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G. Fiorentino, A. Zucaro, G. Ansanelli

Abstract
The environmental and economic sustainability of the urban organic waste management in the Metropolitan Area of Barcelona, Spain, was analyzed in the Biocircularcities (BCC) project, through Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methodologies. The current (Business-as-Usual, BaU) scenario involves voluntary separate collection in open containers, daily transport and processing at a local facility (ECOPARC 2) to produce compost and biogas with the latter being converted into electricity at a Combined Heat and Power (CHP) plant. The BaU scenario was compared with an alternative scenario that envisages biowaste prevention measures, mandatory separate collection through door-to-door or smart bins, less frequent transport and upgrading biogas to biomethane for injection into the natural gas national grid. LCA identified transport, electricity production and anaerobic digestion (for biogas generation) as the primary contributors to environmental burdens. On the other hand, environmental gains arise from the avoided use of natural gas and chemical fertilizers. Moreover, LCC analyses highlighted that the alternative scenario, compared to the BaU scenario, has slightly lower internal costs and almost half the total environmental damage cost. However, due to limited primary data, European averages were used, so the LCA and LCC findings should be considered as merely indicative.

Keywords: *LCA, LCC, Metropolitan Area of Barcelona (Spain), municipal biowaste, biomethane, circular bioeconomy.*

Riassunto
Nell'ambito del progetto Biocircularcities (BCC), è stata analizzata la sostenibilità ambientale ed economica della gestione dei rifiuti organici urbani dell'Area Metropolitana di Barcellona (MAB, Spagna), mediante le metodologie Valutazione del Ciclo di Vita (LCA) e Costo del Ciclo di Vita (LCC). Lo scenario attuale (Business-as-Usual, BaU) prevede la raccolta differenziata volontaria in contenitori aperti, il trasporto giornaliero e il trattamento in un impianto locale (ECOPARC 2) per produrre compost e biogas; quest'ultimo viene poi convertito in elettricità in un impianto di cogenerazione. Lo scenario BaU è stato confrontato con un'alternativa che ipotizza misure di prevenzione della produzione di rifiuti, la separazione dei rifiuti organici obbligatoria tramite raccolta porta a porta o contenitori intelligenti, un trasporto meno frequente e l'upgrading del biogas a biometano da immettere nella rete nazionale del gas naturale. L'analisi LCA ha identificato, come principali responsabili degli impatti ambientali, il trasporto, la produzione di elettricità e la digestione anaerobica (per la generazione di biogas). I benefici ambientali, invece, derivano dall'evitato uso di gas naturale e fertilizzanti chimici. Inoltre, le analisi LCC hanno evidenziato che, rispetto allo scenario BaU, quello alternativo presenta costi interni leggermente inferiori e un costo totale del danno ambientale quasi dimezzato. Tuttavia, a causa della limitata disponibilità di dati primari, sono stati utilizzati valori medi europei, sicché i risultati LCA e LCC sono da considerarsi meramente indicativi.

Parole chiave: LCA, LCC, Area Metropolitana di Barcellona (Spagna), rifiuti organici urbani, biometano, bioeconomia circolare.

CONTENTS

1 INTRODUCTION

The Metropolitan Area of Barcelona (MAB) comprises 36 municipalities, with 3,339,279 inhabitants and an average population density of 4,735 inhabitants/km^2. The waste management in the MAB is outlined in the Metropolitan Program of municipal Waste Prevention and Management 2019-2025 (PREMET25). This plan aims to support the shift from a linear economic model, which focuses on waste disposal, to a circular model that emphasizes waste prevention and its reintegration into the production cycle. Waste prevention should be achieved through an increase of waste separation at source, awareness campaigns and economic incentives. The latter may be used, for example, to adapt existing facilities (i.e., converting mechanical biological treatments of mixed municipal waste into composting or anaerobic digestion plants of separate collected biowaste) or involve citizens in implementing new circular models (i.e. improving biowaste separate collection systems) exploiting waste as resources.

The approval of PREMET25 and the Metropolitan Zero Waste Agreement within all the municipalities in July 2020, forced a change in waste collecting systems, the increase (both quantitative and qualitative) of separately collected biowaste and the adaptation and modernization of metropolitan treatment plants. The competence in the separate collection of municipal waste belongs to the municipalities, while Àrea Metropolitana de Barcelona (AMB) is the local public administration responsible for managing waste in the treatment phase, at the same time as promoting its reduction, selective collection and possible reuse.

PREMET25 is structured in 5 strategic lines, as follows:

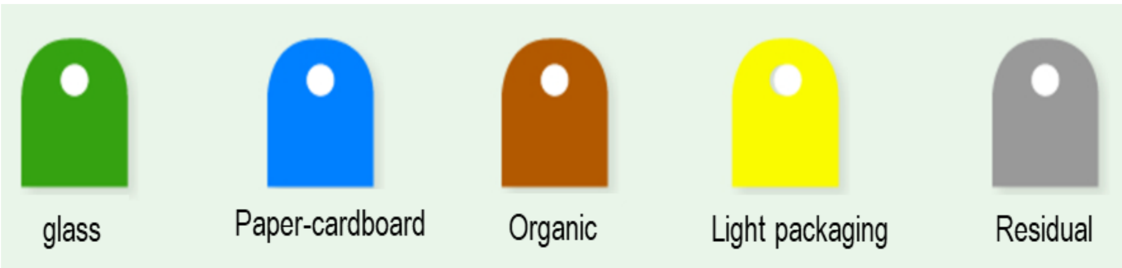
- Waste prevention.
- Separate collection with improved quality.
- Improvement and innovation in the treatment and recovery of materials.
- Education for the transition into a new model.
- A new governance.

