 18% of light packaging, 9% of paper and cardboard, 4% of glass and 44% of actual waste fraction (Waste Agency of Catalonia, 2021).

The Figure 2.5 presents the evolution of the separately waste collections and the waste fraction in Barcelona in the period 2000-2020, in which Barcelona’s population fluctuated between 1,5 and 1,6 million inhabitants. As an overview, the separate waste collection rates increased while the waste fraction significantly decreased. In fact, the waste fraction experienced certain increases, which can be attributable to higher waste generation, however, in general the trend was a significant decrease caused by higher selective collection rates and waste prevention. Since 2000, Barcelona city was already collecting MSW in differentiated fractions, nevertheless, the MSW fractions evolved differently. Glass and light packaging experienced a steady increase throughout this period, having their highest collection rate in 2019 and 2020 respectively. The paper and cardboard collection was quite particular since it experienced a decrease from 2010 due to the economic crisis and the theft of this material from the collection bins.

On the other hand, biowaste presented the highest enlargement of all collections, and this particular fraction had several periods of significant increase. From 2000 until 2007, the intensification of the collection was due to the collection implementation of this fraction starting in 2000. From 2007 to 2010, segregation experienced its highest point thanks to introducing new bin systems in all the city's neighbourhoods, which differentiated the biowaste and the waste fraction.

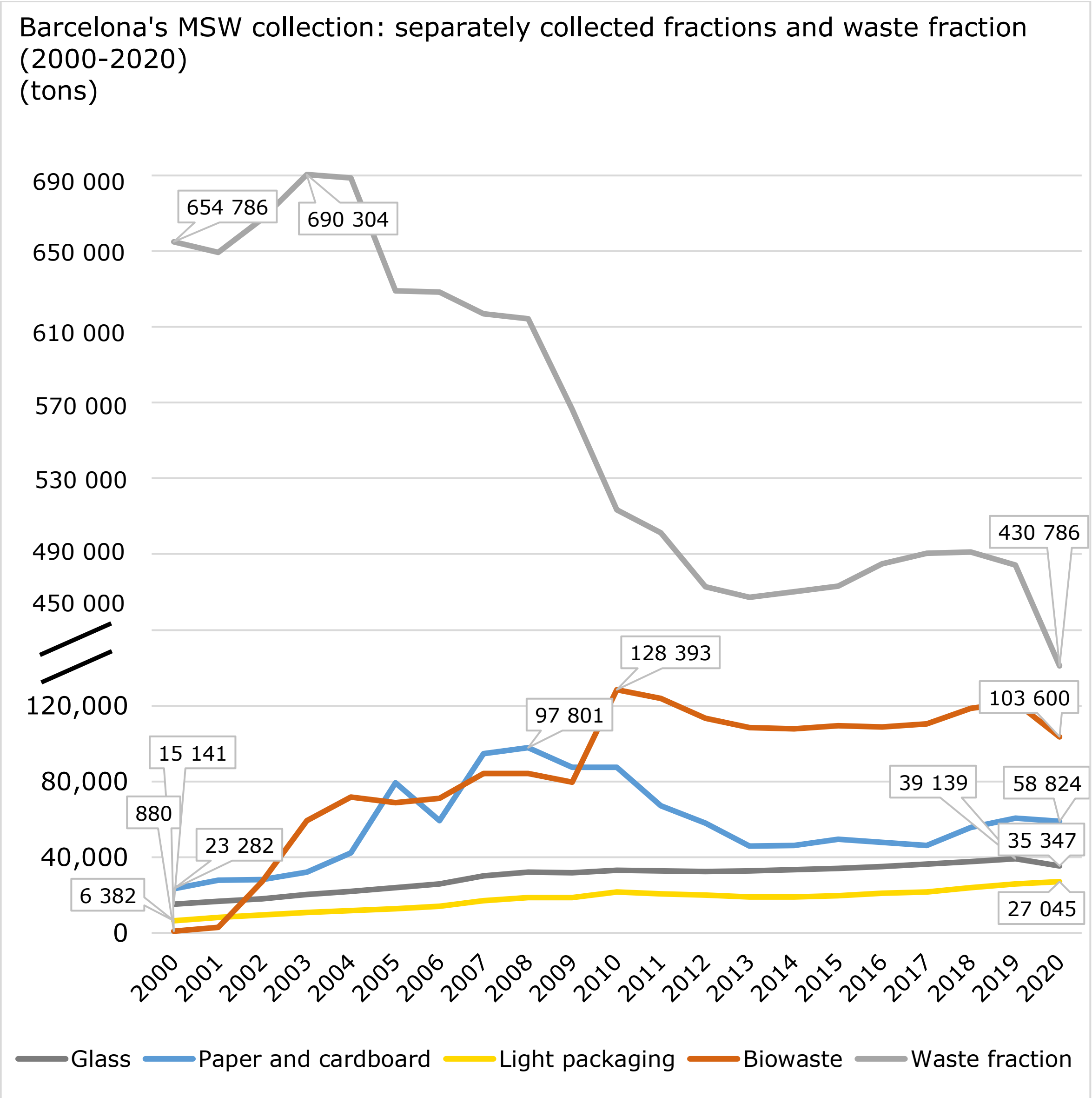

Figure 2.5 Barcelona's MSW collection: separately collected fractions and waste fraction (2000-2020) (Waste Agency of Catalonia, 2021).

Different recycling processes occur for each fraction based on the waste collection bin. Glass, paper and cardboard fractions are externalised to private companies, Ecovidrio and Ecoembes, responsible for these fractions' recycling processes. The local council manages light packaging and the treatment process prioritises the recycling approach.

For this reason, this fraction is directed to specific sorting plants for packaging waste. Ultimately, biowaste and the waste fraction are transported to MBT plants which consist of pre-treatment waste processing facilities that combine mechanical waste sorting with biological treatment. The end products obtained from the overall MBT plants are recyclable materials, biogas, compost, bio-stabilised material, refuse-derived fuel (RDF) and waste fraction (European Commission, 2016).

Overall, selective classification and collection through which five differentiated MSW fractions enable its recycling, the manufacture of new products, and the prevention of this waste ending up directly in landfills or incinerators. Likewise, it facilitates saving energy and resources compared to manufacturing products from raw materials.

2.2.2 Incineration

Waste incineration processes consist of thermal waste treatment method which entail the controlled combustion of waste at high temperatures between 750°C and 1100°C. The main benefit of this technique is the waste reduction in weight and volume, by 75% and 95% respectively (Gómez, 1995). Additionally, some incineration plants are able to recovery energy in form of heat throughout the process, and those plants are known as waste-to-energy facilities or co-incineration plants (Cucchiella, Adamo and Gastaldi, 2014). Throughout the process, organic matter is oxidated and the resulting products are energy, flue gas and slag (Ministry for the Ecological Transition and Demographic Challenge, 2021).

Within the Spanish legislation context, the incineration of mixed municipal waste can be classified as a recovery operation only when it involves energy-recovery methodologies. Based on this fact and considering the waste hierarchy principle established by the EU's WFD, energy-recovery processes should be prioritised against disposal practices such as waste landfilling. However, Barcelona's current reality does not agree with the waste hierarchy approach since landfilling rates are superior to waste-to-energy rates.

In Barcelona, there is uniquely one energy recovery plant located in the city's northern region in Sant Adrià del Besòs neighbourhood. All municipal waste requiring incineration is transported and treated in this facility. Specifically, the waste fraction is the only typology of waste combusted through this process. However, this fraction has multiple origins: waste fraction separated from light packaging sorting plants; waste fraction separated from glass, paper and cardboard sorting plants; waste fraction mechanically sorted in MBT plants from biowaste fraction and from waste fraction itself. Additionally, occasionally the waste fraction sorted from waste fraction collection undergoes pre-treatment processes, which convert the waste fraction into RDF via size sorting and crushing practises beforehand of the incineration operation. The refuse-derived fuel presents several advantages compared to mass burning; firstly RDF does not contain non-combustible components, and secondly its reduced size. In conclusion, these facts enable obtaining a uniform fuel at higher heat values, requiring less excess air, and reducing the costs related to emission controls.

The Figure 2.6 illustrates the energy recovered through cogeneration processes in Barcelona waste facilities from 2007 until 2017. As it can be observed, the energy obtained from the energy recovery plant in use by Barcelona city significantly surpasses the energy generation from the MBT waste facilities. In particular, the energy-recovery facility averaged approximately 178239 MWh per year compared to 11332 MWh per year obtained from MBT waste facilities. The energy origin causes this energy production contrast since the energy-recovery facility obtains energy from incineration practices, and the MBT facilities obtain energy from anaerobic fermentation operations that produce biogas. Afterwards, this is converted to electricity.

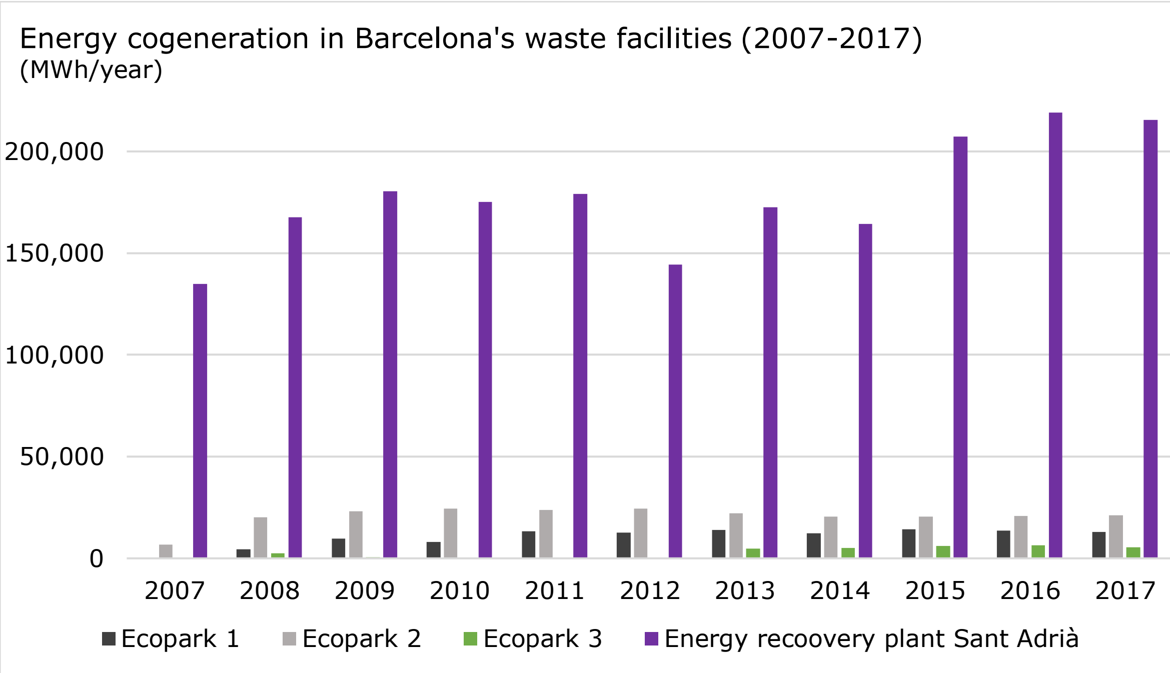

Figure 2.6 Energy generation through cogeneration processes in waste facilities in Barcelona (2007-2017) (Metropolitan Area of Barcelona, 2018).

2.2.3 Landfilling

Landfilling is the most traditional practice of waste management systems involving waste disposal buried between layers of dirt and other materials to stabilise the waste. Initially, municipal waste was dumped in open sites without any safe disposal guidelines implemented on the sites. Regardless of the convenience of this treatment method, shortly society started to realize that dumping sites had an adverse effect on the environment adjacent to the disposal sites (Makarichi, Jutidamrongphan and Techato, 2018). In the 20th century, sanitary landfills appeared as an alternative to open dumps, which were designed to provide safe disposal while protecting the environment and human health, by protecting the soil, groundwater, surface water and air through the implementation of leachate collection and gas collection, among other measures. Moreover, the implementation of liner systems have a crucial role in protecting the environment. Generally, liner systems consists of multiple layers of natural or synthetic liners which prevent the migration of the leachate from the landfill and facilitate the leachate collection.

In fact, in the early 1990s, the autonomous community of Catalonia has 1886 illegal dumps. Thirty years later, dumping sites were regularised and specific requirements were mandatory to be achieved in order to continue operating as a landfill. Nowadays, there are 23 sanitary landfills in the whole territory of Catalonia. For Barcelona's MSW management, twos pecific landfills are being used: sanitary landfill of Tivissa and sanitary landfill of Can Mata. These disposal sites are not located in the region of Barcelona, implying the need for transportation of the waste until those sites located in the surrounding towns of Barcelona city. In particular, the municipal waste disposed in landfills has multiple origins: waste fraction separated from light packaging sorting plants; waste fraction separated from glass, paper and cardboard sorting plants; waste fraction mechanically sorted in MBT plants from biowaste fraction and from waste fraction itself.

The WFD played a crucial role in changing waste management habits regarding landfilling practices within the EU context. Specifically, the disposal of municipal waste has become in Europe the least preferred option for waste management systems, and these kinds of practices do not receive the EU's support legally or economically. Even though the WFD was implemented, the landfilling practices still predominate over incineration operations in Barcelona city. The Figure 2.7 displays the waste fraction destination from 2004 until 2020, and more specifically, the waste fraction directly goes to landfills, avoiding TMB facilities. Overall, the trend of directly disposing the waste fraction into landfills has significantly decreased, and since implementing the WFD, a change in prioritising incineration practices against landfilling can be observed. However, since 2017 this prioritisation has been reversed again towards landfilling. The Catalan current reality is that new dumping sites are being searched because the current operative landfills are reaching their capacity limit.

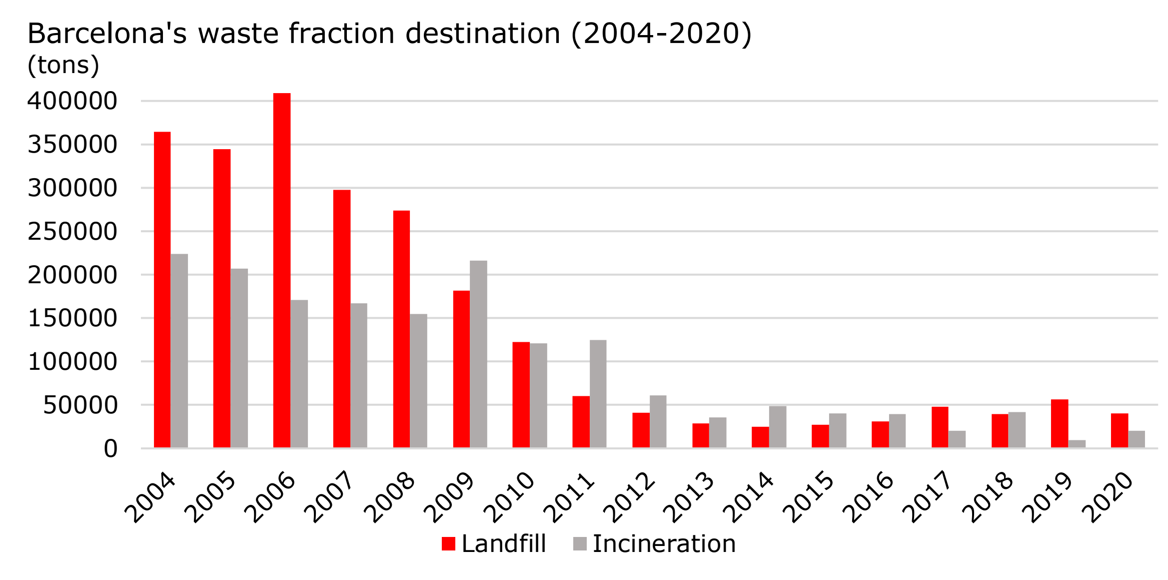

Figure 2.7 Destination of waste fraction in Barcelona (2004-2020) (Waste Agency of Catalonia, 2021).

2.3. Environmental impacts of MSW treatment methods

The primary destination of MSW in Barcelona is MBT facilities, which reflects the governmental efforts toward a circular economy and improvement of waste management systems. Their main objective is to avoid the direct disposal or incineration of municipal waste when more efficient methods exist to treat this waste and obtain high-quality by-products with market value. However, afterwards the MBT, a specific portion of the waste fraction ends up in energy recovery or landfill sites due to the lack of better valorisation methodologies. Additionally, there is still a part of the waste fraction collected nowadays, which is directly dumped in landfills or combusted in waste-to-energy facilities without undergoing any kind of pre-treatment, and simultaneously valuable materials or components present in the waste are neglected.

Firstly, landfilling practices have been questioned since their introduction, and still nowadays there is an environmental and human health concern about the presence of sanitary landfills. The proper utilisation of landfills as waste disposal systems requires considering multiple design and operational factors such as optimal liner selection, suitable leachate and gas collection systems or methane and groundwater monitoring.

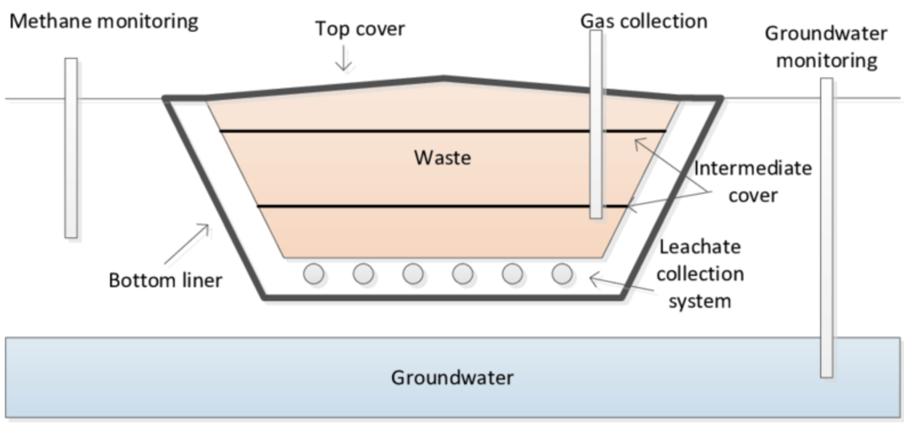

Figure 2.8 Major design components of a sanitary landfill (Danthurebandara, 2015).

In order to avoid any type of soil, air or groundwater contamination, specific monitoring and collection systems need to be in place. Landfill leachate is a liquid that seeps out of a landfill, produced when liquid of external origin, such as rainfall, percolates through the disposed municipal waste and extracts soluble or suspended solids present in the waste. This leachate contains environmentally harmful substances such as ammonia, heavy metals or humic acids. For this reason, appropriate leachate collection systems are needed and the placing of a liner is required to prevent the leachate from infiltrating through the soil. Moreover, the leachate composition can vary based on the age of the landfill and the type of waste it contains. For example, leachate from young sites is usually more polluted than mature landfills. Afterwards the collection, pre-treatment processes are compulsory before discharging it and most frequently occur in wastewater treatment plants.

Additionally, the biodegradable organic matter disposed in landfills decomposes under anaerobic conditions which results in the formation of methane (CH_4), carbon dioxide (CO_2), in less quantity volatile organic compounds (VOCs) and nitrogen oxides (NO_x). These gases need to be collected through gas collecting systems to avoid air contamination since they contribute to the greenhouse effect, and ozone and acid rain formation.

If suitable collection and management systems are implemented in the sites, the environmental and human health impacts associated with this activity can be minimised and additionally the obtention of energy from the landfill gas is possible. However, landfill practices initially involve using untouched land to become a dumping site and the long-term consequences after the site closure are still unpredictable.

Secondly, waste incineration as a waste management method seems a good alternative as it enables up to 90% waste volume reduction, however, it involves severe environmental and human health risks. Throughout the process, organic matter is oxidated and the resulting products are energy, flue gas and slag. The gaseous emissions are considered the primary source of potential pollution from the waste-to-energy processes. There are three main types of components present in the flue gas which require special attention: fly ash, acids and precursors, dioxins and furans. It is essential to remove those compounds from the flue gas to the greatest extent to avoid its presence in the atmosphere (Ministry for the Ecological Transition and Demographic Challenge, 2021).

Fly ash consists of incombustible matter in the form of particulates generated during the combustion which represent up to 10% of the total incineration waste. The polluting potential of this component is significantly high because it contains heavy metals and for this reason it is considered hazardous material. Due to its hazardous character, the fly ash needs to be captured and subsequently treated involving reagents such as lime or powdered activated carbon (Kanhar, Chen and Wang, 2020). The environmental impact of fly ash is caused by the presence of heavy metals and alkaline dust. For example, soil contamination with heavy metals can affect the plants by causing growth and photosynthesis inhibition, altering nutrient assimilation. Additionally, the microorganisms present in the soil can experience respiratory and nitrification reductions (Pandey and Singh, 2010). Furthermore, heavy metals have the capability of bioaccumulating in living organisms and through them move across the food chain. Likewise, fly ash can adversely impact human health buts its impact is dependent on the heavy metal involved and the concentration of this substance. Currently the main focus is deposited on mercury (Hg), since it can damage the renal or nervous systems and cause development problems in children, congenital malformations or neurotoxicological disorders, among other symptoms (Huseen and Mohamed, 2019).

Acids and precursors present in the flue gas are compounds derived from reactions of halogens, sulphur, and volatile compounds such as NO_x, hydrofluoric acid (HF), sulphur dioxide (SO_2) or hydrochloric acid (HCl) (Ministry for the Ecological Transition and Demographic Challenge, 2021). These compounds are responsible for several environmental impacts such as soil and inland water acidification, global warming, ozone layer depletion or acid rain. Moreover, they can affect human health by causing eye and nose irritation, corrosion of the mucous membranes, shortness of breath or formation of liquid in the lungs, among other symptoms (Boningari and Smirniotis, 2016).

Dioxins and furans are non-oxidised organic compounds from the family of polychlorinated dibenzodioxins (PCDD) and polychlorinated dibenzofurans (PCDF) respectively. They are toxic chemicals which are generated in waste combustion processes, metal production, power generation or they are contained in pesticides. These compounds can be found in tiny quantities in the air, water and soil in normal conditions. However, these are persistent compounds which can move across the food chain and end up reaching humans by being contained in meat and dairy products. Their main impact on the ecosystems is because of their toxicity causing illnesses and disorders in wildlife species. Likewise, dioxins and furans have the capability of bioaccumulating in living organisms or fatty tissues, which can become carriers of these compounds and afterwards pass them to humans through dairy products, meat or fish. From the human health perspective, these compounds can be responsible for skin diseases, changed in hormone levels, cancer or changes in the fetus development, among other symptoms (Kanan and Samara, 2018).

For the purpose of preventing and minimizing the impacts caused by incineration activities on human health and environment, several EU directives have been established with the final aim of limiting the quantities of polluting substances discharged into the environment. Additionally, the incineration industry has been adjusting to comply with the regulations and the implementation of the best available techniques is a recurrent practice. For example, electrostatic precipitators or fabric filters are commonly used for removing particles from the flue gas, or the usage of scrubbers is implemented to extract the acid gases.

Thirdly, recycling practices involve material recycling operations and also biowaste transformation into compost or bio-stabilised material. From the EU’s WFD perspective, these treatment methods are the most preferred after the prevention and re-use. However, these processes have also their drawbacks. In fact, material recycling processes can be energy, fuel and water intensive. Even in some instances, recycling and usage might involve higher consumption than the process with newly extracted resources. Additionally, not all materials have the possibility to be recycled due to the product's design or its properties.

On the other hand, biomethanization of biowaste, also known as anaerobic digestion, consists of a process through which organic matter is microbiologically converted to biogas under anaerobic conditions. The products of the anaerobic digestion are CH_4, sludge water, CO_2, and traces of ammonia (NH_3) and hydrogen sulphide (H_2S) (Environmental Protection Agency of United States, 2022).

$$\text{Organic matter} + H_2O \xrightarrow{\text{anaerobic bacteria}} \text{new cells} + CO_2 + CH_4 + NH_3 + H_2S$$

Similarly, aerobic digestion of biowaste, also known as composting, consists of a process through which organic matter decomposes by the action of microorganisms in an oxygen environment. The product resulting from the composting process is compost, an organic amendment commonly used as fertiliser (Ayilara *et al*., 2020).

$$\text{Organic matter} + O_2 \xrightarrow{\text{aerobic bacteria}} \text{new cells} + CO_2 + H_2O + NH_3 + SO_4$$

Likewise, a common practice in waste management systems is the anaerobic or aerobic digestion of waste fraction instead of biowaste. The overall process is optimal, however, the end product of the process is bio-stabilised material. This by-product cannot be used as a fertiliser by the Spanish legislation but currently is being in landscaping (Martinez *et al*., 2021).

From an environmental perspective, anaerobic digestion facilities have greater results than other fermentable treatments since they do not require a significant external supply, which usually comes from fossil fuels. This is feasible due to biogas generation throughout the anaerobic digestion and the later conversion to electricity.

However, the MSW digestion processes require strict monitoring of operational parameters. To give an example, composting processes are highly dependent on the temperature, moisture content, oxygen content, C/N ratio, pH and biochemical composition. Additionally, the presence of heavy metals, excessive odours or inert contaminants in the waste mixture can cause difficulties in the process or the final product acceptance.

To sum up, each waste management method has its advantages and disadvantages, and as a general rule the waste hierarchy principle should be applied. Throughout the last decades, improvements in emission control have been implemented in the waste management systems and a significant abatement of the pollutants discharged into the soil, water, or air has been achieved. Nevertheless, avoiding waste generation, reducing its degree of hazardousness or minimising the impacts of the waste generated by making decisions in the design and manufacture of products is the most efficient approach to avoid damage to the environment and human health. In the end, the best waste is the one that has not been generated and consequently does not require any type of treatment.

2.4. LCA case studies

The continuous worldwide increase of MSW generation throughout the last decades has raised environmental and human health concerns among the population, resulting in implementing waste management systems and strategies (Laurent *et al*., 2014). In order to address these concerns and to develop optimal management systems, life cycle assessment (LCA) has been a widely used tool to quantify the adverse impacts. For this reason, comparative LCA studies of waste management systems have been a subject of interest as they can consider the extraction of resources, collection, transportation, treatment, and disposal of waste.

Although there is an abundance of LCA studies available nowadays, each research has its distinct features and not all of them follow the same methodology, approach (mid-point/end-point), functional unit or database. In this segment of the thesis, 5 LCA articles have been analysed and compared with the current thesis, highlighting its differences and similarities. The Table 2.2 presents a brief summary of the review articles and their primary information.

Table 2.2 Summary of reviewed published articles.

Authors	Title	Journal	Year	Main features	LCA database	LCA approach
Laso, J. *et al.,*	LCA-Based Comparison of Two Organic Fraction Municipal Solid Waste Collection Systems in Historical Centres in Spain	Energies	2019	Biowaste, 4 scenarios, FU: 1 tonne of MSW, Stages: collection, transport, pre-treatment and treatment	Thinkstep	Assess energy primary demand
Bueno, G. *et al.,*	Comparative LCA of two approaches with different emphasis on energy or material recovery for a municipal solid waste management system in Gipuzkoa	Renewable and Sustainable Energy Reviews	2015	MSW, 8 scenarios, FU: 1 tonne of MSW, Stages: collection, transport, pre-treatment and treatment	CML 2001	
Fernández-Nava, Y. *et al.,*	Life cycle assessment of different municipal solid waste management options: a case study of Asturias (Spain)	Journal of Cleaner Production	2014	MSW, 6 scenarios, FU: annual MSW generation (480,000t/year), Stages: collection, transport, pre-treatment and treatment	SimaPRO database Ecoinvent v2.0	Mid-point and End-point
Montejo, C. *et al.,*	Mechanical biological treatment: Performance and potentials. An LCA of 8 MBT plants including waste characterisation	Journal of Environmental Management	2013	MSW, 2 scenarios, FU: 1 tonne of MSW, Only treatment stage	EDIP 1997	Mid-point
Güereca, L. *et al.,*	Life cycle assessment of two biowaste management systems for Barcelona, Spain	Resources, Conservation and Recycling	2006	Biowaste, 2 scenarios, FU: annual biowaste generation (582,66t/year), Stages: collection, transport, pre-treatment and treatment	TRACI	Mid-point

Overall, all the reviewed research articles have conducted a LCA concerning a study case located in Spain. Since waste management systems differ worldwide and still differ in the EU, it is essential to compare studies that could have the most similarities as possible with the current thesis, such as waste generation patterns, collection fractions or population size. Also, even though the reviewed articles are located in Spain, slight differences in MSW composition have been observed. For example, Montejo, C. *et al.,* study's MSW composition is 50% biowaste, 14% paper and cardboard and 11% plastics. In contrast, Laso, J. *et al.,* study's MSW composition was 42% biowaste, 15% paper and cardboard and 9% plastics. These differences in composition can affect the magnitude of benefits or detriment of the waste management systems.

Additionally, all the reviewed papers involved a comprehensive LCA, however, not all of them had utterly the same LCA approach or analysed the same topics. For instance, Laso, J. *et al.,* executed a LCA comparison focalised uniquely on the biowaste fraction and unlike the other papers, it did not analyse the environmental or human health impacts but solely assessed the primary energy demand.

Conversely, the focal point of the remaining published articles is the environmental and human health impacts due to waste management practices. For example, Montejo, C. *et al.,* performed a LCA comparison between 8 existing MBT plants located in the Spanish region of Castilla y León. The research established two scenarios for each MBT plant regarding the MSW composition entering the treatment plants, consisting firstly of the current specific-plant waste composition input for the eight different plants and secondly all the MBT plants had identical MSW composition input. Also, the article from Güereca, L. *et al.,* conducts a LCA comparative focalised uniquely on the biowaste fraction in Barcelona province, and the mid-point results allow the reader to identify the impacts created by each individual treatment method from the entire management process. However, this research differs from the current thesis because its analysis involved Barcelona's province, which involves 33 different municipalities and the current thesis only considered Barcelona city.

Following, it can be concluded that Fernández-Nava, Y. *et al.,* research is the most similar comparative LCA to the present thesis. The article involves an analysis of 6 scenarios based on the mixed MSW treatment type and the separately collected fractions (glass, paper and cardboard, and packaging waste). Overall, the scenarios entail: landfill with recovery of biogas, incineration with energy recovery, biomethanization of biowaste, sorting of mixed MSW fraction and aerobic stabilisation of biowaste. However, the scenarios and their pre-treatment and treatment methodologies are not identical to the analysed in the present thesis.

Eventually, even though particular reviewed articles do not match entirely with the current analysis or LCA approach, several outcomes are still common among all the articles. The results prove that sanitary landfills have the most significant environmental impact compared to any other available treatment method and transportation tasks have a significant impact due to the usage of fossil fuels. Incineration practices present significant drawbacks attributable to heavy metals and fly ash, which have a detrimental impact on human health and climate change. However, the incineration processes also help to reduce resources usage due to electricity generation. Biomethanization practises have been positioned as a preferable treatment in contrast to aerobic digestion of biowaste since the first option produces energy throughout the process. Also, it has been proved that the implementation of pre-treatment processes in MBT involve significant environmental savings, thanks to the sorting tasks and subsequent readjustment of the treatment based on the recovery of materials or specific fractions from the initial mixed MSW. Finally, the efficiency through which citizens separate MSW in their households and in the disposal collection bins plays a fundamental role in the environmental and human health impacts. When high segregation efficiencies are obtained, less impact is recorded because each fraction can be treated through the optimal method from an environmental perspective.

3. METHODOLOGY

3.1. General framework of LCA

Life cycle assessment consists of a decision-making tool capable of quantifying environmental and human health impacts associated with a product or service, starting from raw material extraction, manufacturing, distribution, use, and disposal. Additionally, it is also able to determine the consumption of resources (Klinglmair *et al.*, 2014). The impacts and resource consumption are calculated based on all direct exchanges between the product system and the environment, considering inputs (water, energy or land use) and outputs (emissions to soil, water or air) throughout the whole life of the product/service.

This methodology is standardised by the International Organization for Standardization (ISO) 14000 series standards, specifically ISO 14044:2006, which provides specific requirements and guidelines to conduct a LCA. The required stages include goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), interpretation stage, and limitation statement, among others.

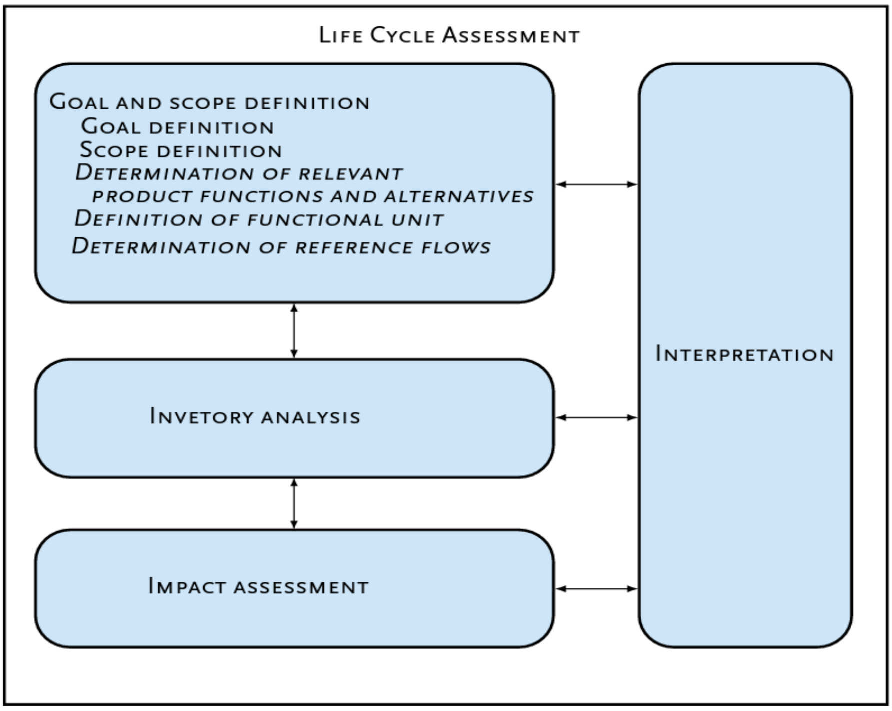

Figure 3.1 Phases of Life Cycle Assessment according to ISO 14044 (Weidema *et al.,* 2004).

Afterwards, to assess and quantify the environmental impacts of the previously defined inputs and outputs, these are classified based on the environmental categories such as climate change, acidification, eutrophication, etc. Moreover, these impact categories, also known as mid-point impact categories, can be grouped into end-point categories. This fact enables us to present the relative importance of the mid-point impacts into a single indicator such as human health, environment or resource usage. As an additional stage, the normalisation process can be conducted which according to ISO 14044, is an optional step of the LCA study. This process determines the severity of an impact related to reference values such as country-specific level.

3.2. Materials

3.2.1 OpenLCA

OpenLCA is an open-source and free software used for sustainability and life cycle assessment purposes developed by GreenDelta in 2006. This software can be used for multiple functions/exercises such as environmental life cycle assessment (LCA), economic life cycle costing (LCC) or carbon and water footprint, among other applications. The success and widespread implementation of OpenLCA is attributable to the free access without any license requirement or cost and user-friendly capabilities. For example, OpenLCA stands out for the rapidity and reliability in LCA calculations, the possibility of offering detailed insights and analysis results, the exporting capabilities or the continuous improvement and implementation of new features (GreenDelta, 2019). In particular, the OpenLCA version used for the LCA is the 1.10.3 version. Overall, the OpenLCA requires to establish/design four types of database elements for the modelling and comparison between products, systems or services. Firstly, the individual flows of the process need to be included which can describe elementary flows (describing material or energy of the environment entering or leaving the product system), product flows (describing material or energy exchanged between the processes of the product system) and waste flows (describing material or energy leaving the product system). Then, the processes need to be created which will be linked to the individual flows. Afterwards, the product system consists of all the processes and based on the environmental impacts of each product system can be calculated. Eventually, the project formation can be used to compare the environmental impacts of different product systems.

3.2.2 Ecoinvent

Ecoinvent consists of a Life Cycle Inventory (LCI) database created by a non-profit association dedicated to the availability of high-quality data for sustainability assessments worldwide. This database contains over 18000 well-documented life cycle inventory datasets covering various sectors. Each dataset can be attributable to a specific geographical location, and the geographic coverage is highly dependent on data quality and availability. Additionally, Ecoinvent provides several impact assessment methods with the corresponding impact categories. In the end, this database helps users to gain a better understanding of the environmental impacts of specific products or services (Ecoinvent, 2007). In particular, the Ecoinvent version used for this thesis is the 3.8 version which expanded the sectorial coverage compared with the previous versions. It includes 360 newly added and 700 updated datasets related to agriculture, batteries, chemicals and plastics, electronics or metals, among others.

3.2.3 Microsoft Office

Microsoft Office consists of a set of applications designed to help the users with their productivity and complete everyday tasks on a computer. Particularly, Microsoft Excel consists of a spreadsheet program which enables users to format, organise and calculate data. The Microsoft Excel version used for this thesis is the 2016 version specific for Apple laptops (Macbook). This tool allowed to calculate all the waste flows, transportation activities, and sorting efficiencies which were used as data inputs for the obtention of results in the OpenLCA software.

3.3. Waste treatment scenarios

This thesis aims to perform a comparative life cycle assessment of four different waste treatment scenarios in Barcelona city. The base scenario (S1) consists of the current treatment practices implemented in Barcelona city in 2020, and the percentages concerning the treatment options are calculated based on the initial weighted quantities in the primary destination facilities and taking into account the efficiency rates of each process from the treatment process. The second hypothetical scenario (S2) describes the treatment options according to the EU’s municipal waste objectives, such as limiting landfilling tasks up to 10% or reaching recycling rates of minimum 65%. The recycling activities include material recycling but also aerobic and anaerobic digestion of biowaste. The third hypothetical scenario (S3) consists of the same treatment practices as the S2, however, it entails 20% of overall MSW reduction. The fourth hypothetical scenario (S4) presents a future optimistic waste treatment hypothesis in which the recycling rate reaches up to 90%, landfilling is not available as a disposal option, and the remaining 10% is incinerated through energy recovery tasks. Additionally, the Table 3.1 apart from reflecting the MSW treatment options, it includes relevant data to each scenario such as the amount of MSW sorted per year, and the amount of MSW transported and the travelled kilometres.

Table 3.1 MSW treatment scenarios.

	S1	S2	S3	S4
Landfilling	29%	10%	10%	0%
Energy recovery	22%	25%	25%	10%
Material recycling	23%	31%	31%	50%
Anaerobic/Aerobic digestion of biowaste	26%	34%	34%	40%
Waste prevention	0%	0%	0%	0%
Transportation t per km	156827,56 * 575637,90	115131,75 * 255903,34	92539,85 * 205303,61	45081,65 * 54134,33

3.4. Goal and scope definition

3.4.1 Goal of the study

The study aims to perform and compare the life cycle impact assessment of four different scenarios, focusing uniquely on the treatment and disposal techniques implemented to the municipal solid waste in Barcelona city. The scenarios describe the current treatment options and three additional hypothetical situations, such as treatment practices according to the EU’s 2035 municipal waste objectives or future optimistic treatment practices in which the recycling rate reaches up to 90%. The intended audience of this assessment are governments of autonomous communities since they are accountable for developing regional waste management programs; local entities since they are responsible for providing the management services; policymakers; environmental agencies; and also the general public since it can be used as an awareness tool to present the human health and environmental impacts associated to the waste generated. The results could potentially be used to make decisions in the design of management systems, make recommendations to improve current legislation, and to provide insight into the waste treatment options where environmentally friendly adjustments could be implemented.

3.4.2 Definition of function and functional unit

The definition of the function of the product system and functional unit (FU) are a crucial initial phase of the scope's definition of the LCA. The FU is a key element of the analysis because it measures the function of the studied system, and it provides a reference to which inputs and outputs can be related (Weidema *et al.,* 2004). Moreover, the FU needs to be precise in order to set the bases to compare different scenarios, and it always needs to be related to the function or goal of the study. For this particular LCA of MSW treatment options in Barcelona, the four waste management scenarios have waste treatment as the primary function. The FU is determined based on the MSW treated in Barcelona city in 2020, being 630523,50 tons of MSW separately collected fractions and waste fraction.

3.5. Inventory

3.5.1 Inventory analysis

In order to conduct a comparative LCA of different MSW treatment scenarios in Barcelona city and to assess the environmental impacts generated by the waste treatment, it is necessary to have a detailed understanding of the process, facilities and types of waste involved. Particularly, the treatment facilities mapped in the Figure 3.2 are directly implicated in the MSW treatment of waste generated in Barcelona city.

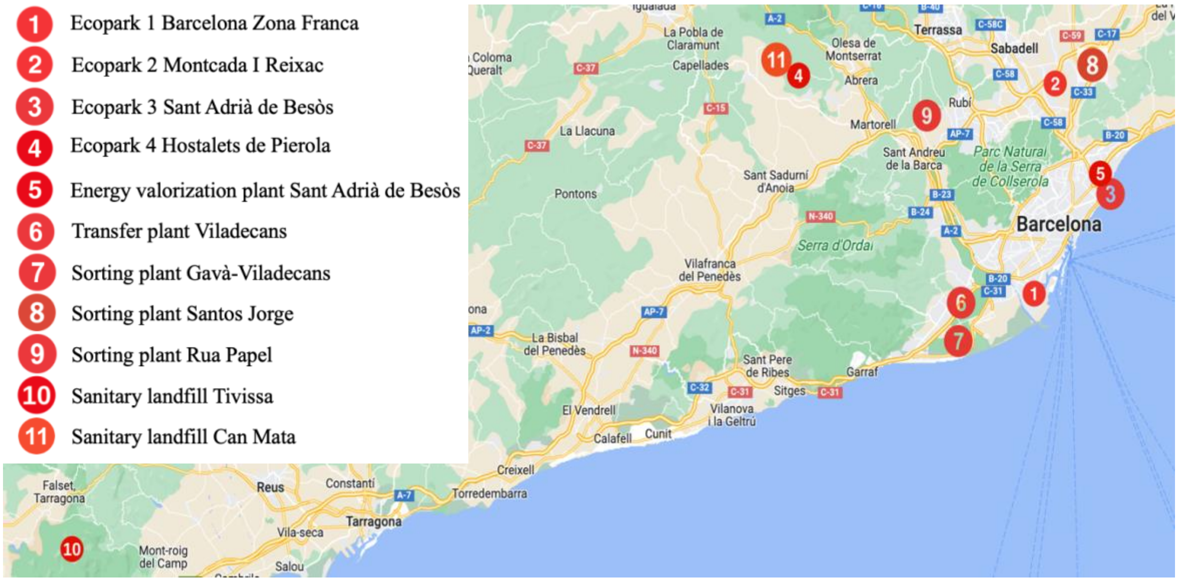

Figure 3.2 Treatment facilities involved in MSW waste management in Barcelona (2020) (Metropolitan Area of Barcelona, 2021).

Once the type of waste and the facilities are identified, it is crucial to search for actual data which is used as the basis of the analysis and LCA. In the Table 3.2, the MSW treated quantities are presented by treatment options and by facilities. These quantities are provided by the Metropolitan Area of Barcelona and they represent the MSW weighted once it reaches the first treatment facility after the collection process, such as the MBT plant, energy recovery plant, landfill or transfer plant. Additionally, the recovered material quantities and the anaerobic and aerobic digestion of biowaste quantities have been calculated based on the initial waste flow of the collected fractions and the efficiency rates provided by each treatment plant. The insertion of these waste quantities and the process flows in OpenLCA enables us to assess the environmental impact associated with these treatment activities.

Table 3.2 MSW treated quantities by treatment options and by facilities in Barcelona city in Scenario 1 (Metropolitan Area of Barcelona, 2021).

(tons/year)	Ecopark 1	Ecopark 2	Ecopark 3	Ecopark 4	Sorting plant	Paper & Glass	Directly disposed	Total
Landfilling	24227,88	51672,79	0,00	46013,34	3441,82	4236,42	51280,17	180872,42
Energy recovery	17544,32	57768,48	43613,24	0,00	0,00	0,00	20247,94	139173,98
Recovered materials	8776,96	19056,56	9912,10	10113,10	6073,80	89935,25	0,00	143867,77
Anaerobic digestion from biowaste separately collected	26736,84	29767,14	0,00	0,00	0,00	0,00	0,00	56503,98
Aerobic digestion from biowaste separately collected	0,00	0,00	0,00	12850,50	0,00	0,00	0,00	12850,50
Anaerobic digestion from biowaste sorted from mixed MSW	0,00	0,00	34692,35	0,00	0,00	0,00	0,00	34692,35
Aerobic digestion from biowaste sorted from mixed MSW	28319,90	0,00	0,00	34242,60	0,00	0,00	0,00	62562,50
Total	105605,90	158264,97	88217,69	103219,54	9515,62	94171,67	71528,11	630523,50

3.5.2 Process map and system boundaries

In order to deepen the understanding of the life cycle assessment of the MSW treatment options in Barcelona, it is essential to have an overview of all the processes involved in the waste management tasks and the relationship between them. For this purpose, the Figure 3.3 provides a clear and schematical representation of the waste management tasks, including fractions collected, type of facilities involved, transportation activities, treatment processes, by-products obtained, emissions, and also the system boundaries indicating which processes or elements are excluded or omitted from the study. However, it is important to acknowledge that the following figure consists of a summarised representation of the current practices since up to five different ecoparks, one transfer plant, one sorting plant, one energy-recovery plant, three sanitary landfills and two externally managed sorting facilities are involved in the overall treatment process. Precisely, the APPENDIX 1: PRIMARY AND FINAL DESTIONATION OF MSW IN BARCELONA (2020) presents a flowchart describing the primary destination and final destination (energy recovery or landfilling) of the separately collected fractions (biowaste, glass, light packaging and paper and cardboard) and the waste fraction. Additionally, APPENDIX 2: TREATMENT FACILITIES INVOLVED IN BARCELONA'S MSW MANAGEMENT SYSTEM and its sub-appendixes include individual flowcharts of the waste treatment facilities involved, the MSW fractions handled, the treatment processes and the end destination of each fraction collected.

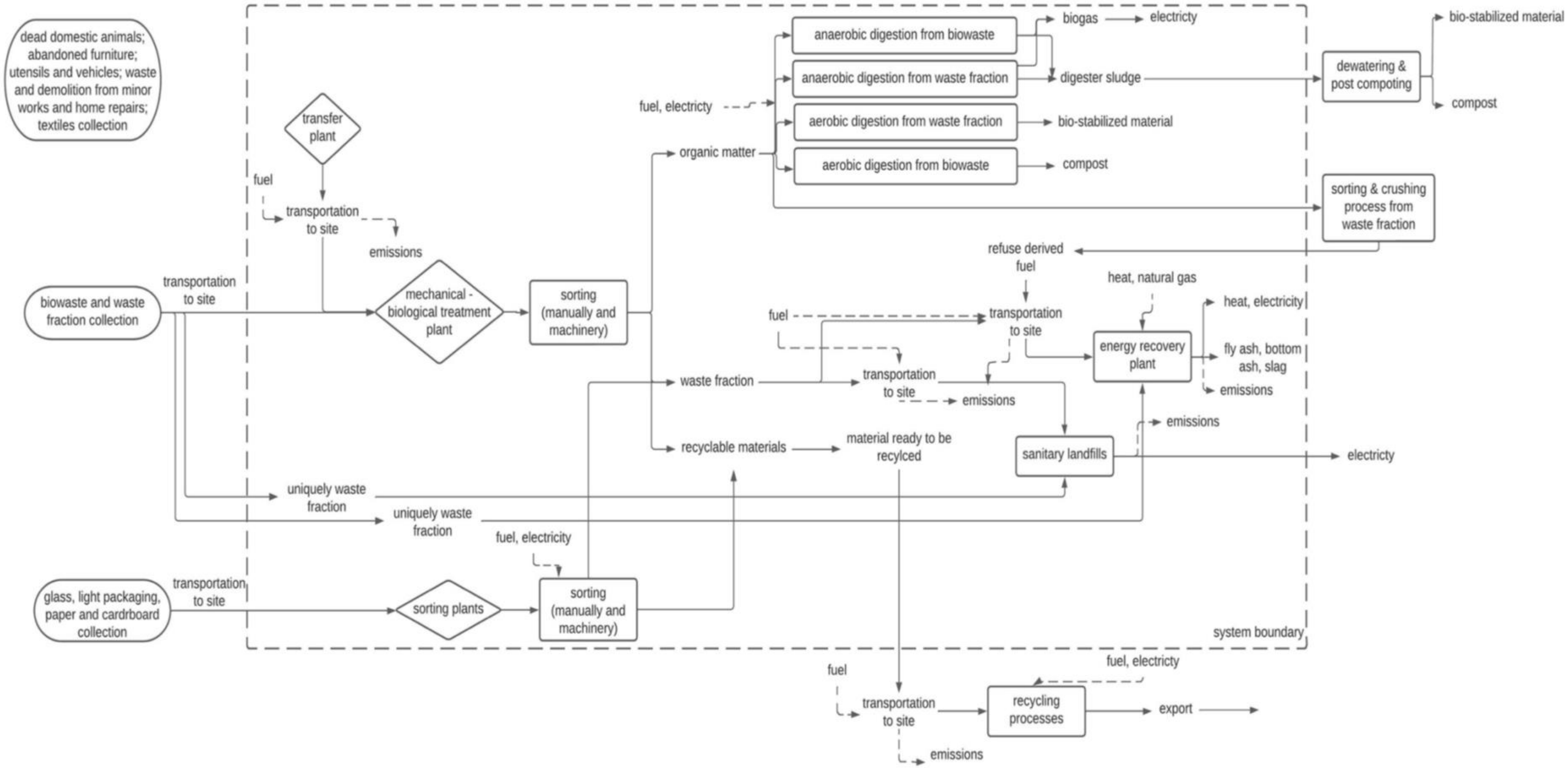

Figure 3.3 MSW management process map and system boundaries in Barcelona (Metropolitan Area of Barcelona, 2021).

Mechanical-biological treatment plants: Overall, in Barcelona's municipal waste management system, there are four mechanical-biological treatment plants involved which are located in ecoparks. These facilities are responsible for treating two fractions of MSW, the organic matter collected through selective collection and the waste fraction. Generally, the MBT plants combine mechanical sorting with biological treatment. However, not all the MBT plants involve the same waste treatments in Barcelona's scenario since it highly depends on the available facilities of each ecopark.

Initially, the biowaste and a certain portion of the waste fraction are collected and transported by trucks to the ecoparks in order to conduct pre-treatment and treatment processes. Throughout the whole process, these two fractions might go through similar operations but they are always handled in different waste streams to avoid the contamination of the fractions. A common first step of all the MBT plants once the fractions reach the ecoparks is the manually and mechanically waste sorting to separate three components: recyclable materials, organic matter and waste fraction. The mechanical sorting is generally done by a rotatory sieve which separates the waste by size; a ballistic separator which sorts the waste based on the shape, size and density; an electromagnet and electric inductor which separate the metal waste by electromagnetic currents; and an optical separator which separates the packaging waste based on the material type.

The recyclable materials extracted (glass, paper and cardboard, plastic and metals) are firstly compressed, packed and transported to recycling centres, where they are treated to obtain secondary raw materials, which afterwards are exported. However, the scope of this study does not analyse the transportation tasks to the recycling sites and the recycling processes.

On the other hand, the waste fraction separated from the MBT plants is partially sent to sanitary landfills and partially sent to energy recovery plants to obtain energy in the form of heat or electricity.

Finally, the biowaste sorted is subjected to biological treatments such as aerobic/anaerobic digestion or RDF fabrication. For this fraction is fundamental to keep the biowaste in separate streams, keeping apart the organic matter sorted from the waste fraction and the organic matter sorted from the biowaste collection. The organic matter obtained from the waste fraction can go through three different processes: aerobic digestion, anaerobic digestion and crushing process to obtain RDF. The products from these three processes are biogas converted to electricity, RDF combusted in energy recovery processes, and bio-stabilised material. In particular, the biowaste sorting by size and crushing to produce RDF uniquely takes place in the Ecopark 2 – Montcada I

Reixac. On the contrary, the organic matter obtained from biowaste collection can go through two processes: aerobic or anaerobic digestion. The products obtained are biogas converted to electricity and organic amendment (compost). The digestion processes are the same, however, the obtention of compost or bio-stabilised material depends on the origin of the organic matter, and its future utilisation is highly regulated by the law. For example, the bio-stabilised material cannot be used as an organic amendment in agriculture fields. Afterwards the anaerobic digestion processes, apart from obtaining biogas, there is the production of digester sludge. This product is dewatered and composted to obtain compost or bio-stabilized material. However, the treatment of the digester sludge is out of scope of this study.

Lastly, the electricity obtained from the biogas is re-used in the ecopark in which it has been generated. This electricity is used for multiple purposes such as lighting requirements or machinery requirements.

Sorting plants: The fractions composed of recyclable materials are sent to sorting plants to extract the recyclable materials (glass, paper and cardboard, plastic and metals) from the non-recyclable materials which have been wrongly sorted. For the Barcelona scenario, there are three sorting plants involved. The light packaging sorting plant is part of Ecopark 2 – Montcada I Reixac, and it is responsible for recovering recyclable materials from the light packaging fraction collection. Once the recyclable materials are separated, they are compressed, packed and transported to recycling centres. In the recycling facilities, the treatment of theses recyclable materials takes place with the final goal of obtaining secondary raw materials and afterwards export them to manufacturing processes. The waste fraction obtained from the light packaging sorting is sent to the energy recovery plant in Sant Adrià del Besòs. On the other hand, the glass and paper and cardboard separately collected fractions are externally managed by private companies: Ecovidrio for the glass fraction and Ecoembes for the paper and cardboard fraction. These fractions are sorted in the Sorting plant of Santos Jorge and Sorting plant Rua Papel respectively, to extract the recyclable materials and they will also will undergo recycling processes to obtain secondary raw materials. However, the waste fraction obtained from the glass and paper and cardboard fractions is transported and deposited in the sanitary landfill of Can Mata. Once again, the transportation to the recycling centres, the recycling treatment processes and the subsequent exportation are out of scope of this study.

Energy recovery: The waste fraction and derived refuse fuel are the only two fractions combusted in Barcelona’s waste management scheme, which currently account for 22% of Barcelona's total MSW treatment practices. The incineration processes uniquely take place in the energy valorisation facility located in the city's northern region of Sant Adrià del Besòs. The RDF reached the incineration plant from the Ecopark 2 – Montcada I Reixac, where the biowaste contained in the waste fraction collected is size sorted and crushed to form the derived fuel. On the other hand, the totality of the waste fraction, which has energy recovery as its final treatment destination, is transported to Sant Adrià del Besòs. The origin of the waste incinerated varies since it comes from multiple sources. Firstly, a certain portion of the waste fraction collected is directly sent to the incinerator without any kind of pre-treatment or valorisation process. Secondly, the Ecopark 1 – Barcelona Zona Franca and Ecopark 2 – Montcada I Reixac send the sorted waste fraction from the mechanical-biological treatments and the light packaging sorting plant to the energy recovery plant. Thirdly, the MBT plant in the Ecopark 3 - Sant Adrià del Besòs also sorts out the waste fraction, recovering the recyclable materials and incinerates the remaining fraction.

The energy recovery process begins when the waste fraction and RDF reach the incinerator plant. Initially, the incinerator chamber is fed with waste for at least three consecutive days. The combusted material must have a homogenous composition to achieve optimal waste incineration while avoiding temperature oscillations. In order to avoid temperature variations, the waste is continuously mixed. Additionally, there is a need for oxygen supply to maintain the flame and simultaneously prevent bad odours from escaping outside the facility. For twenty minutes, the waste is burned at a constant temperature of 900 degrees which ensures the complete incineration of the municipal waste and also guarantees the elimination of volatile compounds. Usually, there is no need to add extra fuel, except for the ignition, if any technical or maintenance shutdowns or if a sudden temperature outage happens. In those cases, natural gas is used to activate the auxiliary burners. The products of this energy recovery process are slag and heat. The smoke from the furnaces passes through a series of filters that prevent the emission of harmful pollutants into the atmosphere. Also, the slag (incombustible inert material) is collected, cooled down with water and transported to authorised handlers. This material can be used as road construction material or disposed of in a special sanitary landfill. The steam produced by the heat from the furnaces passes through the turbines and generates 200,000 MWh of electricity per year. In addition, about 100,000 tons of steam are supplied to the urban heat and cold network.

Landfilling: In Barcelona’s municipal waste management system, uniquely waste fraction is landfilled, and in particular, this fraction comes from different sources. Firstly, a certain portion of the waste fraction collected is directly transported to the sanitary landfill of Tivissa without any pre-treatment or valorisation process. Secondly, the waste fraction is sorted from the separately collected municipal waste fractions (glass, paper and cardboard, light packaging and biowaste) in the mechanical-biological treatment plants and sorting plants. This second source of waste is landfilled in two different sites in Catalonia: the sanitary landfill of Tivissa and the sanitary landfill of Can Mata. Overall, landfilling accounts for 29% of Barcelona's total MSW treatment practices.

Landfilling involves stabilising the disposed waste fraction, and the process entails five phases. Initially, the first phase occurs in aerobic conditions and the following four phases happen in an anaerobic environment. Precisely, due to the anaerobic digestion of biodegradable waste, landfill gas is produced which consists of approximately 60% of CH_4 and 40% CO_2. A network of chimneys is responsible for the collection of the landfill gas produced at the site, and afterwards, the gas is utilised for heating and electricity purposes. Additionally, landfill leachate is produced throughout the landfill process when liquid of external origin, such as rainfall, percolates through the disposed municipal waste and extracts soluble or suspended solids present in the waste. This leachate needs to be collected, and afterwards, it is treated in wastewater treatment plants.

Transfer plant: For logistic purposes, the transfer plant of Viladecans is involved in Barcelona's municipal waste management systems. This temporary plant stores a certain portion of the waste fraction collected. It is then transported to Ecopark 1 – Barcelona Zona Franca, Ecopark 2 – Montcada I Reixac and Ecopark 3 – Sant Adrià del Besòs. The waste transition between the transfer plant and the ecopark is needed to avoid surpassing the daily capacity of the mechanical-biological treatment plants. Currently, the transportation from the transfer plant accounts for 0,5% of the total transportation tasks.

Transportation: In the scope of this study, transportation activities are required for a couple of situations. Firstly, transportation between the transfer plant and the mechanical-treatment plants is needed to proceed with the treatment of the waste fraction without exceeding the total treatment capacity of the MBT plants. Secondly, transportation of waste fraction to energy recover plants and landfills, once the waste fraction is sorted from the separate collection fraction in MBT plants and sorting plants. The transportation tasks are conducted by a truck belonging to the EURO 5 emission standard, and its load capacity is 20 tons. This fact means that the trucks involved in the transportation tasks have installed diesel particulate filters (DPF), what allows to capture 99% of particulate matter reducing their total emissions, and they are registered from the 1st of January 2011. Even though the implementation of DPFs, these tasks are responsible for significant environmental emissions and important quantities of diesel.

3.5.3 Allocation

In the course of a process, sometimes more than one product is produced. This fact needs to be addressed by the life cycle assessment so that the environmental impacts from the process are distributed between the resulting products. This procedure can present difficulties because the impacts cannot be straightforwardly divided. In order to solve this issue, the allocation takes place. However, the ISO 14040 series recommends to avoid the allocation whenever is possible by two suitable methods: dividing the unit process into the number of sub-processes and collecting the input and output data related to these sub-processes or expanding the product system to include the functions related to the co-products.

For this study, the allocation has been avoided through system expansion. Several valuable by-products have been obtained from the MSW treatment operations and the system boundaries have been expanded in order to take them into account in the overall system. The production of biogas and subsequent electricity from anaerobic digestion; the production of compost and bio-stabilised material from aerobic digestion; and the obtention of electricity and heat from incineration processes have been added to the process map as it is shown in the **Error! Reference source not found.**.

3.5.4 Assumptions and limitations

The comparative LCA assessment of the treatment options of MSW in Barcelona encountered some limitations throughout the process, mainly due to the lack of available data. The study required to make certain assumptions to conduct the assessment:

- The total amount of MSW treated in the four scenarios remains the same as the quantities registered during the current practises (S1), except for the S3 which presents a 20% of waste prevention.
- The recoverable materials sorted from the collected fractions consist of glass, paper and cardboard, metals and light packaging.
- The biowaste fraction is uniquely manually sorted in the mechanical-biological treatment plants, meaning that no energy requirement is involved in the sorting process.
- The paper and cardboard separately collected fraction consist of 50% paper and 50% paperboard.

- The transportation tasks, from the transfer plant to the treatment plants and from the treatment plants to the landfills and energy recovery facilities, are conducted by trucks belonging to the EURO 5 emission standard.

- All the transportation distances have been estimated based on traditional truck routes.

- For all four scenarios, the waste initially transported to the transfer plant is the same as the transported in the current practises (S1). In fact, the MSW currently transported to the transfer plants only account for 0,5% of the total transportation activities. Additionally, the treated MSW quantities remain equal or decrease in the four scenarios, meaning there would not be an additional necessity to transport higher quantities of MSW to the transfer plant.

- In the S4, the waste fraction sorted from the glass and paper and cardboard collected fractions is incinerated instead of landfilled because in the S4 the landfill rate is 0%.

- The biogas, compost and bio-stabilised material production have been calculated individually for each mechanical-biological treatment plant considering the total amount of the respective by-product produced by the entire treatment facility and the biowaste input corresponding to Barcelona neighbourhoods.

- The plastic fraction from the light packaging in OpenLCA has been represented by waste polyethylene for recycling.

- The metal fraction from the light packaging in OpenLCA has been represented by tinplate scrap.

Additionally, the study presented the following limitations:

- The comparative LCA of the MSW treatment options in Barcelona has used data from 2020 instead of the most recent year since there is no data available for the last year, 2021.

- For the overall obtention of the scenarios data inputs, the calculation of the inputs has been done taking into account the treatment objectives set by the scenarios and also maintaining waste proportions from the recorded data published by the municipalities reflecting the current practices (S1).

- The collection tasks involved in the municipal waste management systems are excluded from this study due to the complexity and lack of information relative to these collection tasks.

- The scope of this study is the treatment of municipal solid waste, however, certain fractions of the MSW have been neglected, such as bulky waste, abandoned furniture, dead domestic animals or vehicles, among other fractions.
- The transportation of the recyclable materials from the sorting plants to the recycling centres and the recycling processes of the recyclable material fraction are excluded from this study.
- For the treatment of biowaste collected from waste fraction, there is no process available in OpenLCA to reflect this fraction's aerobic and anaerobic digestion. For this reason, the same treatment process has been implemented for biowaste separately collected and biowaste sorted from the waste fraction.
- In the current practices, after the anaerobic digestion of biowaste or waste fraction, there is an additional step which consist of dewatering and composting the digester sludge. This post-treatment of the digester sludge is out of scope of this study.
- The sorting by size and crushing process of the biowaste separated from the waste fraction in the Ecopark 2 - Montcada I Reixac is out of scope of this study, due to the lack of data.
- Even though, the process describes the conversion of biogas obtained from anaerobic digestion treatments to electricity. When addressing the LCA impact assessment and quantifying the impacts generated by anaerobic digestion, the electricity obtained from biogas was not included as an output due to data limitations and instead the biogas as a product itself was accounted.
- The database inputs used in OpenLCA do not correspond entirely to the actual treatment techniques. For example, the resource and energy consumptions or the emissions might not reflect the current practices.
- When available in OpenLCA, the data inputs and processes have been chosen to represent the European perspective. However, such data is not accessible for some processes, and global data is used instead.

4. RESULTS

4.1. LCA impact assessment

The Life Cycle Impact Assessment (LCIA) constitutes the third phase of the overall LCA framework, which assesses and quantifies the human health, resource and environmental impacts based on the life cycle inventory data. For this study, a full LCA impact assessment was conducted, including all the operational stage besides the facility construction, energy production, wastewater treatments, among other stages. Precisely, this phase of the LCA was conducted through the OpenLCA software using Ecoinvent databases. The results obtained are grouped and presented by eight different impact categories assessed at intermediary level. The assessment at midpoint level enables to address the impact earlier along the cause-effect chain before the endpoint is reached. The assessment of the magnitude of each impact category is directly correlated to the inputs and outputs flows of each scenario. The Table 4.1 contains the selected impact categories, its reference unit and brief description.

Table 4.1 Selected midpoint impact categories.

Impact category	Reference unit	Impact category description
Input-related impact category		
Energy resources: non-renewable – abiotic depletion potential (ADP): fossil fuels	MJ	Consumption of non-renewable energy resources such as fossil fuels for energy production purposes.
Output- related impact category		
Acidification	kg SO2-eq	The oxidation of polluting substances such as NO_x or SO_2 in contact with water, leads to the formation of acids such as nitric acid (HNO_3) and sulfuric acid (H_2SO_4).The deposition of this acids can harm the soil and water ecosystems, by decreasing the pH, causing seed germination failure, reducing photosynthesis rates, etc.
Climate change (GWP 100)	kg CO2-eq	Greenhouse gasses emitted to the atmosphere, by anthropogenic activities, contribute to the long-term alteration of the temperature and the alteration of the typical weather patterns.
Climate change: biogenic	kg CO2-eq	Biogenic climate change has the same consequences as the generic climate change impact category, but the difference relies in the source of the emissions. The CO_2 emissions are related to the natural carbon cycle, meaning that the emissions come from natural sources such as decomposition of organic matter.

Impact category	Reference unit	Impact category description
Eutrophication	kg PO4-eq	Eutrophication takes place in aquatic systems when greater abundance of limiting nutrient (nitrogen and phosphate) are found in the water body. The consequence of this phenomena are the increase in primary production and biomass of algae, and subsequent degradation of water quality and deterioration of the overall ecosystem.
Human toxicity (HTP inf)	kg 1,4-DCB-eq	The direct or indirect human exposure to chemical emission can have adversely affect on human health. There is a wide range of harmful substances such as persistent organic compounds (POPs), VOCs or heavy metals.
Photochemical oxidant formation (POFP)	kg ethylene-eq	The oxidation of VOCs and carbon monoxide (CO) in the presence of NO_x and sunlight, leads to the formation of ozone at ground level. This new component in the troposphere can damage the vegetation and causes human respiratory problems.
Land use	m2a	Land occupation for anthropogenic purposes such as facility construction, disposal landfills, road construction, etc.

4.2. Midpoint results interpretation

In order to assess the environmental and human health impacts generated by the current MSW treatment practices in Barcelona city and to compare the impacts generated by the three additional hypothetical situations, it is needed to compare the four scenarios based on the midpoint impact categories previously presented.

The results obtained for the four scenarios and for each midpoint impact category present the same form, since transportation activities are the primary and greatest contributor to the environmental and human health impacts of the overall waste treatment scheme in Barcelona city. From the Figure 4.1 and the Figure 4.2, it can be observed that the major contributor to climate change and human toxicity for all the scenarios are the transportation activities. Transportation tasks itself involve high quantities of greenhouse gas emissions and other emissions like nitrogen compounds. Additionally, these high-polluting tasks involve the production of diesel, road construction, truck production and maintenance, among other activities. However, a reduction of the transportation impact can be noticed throughout the four different scenarios, S1 having the greatest impact and S4 having the lowest impact. This reduction is related with the fact that transportation tasks are mainly required for the transportation of the waste fraction to landfills and incineration plant. The S1 describes the current practices and S2, S3 and S4 describe a change in the waste treatment approach towards waste prevention and circular economy meaning that those transportation activities would almost not be needed in S4.

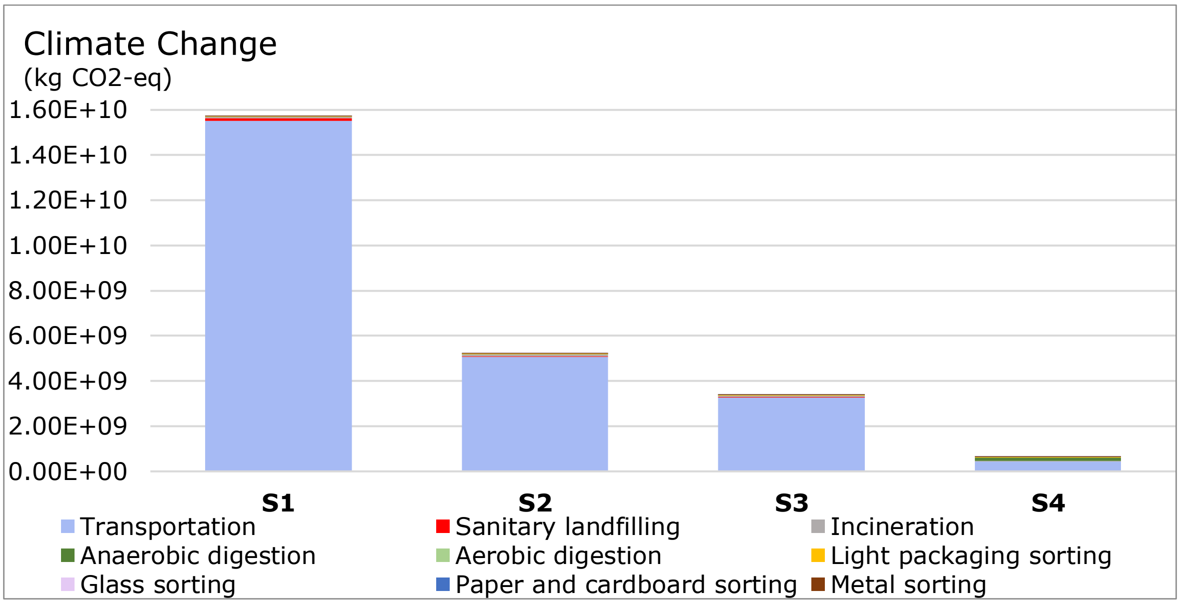

Figure 4.1 Midpoint level impact of climate change for scenarios including transportation tasks.

Additionally for the human toxicity results, the incineration practices represent the second most noticeable contributing activity due to the impact caused by the flue gas and slag which contain highly-polluting/harmful substances such as acids, heavy metals and dioxins and furans. Also, incineration processes present its lowest impact in S4 because it is the scenario with less amount of waste incinerated.

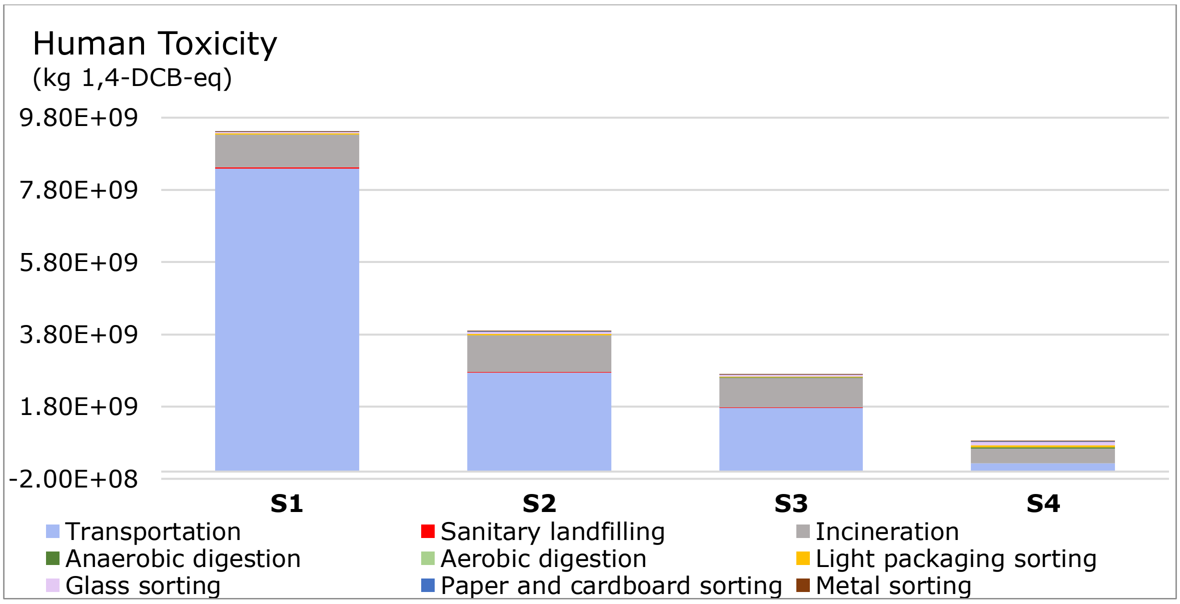

Figure 4.2 Midpoint level impact of human toxicity for scenarios including transportation tasks.

Since the transportation tasks represent the largest impact for all the impact categories and scenarios, and with the intend of focusing on the waste treatment options, the following results presented excluding the transportation activities from the assessment.

In the Figure 4.3, it can be observed that the main contributing activities to climate change are landfilling and incineration for the first three scenarios. The climate change main impacts generated by landfilling are due to emissions of CH_4, CO_2 and NO_X which are three of the main greenhouse gases which contribute to climate change. Also, further contribution is due to the sanitary landfill construction, the electricity requirements for the operation or the wastewater treatment plant construction. On the other hand, the incineration impact is mainly caused by the CO_2 and NO_X emissions which again are greenhouse gases. Additionally, several compounds or activities required for the treatment of the flue gas and slag end up contributing significantly to climate change. For example, the production of quicklime or ammonia used to neutralise the acidic pollutants contained in the flue gas, or the landfilled slag contribute to impact caused by incineration tasks. Likewise, the impact generated by the light packaging sorting is primarily attributable to the electricity and fuel requirements of the machinery and the steel production for the construction of the machinery.

For the first three scenarios, the climate change impact is progressively decreasing because the main two contributing activities become less relevant in the waste treatment scheme. In the S4, the results completely differ since the waste treatment is based 90% on recycling and 10% on incineration. Precisely, the two main contributing activities to climate change are the anaerobic digestion and incineration. In particular, the anaerobic digestion of waste presents the highest impact in S4 because this treatment method requires a lot of inputs such as heat or electricity and also generates high quantities of CH_4 and CO_2. Also, in this last scenario the quantities of biowaste treated by anaerobic digestion are significantly larger than in previous scenarios and that would explain the increase in its impact.

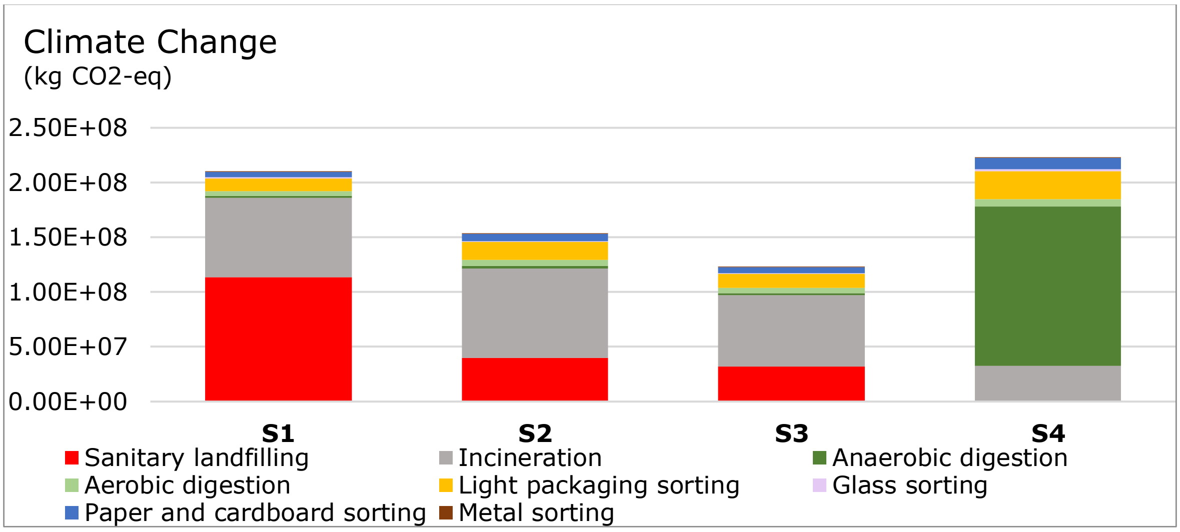

Figure 4.3 Midpoint level impact of climate change for scenarios excluding transportation tasks.

The biogenic climate change results reflect the climate change impact caused by the carbon emissions generated from natural sources such as the decomposition of organic matter. For the S1, S2 and S3, sanitary landfilling constitutes the principal source of biogenic carbon emissions. The landfill practices involve the decomposition of the biodegradable organic matter disposed in the landfills under anaerobic conditions which result in the formation of natural carbon emissions such as CH_4 and CO_2. On the other hand, the main source of biogenic carbon emissions in S4 is the anaerobic digestion of biowaste. This process involves the digestion of organic matter by the action of microorganisms under anaerobic conditions and this precise decomposition generates high quantities of CH_4 and CO_2 which consists of a natural source carbon emission.

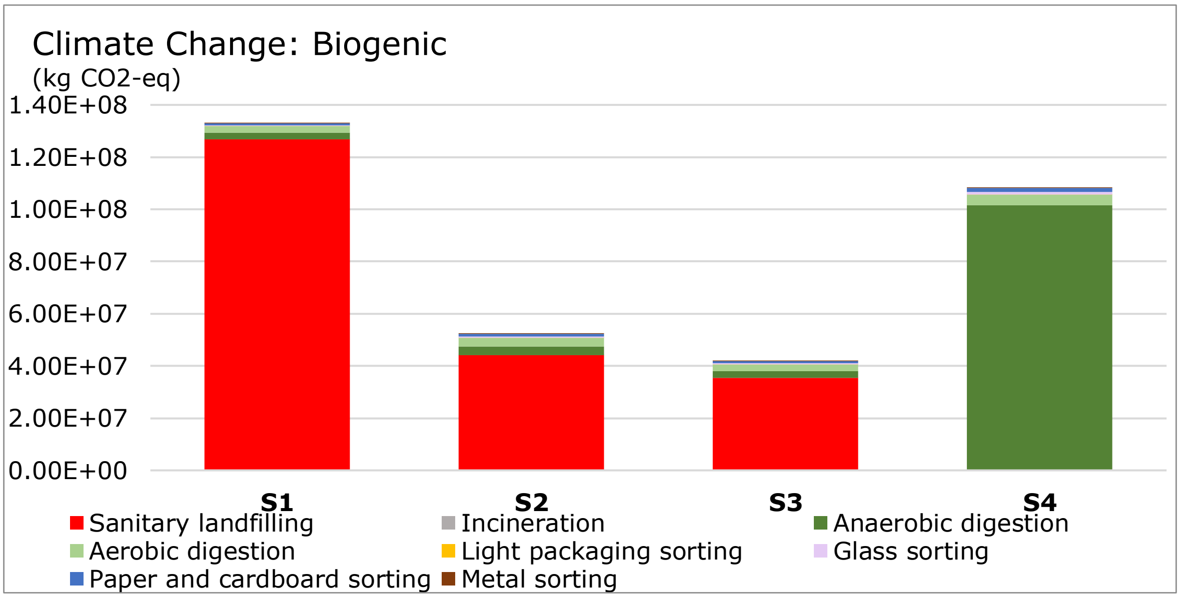

Figure 4.4 Midpoint level impact of biogenic climate change for scenarios excluding transportation tasks.

The acidification impact for the first three scenarios is quite similar based on the contributing treatment methods, being aerobic digestion the greatest contributor and afterwards all the remaining treatment options having comparable impacts. The aerobic digestion has a high impact due to the production of ammonia during the composting process. Likewise, in the S4, ammonia is produced during the anaerobic digestion of biowaste and that explains the higher impact on this category. Additionally, it needs to be considered that in S4, larger amounts of biowaste are anaerobically digested than composted.

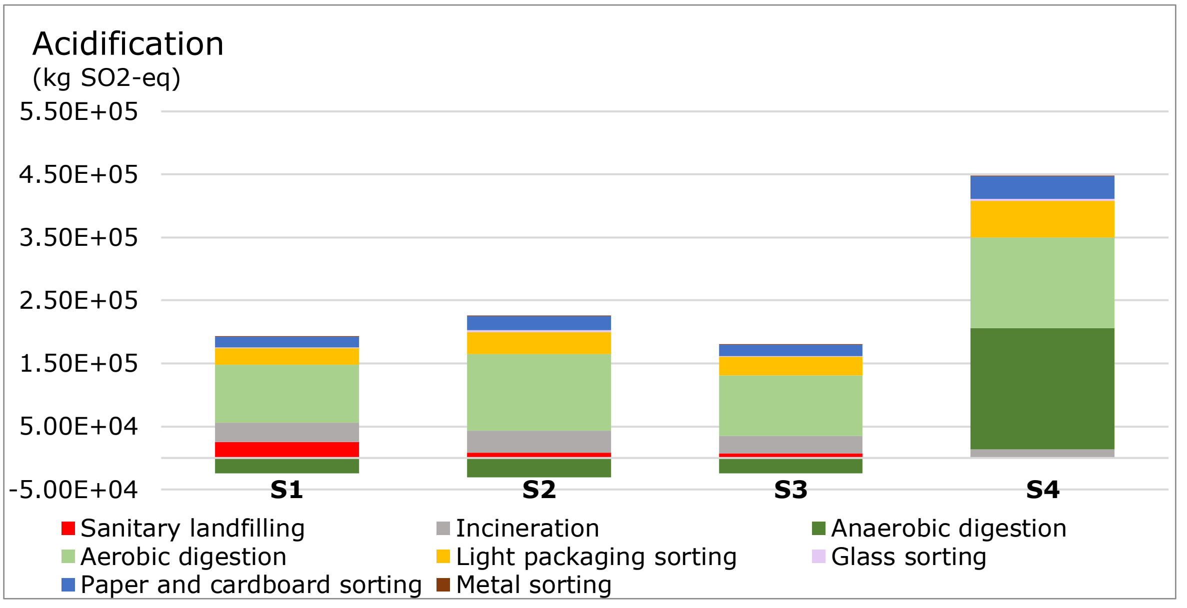

Figure 4.5 Midpoint level impact of acidification for scenarios excluding transportation tasks.

The principal waste treatment which contributes to the eutrophication impact are sanitary landfilling. The element causing this impact is the leachate generation which contains contributing substances to this impacts such as ammonia or dissolved organic. Additionally, it is important to acknowledge that even though the incineration rate drops until 10% of the total MSW treated in S2 and S3, it would still be the main contributor to this impact category.

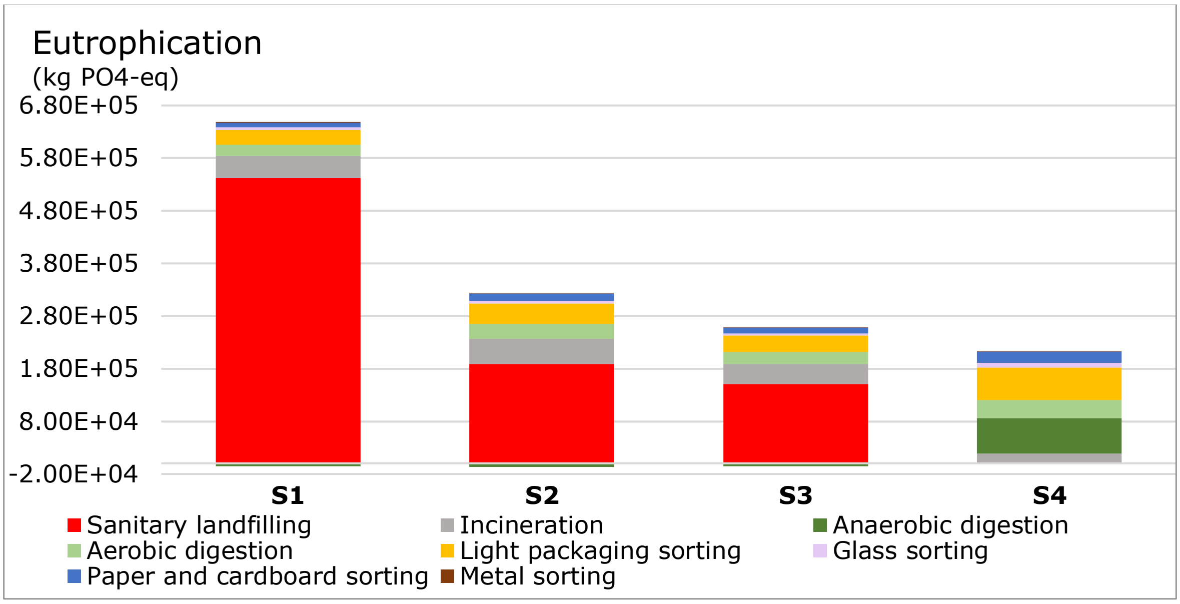

Figure 4.6 Midpoint level impact of eutrophication for scenarios excluding transportation tasks.

In the Figure 4.7, it can be observed that the incineration tasks are the most impactful activity to human health among the other treatment methods for all the four scenarios. The toxicity towards humans is consequence of the presence of certain compounds in the flue gas and the slag, since they contain acids and precursors; dioxins and furans; and heavy metals. All the mentioned substances/compounds can have a detrimental impact on humans and the last two have the ability of bioaccumulating and moving across the food chain what makes them even more dangerous in the long term. The increase in the human toxicity in S2 is caused by a higher incineration rate. Overall, these results reflect a positive fact because if incineration practices are not being conducted for waste treatment, the human toxicity impact related to waste treatment is significantly reduced since there are no other major contributors.

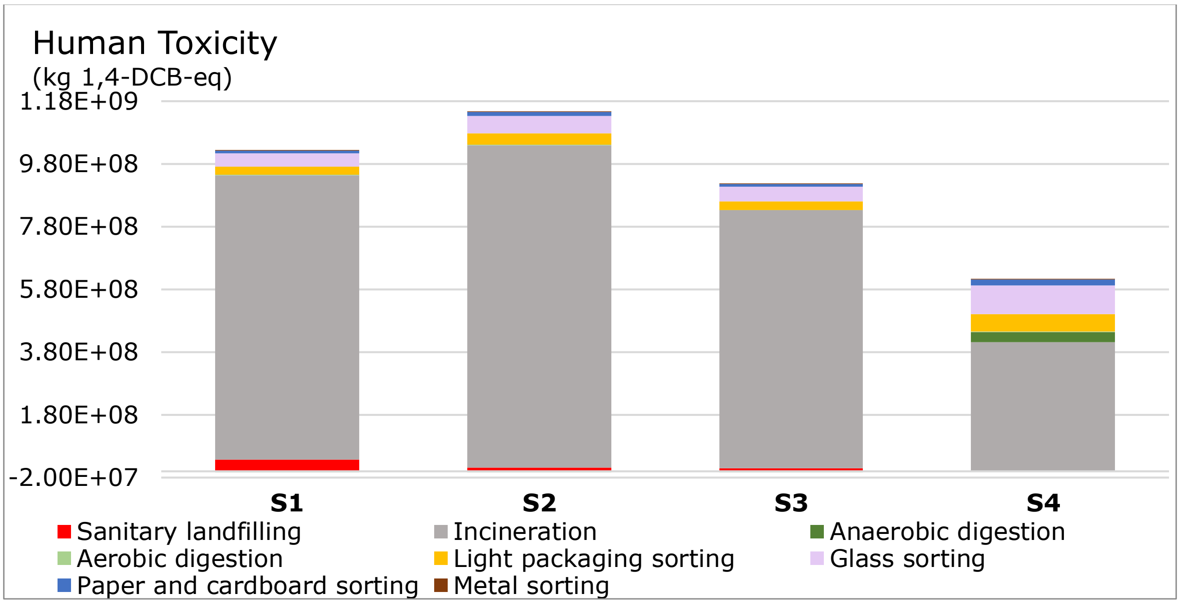

Figure 4.7 Midpoint level impact of human toxicity for scenarios excluding transportation tasks.

The photochemical oxidant formation is associated to the oxidation of VOCs and CO. The main treatment contributing to this impact category are the sanitary landfills because during the decomposition of the biodegradable organic matter in the disposal sites, emissions of VOCs are generated. The decrease in the impact throughout S2 and S3 is simply justified as lower landfilling rates in S2 and less waste generated in S3 while maintaining the landfilling rate the S2. However, in the S4 anaerobic digestion becomes the main contributor to this impact and in particular, the heat input requirements is the responsible for the 80% of the impact. Precisely, the heat input is required to be able to obtain the optimal temperature inside the reactor. In fact, NO_x and VOCs are generated during the production of heat and electricity in power plants, which are strong contributors to the photochemical oxidant formation impact. Additionally, it is worth to mention that anaerobic digestion with biogas production and incineration with energy recovery are located at the same level in the waste hierarchy and therefore in certain categories the impact from anaerobic digestion processes can have even a higher impact.

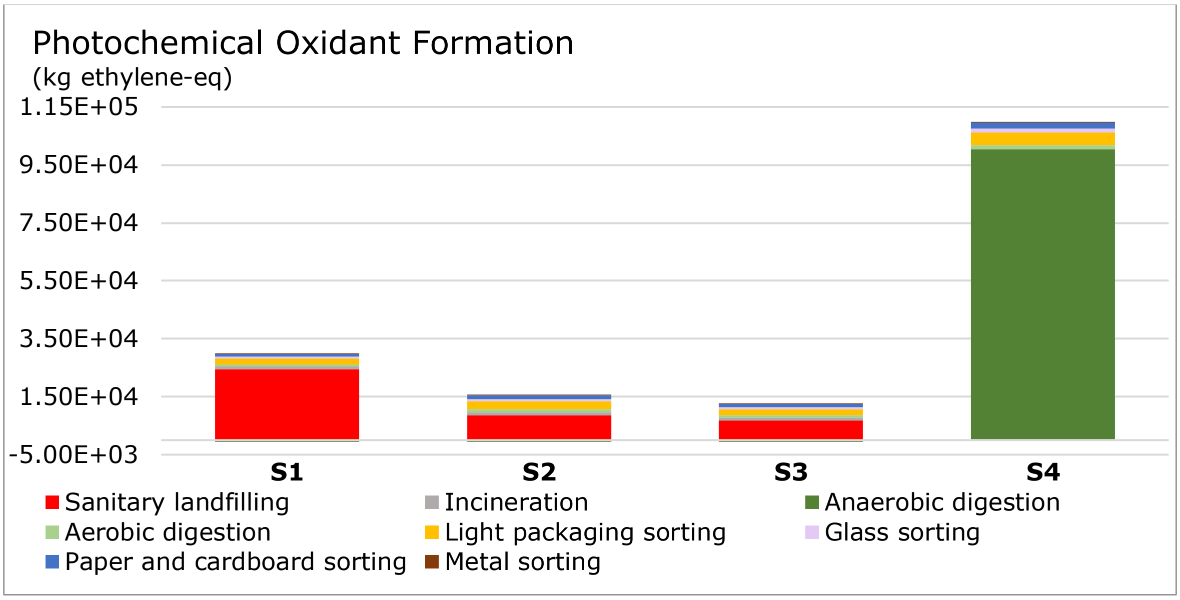

Figure 4.8 Midpoint level impact of photochemical oxidant formation for scenarios excluding transportation tasks.

The fossil fuels depletion impact is based on the consumption of fossil fuels during the treatment processes. The impact results reflect that the sorting processes such as light packaging sorting or paper an cardboard sorting require significant amounts of energy for the machinery operation. For the S4, the main activity contributing to the fossil fuel depletion is the anaerobic digestion and as it has been previously mentioned this technique requires a lot of inputs of which heat and electricity are present. Important to highlight that in the incineration processes have a lower impact on this category because the incineration plant is capable of recovering heat and electricity from the combustion process and this fact reduces significantly its impact.

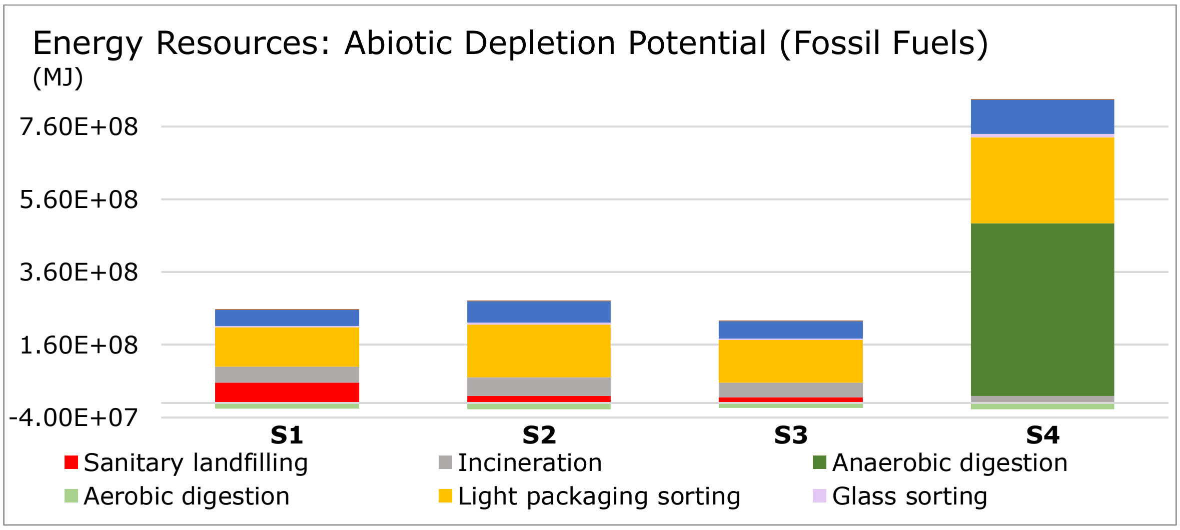

Figure 4.9 Midpoint level impact of fossil fuels depletion for scenarios excluding transportation tasks.

In the Figure 4.10, the land use impact is presented and the results differ between the first three scenarios in comparison with the S4. Initially, land use had five main activities which require greater amount of land. Firstly, sanitary landfills have the greater impact on land use because they require large land spaces to locate the disposal sites. In addition, once the disposal site is closured, it requires several years of monitoring and rehabilitation before the land is usable again which entails that the land use impact is created during the operational period but also during the closure period. Secondly, the aerobic digestion of biowaste requires land use to locate the space for the composting tunnels. Moreover, it required additional space for the operation of the different machinery for aerating, the watering systems, the odour treatment components such as the biofilters. Thirdly, the sorting processes of recyclable material do require certain space for the big machinery involved in the separation processes, being the plastic sorting the most demanding and the metal sorting the least demanding. Likewise, incineration processes also require certain space to be able to locate the combustion chamber and adjacent machinery involved in the incineration and energy recovery process. In particular, the anaerobic digestion presents negative values for the first three scenarios since the biogas produced during the process compensates the land use impact. However, in the S4 where anaerobic digestion process is one of the main treatment methods, its impact to land use becomes the most significant. This impact is caused by the necessity of locating the digestor and biogas storing facility. Additionally, a significant contribution to land use comes from the location of power plants to fulfil the huge heat requirements.

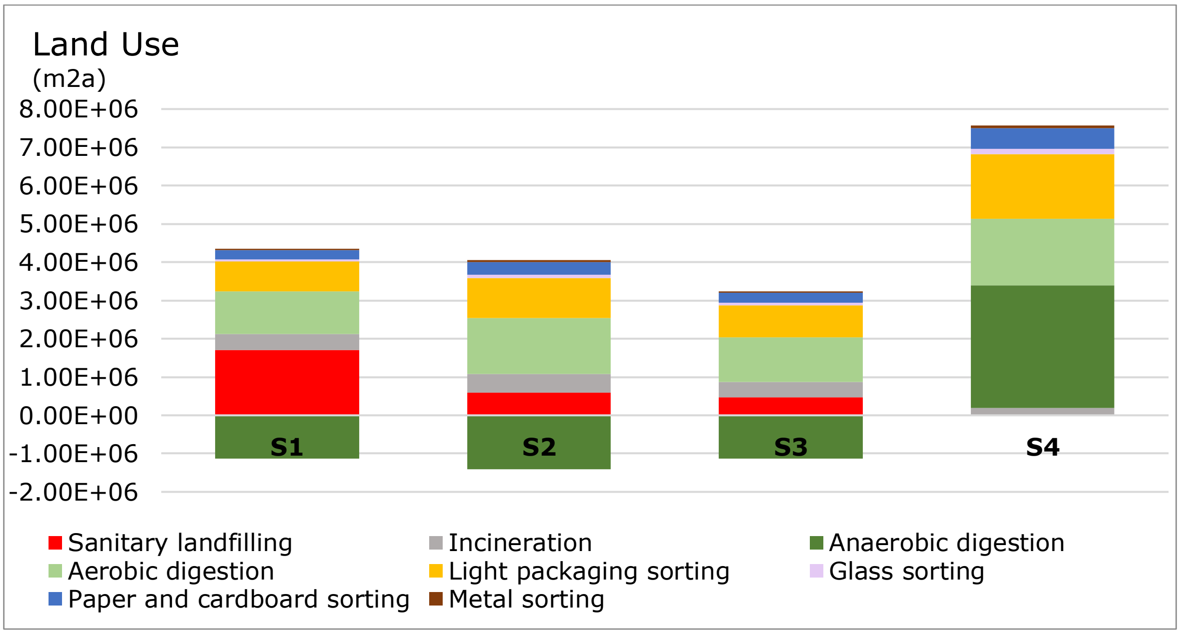

Figure 4.10 Midpoint level impact of land use for scenarios excluding transportation tasks.

Additionally, it is important to stand out that several valuable by-products are obtained from different treatment methods as it is shown in the Table 4.2. From incineration tasks, energy is recovered in form of heat and electricity which afterwards is supplied to the urban heat and cold network. From the sorting processes, recyclable materials (plastic, glass, metals, paper and cardboard) are recovered and they can potentially be used as secondary raw materials afterwards they undergo recycling processes. From the anaerobic digestion, biogas is obtained which is converted to electricity to be used in the ecopark for multiple purposes such as machinery requirements. Finally, from aerobic digestion two products are obtained based on the origin of the biowaste, compost and bio-stabilised material which can be used as organic amendment and landscaping material respectively.

Table 4.2 By-products obtained during the waste treatment in Scenario 1.

By-products	Waste input (tons)	Energy recovered (MWh)	Recyclable materials (tons)	Biogas (m^3)	Compost (tons)	Bio-stabilized material (tons)
Incineration	139173,98	88400,00	-	-	-	-
Sorting processes	569404,67	-	143867,77	-	-	-
Anaerobic digestion	91196,33	-	-	14422161,35	-	-
Aerobic digestion	75413,00	-	-	-	8086,65	22949,95

Table 2.1

4.3. Results and discussion

In order to provide an additional perspective and validation to the results obtained in this study, the results have been compared with results from published articles which were addressed in the theoretical overview in the LCA case studies section. Also, it has to be mentioned that the published papers do not have the same intended scope but general results about waste management systems and most specifically about treatment options can still be compared.

From the article of Fernández-Nava, Y. *et al*. and Güereca, L. *et al*., it can be contrasted that transport tasks produce significant environmental impacts in all the midpoint impact categories analysed.

Particularly in the article published by Fernández-Nava, Y. *et al*., incineration processes were the main contributor towards human toxicity and climate change. These facts match with the obtained results, except for the climate change impact category being the greatest contributor, since in this study sanitary landfills were the first and incineration activities were second.

From the article published by Montejo, C. *et al*., firstly it is stated that MBT plants play a crucial role in recycling activities since they are capable of sorting out the recyclable materials from the collected fractions. This is the precise reality in the current MSW treatment scheme in Barcelona city because the biowaste separately collected fraction and the waste fraction undergo pre-treatment and treatment processes in the MBT plants, through which we are able to obtain recyclable materials, compost, bio-stabilized and biogas which afterwards is converted to electricity. Also, their results agree with the fact that landfilling practices are the main contributor to climate change and also predicts that anaerobic digestion practices can be an important source of carbon emissions if large quantities of biowaste are involved. Finally, the article mentions that the RDF could be beneficial only if the right type of waste material is implemented.

The articles of Bueno, G. *et al*. and Güereca, L. *et al*., highlight the fact that when incinerating plants have the possibility of energy recovery, its impacts related to climate change and fossil fuel depletion are considerably minimised. This phenomena has been observed in this study for the same midpoint impact categories.

From the article of Güereca, L. *et al*., firstly, it can be corroborated that eutrophication impact is primarily derived from landfilling practices due to the leachate's components such as ammonia or chemical oxygen demand. Secondly, it is described that acidification impact category can potentially rise significantly due to composting activities when increasing amounts of biowaste are involved, mainly caused by the ammonia emissions. Thirdly, it validates the fact that the land use impact will increase when large amounts of biowaste are composted due to the space requirements for composting tunnels.

Finally, based on by Güereca, L. *et al*. and Montejo, C. *et al*. recommendations, anaerobic digestion with electricity recovery should be prioritized against aerobic digestion because those facilities would not require external electrical power and its environmental impact would be minimised. However, this studies' results disagree with the recommendation because anaerobic digestion obtained greater impact results than composting. Precisely, the difference is caused by the fact that this study conducted a full LCA and only considered the environmental perspective, and the analysed published papers uniquely addressed the operational stages and provided recommendations from an economically, efficiency point of view besides the environmental.

5. CONCLUSIONS AND RECOMMENDATIONS

Throughout this study, the current municipal solid waste treatment practices in Barcelona city have been analysed and its environmental impacts have been quantified. Additionally, three hypothetical scenarios were set accordingly to the transition towards the EU waste targets and circular economy approach.

Initially, the LCA impact assessment results revealed that the transportation activities are the primary and greatest polluting source among the other treatment activities for all the scenarios. For this reason and with the intent of focusing on the MSW treatment options, the comparative results excluding transportation tasks were presented for eight different midpoint impact categories: acidification, climate change, biogenic climate change, eutrophication, human toxicity, photochemical oxidant formation, energy resources: fossil fuel depletion and land use.

Overall, from a waste treatment perspective, human toxicity was the highest impacted category for all the four scenarios and it was mostly caused by incineration processes and the emitted substances: acids and precursors, heavy metals, dioxins and furans.

Also, the sanitary landfill results revealed that this treatment method is the worst from an environmental point of view since it is the main contributor for five of the eight midpoint impact categories addressed: climate change, biogenic climate change, eutrophication, photochemical oxidant formation and land use.

The sorting processes of light packaging, glass, metals and paper and cardboard only presented significant environmental impacts for fossil fuel depletion and land use. This results are logical since the sorting machinery require electricity and fossil fuels for its operation, and the sorting facilities require large spaces to locate the machinery and storage areas. Precisely, the sorting process of light packaging was the major contributor to fossil fuel depletion among all the treatment methods analysed.

The biowaste aerobic and anaerobic digestion results for S1 revealed that both types of treatments have small environmental impact in almost all the assessed categories. Except for acidification and land use, because firstly the aerobic/anaerobic digestion of biowaste entails the production of ammonia what triggers the acidification impact, and secondly the composting tunnels and the anaerobic digestors, gasometer and power plants require large spaces. However, the results reflected that if larger amounts of waste would be treated through these methods as the S4, its impacts would also become more significant. Overall, anaerobic digestion presented worse environmental profile than aerobic digestion, fact that contradicts other published articles. These results can be explained because the anaerobic process used for the LCA impact assessment had a lot of inputs such a heat and electricity. Additionally, the analysed articles conducted an LCA uniquely taking into account the operational stages, and evaluating the treatment process from different perspectives such as financially, efficiency or environmental. However, this study evaluated the treatment options uniquely from an environmental point of view and conducted a full LCA considering the operational stages besides the facility construction, transportation tasks, wastewater treatment, among other stages.

For all the impact categories, the S3 results were better compared to S2 from an environmental perspective, what demonstrates that waste minimization is a key goal to meet in order to reduce the impacts associated to MSW treatment. Additionally, the results reflected that even the most sustainable treatment practices have its own environmental impacts and for this reason, the waste minimization approach would be the correct path to follow and complemented with treatments following the waste hierarchy. Furthermore, from waste treatments, it is possible to obtain valuable by-products such as secondary raw materials, compost, bio-stabilised or biogas.

However, additional changes can be implemented to improve the waste management systems in Barcelona city. Firstly, it is suggested to avoid the direct disposal or incineration of waste fraction, without any pre-treatment or valorisation process. Also, it is recommended to reduce the amounts of waste incineration and landfilling in order to avoid the majority of transportation tasks and its main impacts to climate change, human toxicity and eutrophication. Secondly, related to the RDF formation, it would be recommended that the material used as RDF would not be biowaste because precisely, this type of waste do not have high calorific values and for incineration purposes does not provide much value. Additionally, the production of RDF involves energy-intensive processes. Thirdly, the MSW separation and collection should be improved by the citizenship since the waste fraction is still the predominant fraction collected and 56% of its composition could be potentially recycled. Finally, it is recommended that for the following decades, the emphasis is laid in the recycling activities since waste is utilised and it is possible to offer a new life to materials which are still valuable.

Additionally, future assessments would be recommended to improve the overall accuracy of the results since the database processes used in the OpenLCA software did not entirely correspond to the actual treatment practices. Additionally, several limitations related to the complexity or lack of data availability were encountered. Consequently, certain assumptions were made and the scope of the study was narrowed down, neglecting the transportation collection systems, recycling processes and certain MSW fractions such ad bulky waste or abandoned furniture.

Finally, the implementation of data collection tools with updated data of the waste generation and process-specific information of Barcelona city would improve the transparency of the process and its organizations involved, and also it would facilitate future assessments of the waste management systems.

SUMMARY

Municipal solid waste has experienced a worldwide increase during the last centuries and waste management systems have been fundamental to address the proper collection, transport, treatment and disposal of the waste. Precisely, these processes entail a high complexity due to the MSW composition and its complex character, which can lead to a potential adverse impact on the environment and human health.

Barcelona's waste management scheme is rather challenging due to the large amounts of handled waste and due to the complexity of the process in which several governmental bodies and private companies are involved throughout the whole process.

The MSW in Barcelona city is composed of biowaste in its bigger proportion, and then the separate collection of paper and cardboard, glass and light packaging matches the total amount of biowaste collected. Nonetheless, in the waste collection system, there is an additional fraction called waste fraction which should collect the waste without available valorisation methodologies. However, this fraction is still nowadays the predominant fraction collected and its composition is 44% of actual waste fraction and 56% of recyclable waste. This fact reflects the necessity of improvement in waste separation tasks by the citizenship and the huge potential for further recycling what would ease the process of reaching EU waste goals.

The aim of this study is to assess and quantify the environmental impacts generated by the current municipal solid waste treatment practices in Barcelona city. Moreover, three additional hypothetical MSW treatment scenarios, which describe treatment options prioritizing waste minimization and circular economy, have been addressed and compared with the current practices. Finally, the end goal is to provide a comprehensive understanding of the environmental impact associated to the MSW treatment and to recommend improvements for Barcelona's municipal waste treatment scheme.

In order to achieve these objectives, a comparative life cycle assessment of the current MSW treatment practices and three hypothetical scenarios was conducted using the OpenLCA software and Ecoinvent database. Within the LCA, three separately collected waste fractions (light packaging, glass, paper and cardboard) and the waste fraction collection were assessed. Additionally, Barcelona's waste management system included four MBT plants, three sorting facilities, two sanitary landfills, one energy valorisation facility, one transfer plant and the transportation tasks within the treatment processes.

The autonomous, regional and European legal framework related to MSW management was analysed to obtain a comprehensive understanding of the current direction and

approach towards waste management systems. Precisely, the three additional hypothetical scenarios were set according to the EU waste management targets and the waste hierarchy concept.

The LCA impact assessment results revealed that the transportation activities are the primary and greatest polluting source among the other treatment activities throughout all the four scenarios. However, the reduction in landfilling and incineration rates involve an implicit and significant reduction of the transportation tasks and consequently its associated impacts. On the other hand, focusing uniquely in the MSW treatment options, the comparative results were presented at midpoint impact level for eight different impact categories: acidification, climate change, biogenic climate change, eutrophication, human toxicity, photochemical oxidant formation, energy resources: fossil fuel depletion and land use.

Focusing uniquely on the waste treatment options, human toxicity was the highest impacted category for all the four scenarios and it was mostly caused by incineration processes. Also, sanitary landfill results revealed that it is the worst method from an environmental point of view since it's the main contributor for climate change, biogenic climate change, eutrophication, photochemical oxidant formation and land use. The sorting processes did not present huge impacts, except for fossil fuel depletion and land use due to the machinery requirements. The biowaste aerobic and anaerobic digestion treatments for the current practices have rather small environmental impact, except for acidification and land use, and when larger amounts of waste would be involved, its impacts become more significant. Overall, with the results from S3 compared to S2, it has been demonstrated that waste minimization is the correct approach to follow while being complemented by sustainable treatments, which also enable the obtention of valuable products. Finally, several recommendations to the governmental bodies have been proposed in order to improve the MSW management systems.

Future assessments should be conducted to improve the overall quality of the results since the database processes used in the OpenLCA software do not correspond entirely to the actual treatment practices. Additionally, several limitations related to the complexity or lack of data availability were encountered. Consequently, certain assumptions were made and the scope of the study was narrowed down, neglecting the transportation collection systems, recycling processes and certain MSW fractions.

Key words: Municipal Solid Waste, Waste management systems, Waste treatment, Life Cycle Assessment, , Impact categories, Environmental Impacts, Impact Assessment.

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APPENDIX 1: PRIMARY AND FINAL DESTIONATION OF MSW IN BARCELONA (2020)

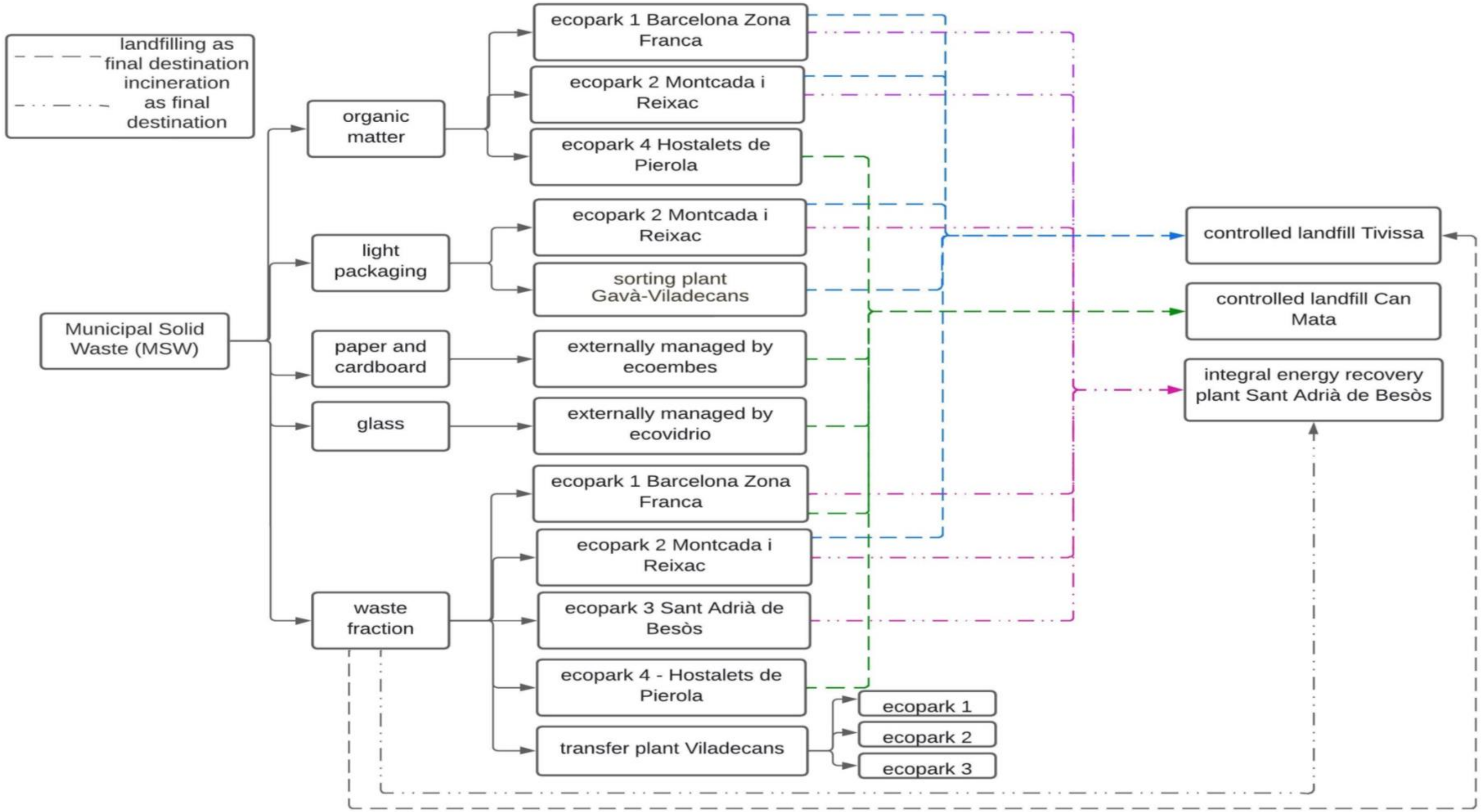

Figure 7.10.1MSW management in Barcelona by collected fractions and primary and final destination of the MSW (Metropolitan Area of Barcelona, 2021).

APPENDIX 2: TREATMENT FACILITIES INVOLVED IN BARCELONA’S MSW MANAGEMENT SYSTEM

The following appendix comprises seven different sub-appendixes consisting of individual flowcharts which describe the waste treatment facilities involved in Barcelona’s municipal solid waste treatment:

- A2.1 Ecopark 1 – Barcelona Zona Franca
- A2.2 Ecopark 2 - Montcada I Reixac
- A2.3 Ecopark 3 - Sant Adrià de Besòs
- A2.4 Ecopark 4 - Hostalets de Pierola
- A2.5 Sorting plant - Gavà-Viladecans
- A2.6 Transfer plant – Viladecans
- A2.7 Fractions externally managed by private companies

Each diagram, describes the typology of treatment facility (mechanical-biological treatment plant, sorting plant or transfer plant) involved in the waste management process. Additionally, it is detailed the MSW fractions handled by each facility, the different treatment processes (aerobic or anaerobic biowaste digestion, incineration, landfilling, recycling activities), the end destination of each fraction collected and the by-products obtained.

A2.1 Ecopark 1 – Barcelona Zona Franca

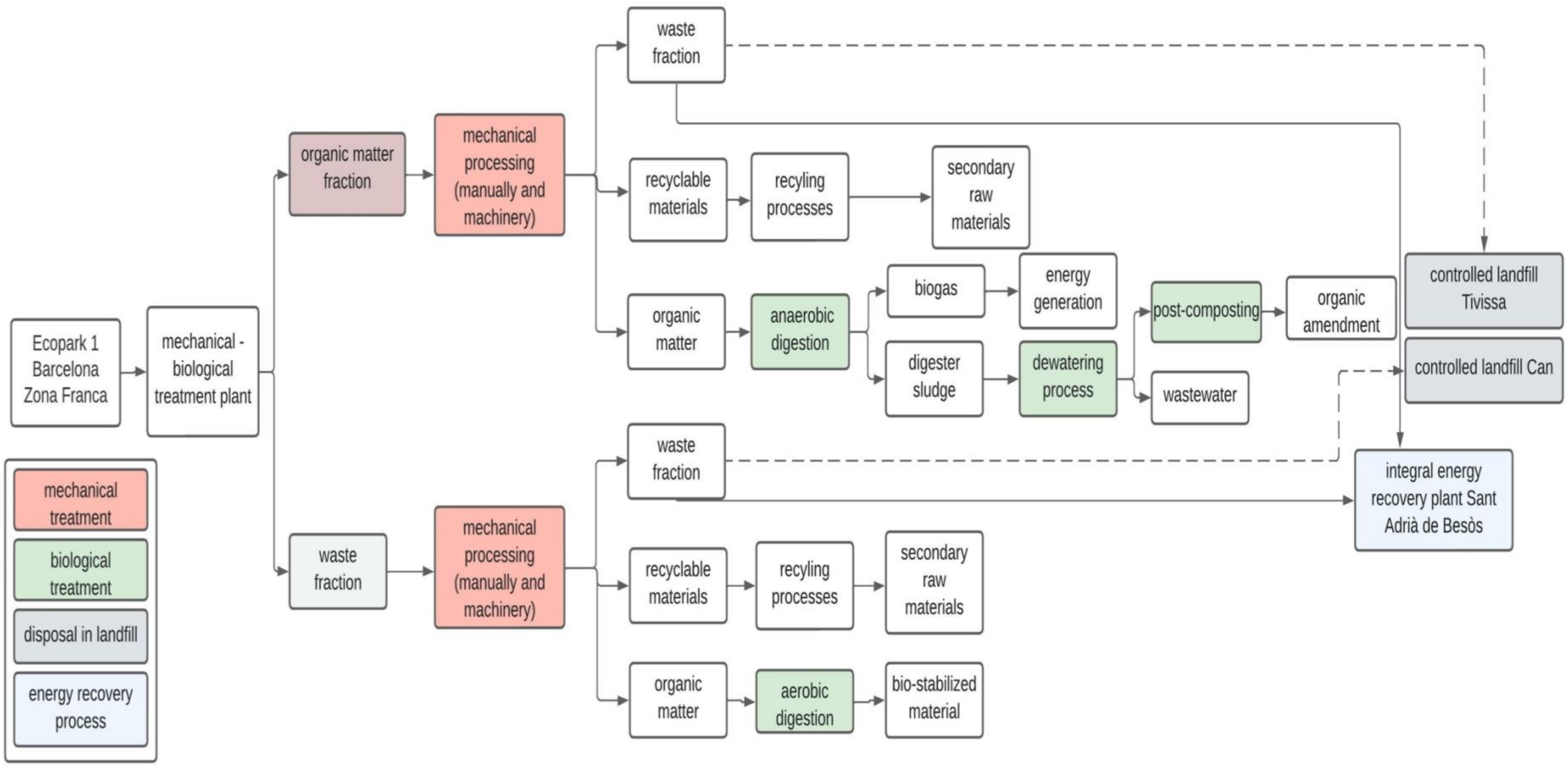

Figure 8.10.1MSW pre-treatment and treatment processes in the ecopark 1 Barcelona Zona Franca (Metropolitan Area of Barcelona, 2021).

A2.2 Ecopark 2 - Montcada I Reixac

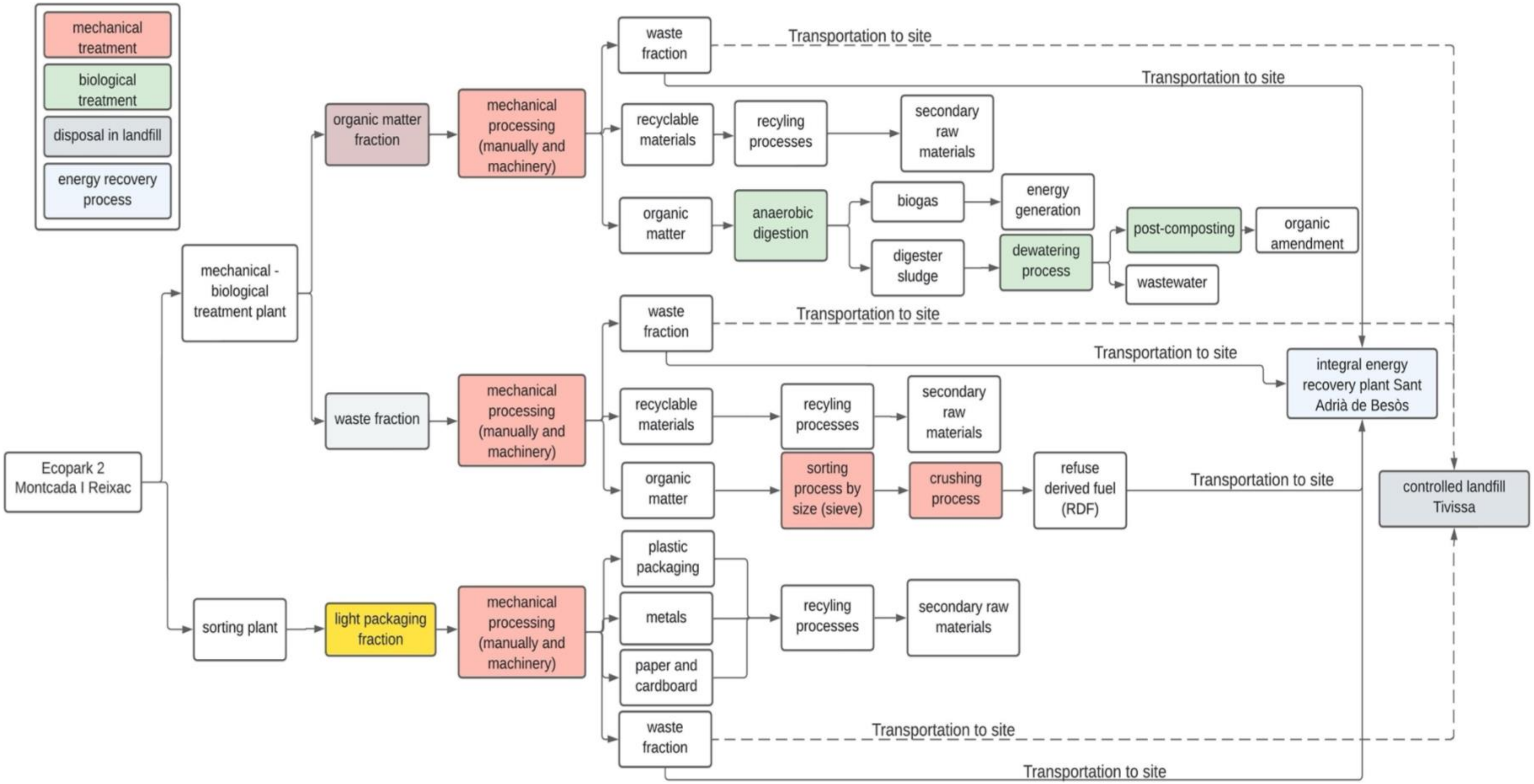

Figure 8.20.1MSW pre-treatment and treatment processes in the ecopark 2 Montcada I Reixac (Metropolitan Area of Barcelona, 2021).

A2.3 Ecopark 3 - Sant Adrià de Besòs

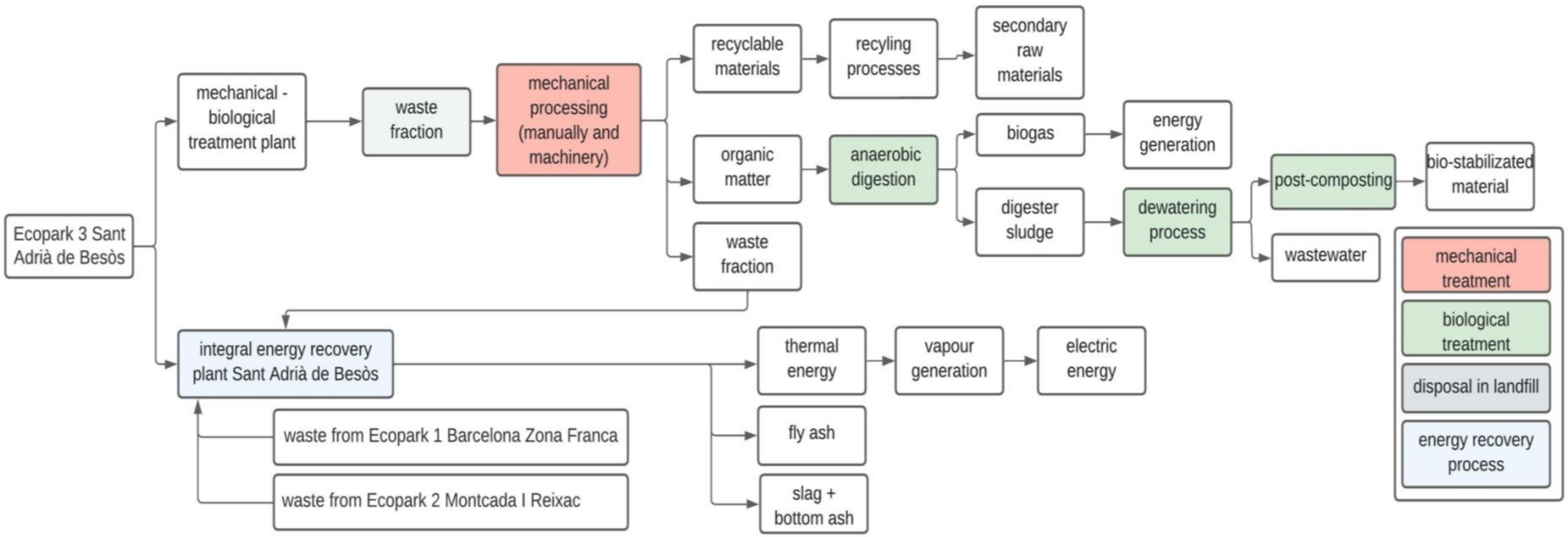

Figure 8.30.1MSW pre-treatment and treatment processes in the ecopark 3 Sant Adrià de Besòs (Metropolitan Area of Barcelona, 2021).

A2.4 Ecopark 4 - Hostalets de Pierola

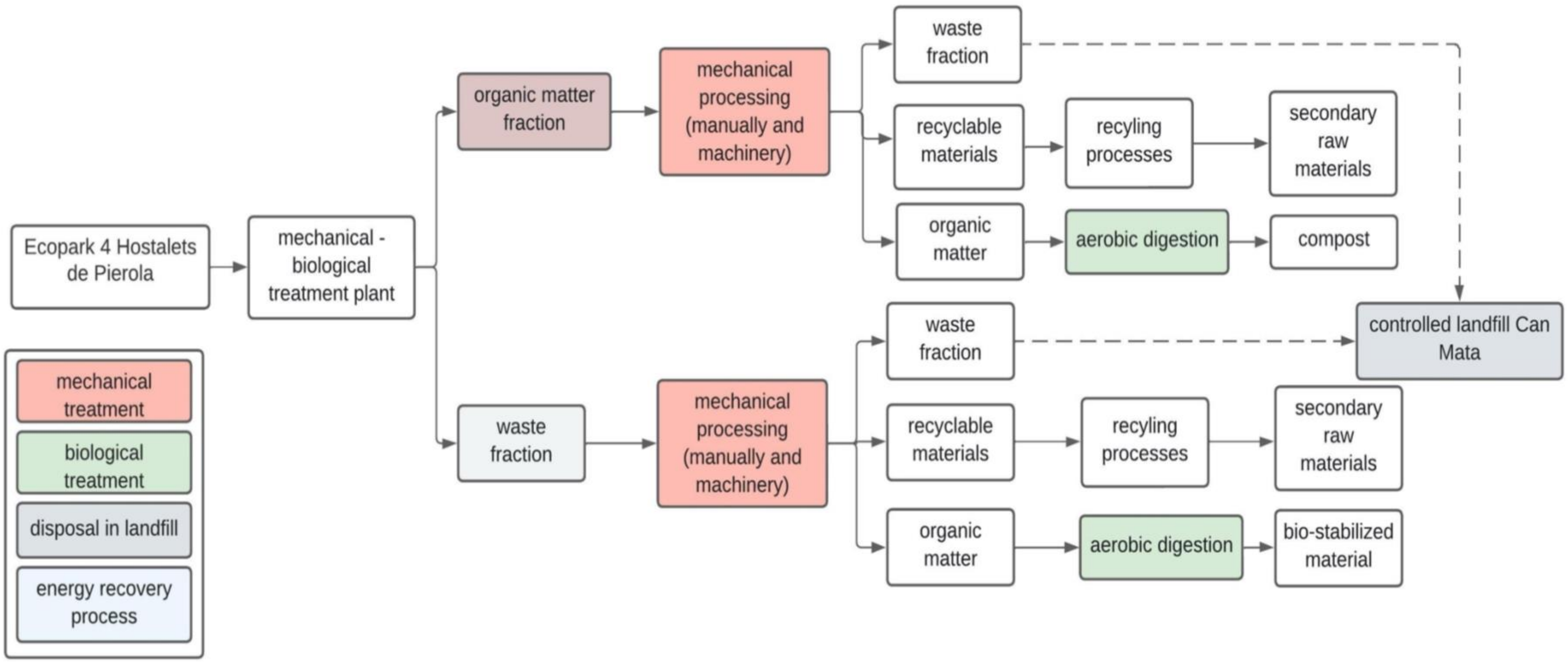

Figure 8.40.1MSW pre-treatment and treatment processes in the ecopark 4 Hostalets de Pierola (Metropolitan Area of Barcelona, 2021).

A2.5 Sorting plant - Gavà-Viladecans

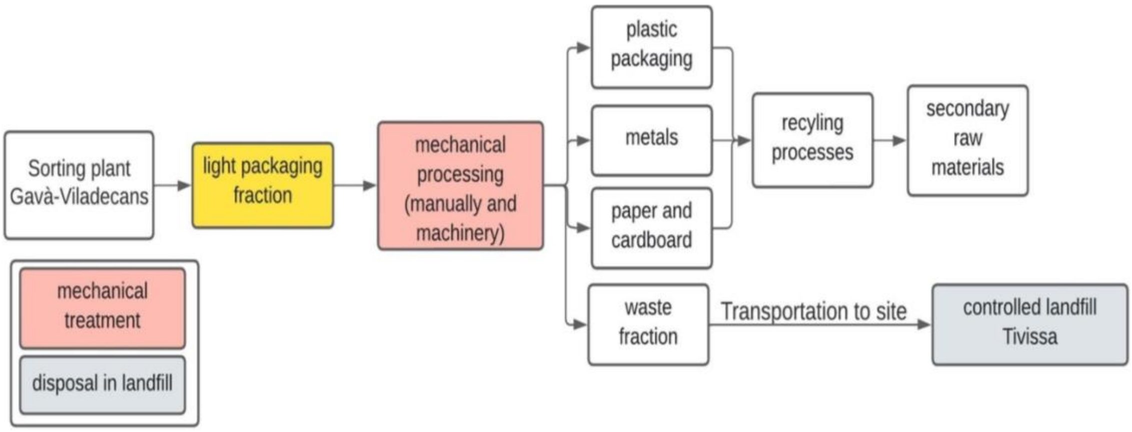

Figure 8.50.1MSW pre-treatment and treatment processes in the sorting plant Gavà-Viladecans (Metropolitan Area of Barcelona, 2021).

A2.6 Transfer plant – Viladecans

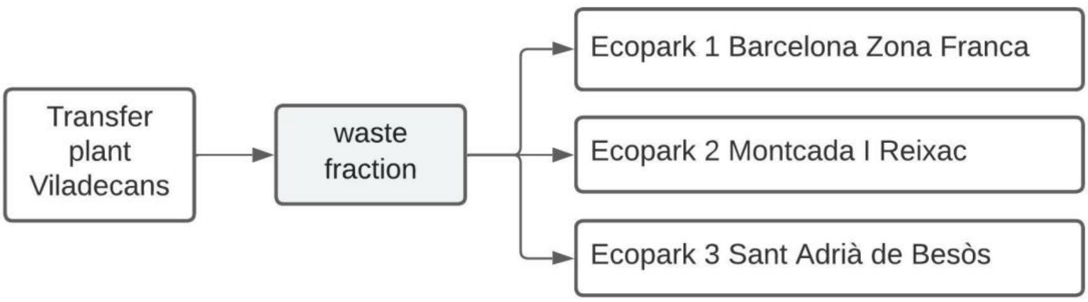

Figure 8.60.1Transfer plant Viladecans and future ecopark destinations (Metropolitan Area of Barcelona, 2021).

A2.7 Fractions externally managed by private companies

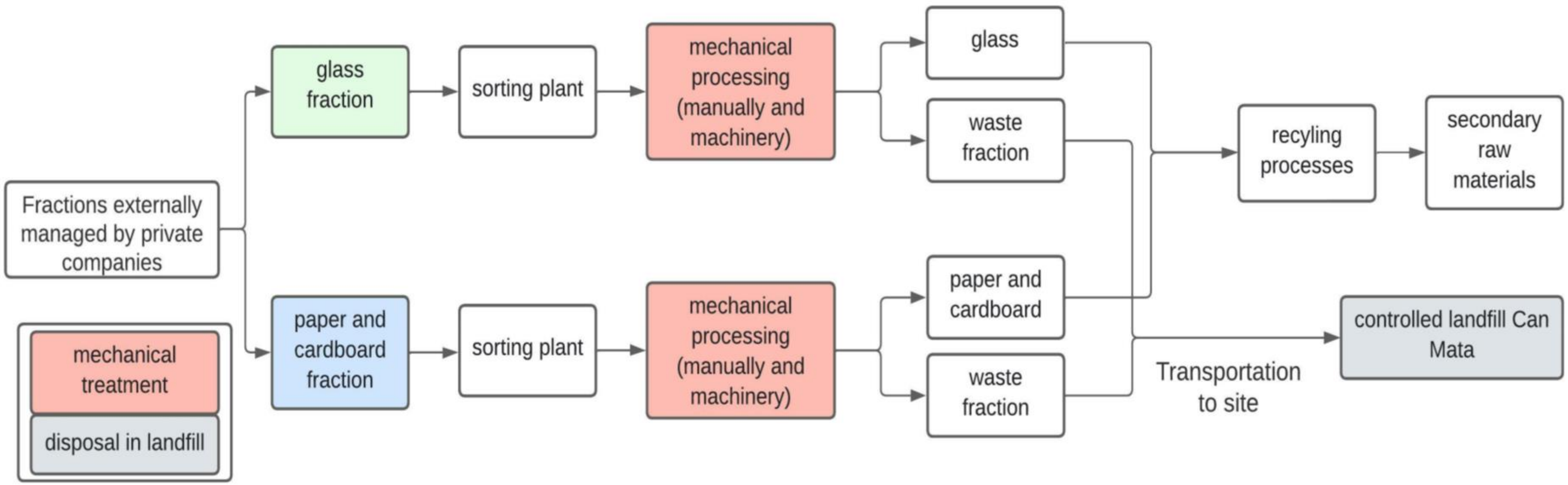

Figure 8.70.1Externally managed fractions by private companies and its pre-treatment and treatment (Ecovidrio and Ecoembes, 2019).