The first 3 lines include all materials cycle, whereas the others are transversal and are required for the successful implementation of the Plan. Each line consists of several actions, among them some biowaste prevention measures that will be detailed later.

The waste management chain includes the sorting of waste, the separate collection and the transport to the treatment plants in order to recover materials, to obtain energy or finally to dispose of waste in the best possible environmentally sustainable way.

During in the last 20 years, two different separate collection models have been consolidated in the Metropolitan Area of Barcelona, both including the separate collection of biowaste:

- 5-fraction model: organic, glass, paper and cardboard, light packaging and residual (non-segregated fraction)



- 4-fraction model: the so called "minimum waste" model, with organic, glass, paper and cardboard, and light packaging together with residual

Each model of waste segregation has different collection systems (i.e. surface street containers, underground containers, door-to-door and pneumatic), according to the characteristics and preferences of each municipality.

The 5-fraction model with surface street containers prevails in the Metropolitan Area of Barcelona. Organic waste (brown container) is intended for food waste, kitchen waste, grass clippings, flower trimmings, small yard waste, leaves, etc., from domestic users as well as some non-domestic users (that are assimilated to domestic). In some municipalities, there are specific collection systems for non-domestic users, according to the characteristics and needs of each activity. Moreover, in a few municipalities, garden waste is collected separately (in proper bins or bags) or, if there is not a specific service, it has to be brought to collection centres where specific containers for big garden waste (pruning waste) are available. There are also specific collection services for bulky waste, otherwise it is accepted in reuse and recycling centres. As said before, each municipality has the responsibility for separate waste collection and its delivery to the treatment plant, whereas the AMB has the responsibility for waste treatment. Each municipality transports waste to the closest facility in the Metropolitan Area of Barcelona. The available treatment facilities in the AMB are summarized in *Table **1***.

Table 1 Treatment facilities at Metropolitan Area of Barcelona

Type of facility	Number	Location
Bulky items treatment plant	1	Gavà – Viladecans
Sorting plant	2	Molins de Rei Gavà – Viladecans
Composting plant	2	Torrelles del Llobregat Sant Cugat
Ecoparc (MBT plants)	4	• Ecoparc 1. Barcelona Zona Franca • Ecoparc 2. Montcada I Reixac • Ecoparc 3. Sant Adrià del Besòs • Ecoparc 4. Hostalets de Pierola
Integral waste recovery plant	1	Besòs
Transfer plant	1	Viladecans

Waste treatment includes a range of technologies and processes that enable reuse, recycle, energy recovery, or controlled landfilling. The main treatments applied to waste at the Metropolitan Area are:

- Recycling.
- Waste-to-energy.
- Composting (biowaste – garden fraction and food waste fraction).

- Mechanical Biological Treatment (MBT).
- Landfilling.

Waste treatment at the Metropolitan Area of Barcelona has changed over time. In 2011, 10.89% of waste was landfilled, whereas in 2020 the total amount of waste directly sent to landfill was 1.65%. The amount of waste that go straight to landfilling or inceneration are tonnes from "street cleaning" or due to the maintenance of the plants. The percentages of waste recycled, as well as of waste subjected to MBT, have increased from 22.47%, in 2011, to 25.33% in 2020, and from 41.02% in 2011 to 60.62%, in 2020, respectively. It is important to highlight that in 1993, the Catalan Parliament introduced a regional waste law, establishing the obligation to collect biowaste separately in cities above 5,000 inhabitants, starting from 1999. Moreover, in 2004, a regional landfill tax of 10 €/t, was adopted and, in 2008, a tax on waste incineration (5 €/tonne) was also added. The amount of these taxes has progressively increased, reaching 47.10 €/tonne for landfill and 23.60 €/tonne for incineration, in 2020. Because of these measures, the number of municipalities introducing separate collection of biowaste in the region has increased steadily. At the same time, the amount of waste brought directly to landfill or incinerated has been reduced.

In the MAB pilot the biowaste can be classified according to its origin, as follows:

- Domestic: it refers mainly to residential waste, comprising households and commercial activities equivalent to domestic. It consists of all the biowaste collected through the brown containers (or brown bins door-to-door).
- Non-domestic: it refers to the waste from commercial activities (restaurants, hotels, caterers, retail premises, etc) and other facilities, such as markets, which are considered large producers of biowaste and have a specific collection route.
- Garden waste: it consists of residues from mowing and pruning of private and municipal gardens and parks.

Regarding the **total amount of the generated biowaste (tonne/year)**, during the year 2020, each inhabitant of the Metropolitan Area of Barcelona generated 1.17 kg per day of household waste. Figure 6 shows the evolution of waste generation (total tonnes and per capita) from 2011 to 2020. Based on AMB studies of waste in the Metropolitan Area of Barcelona, in 2020, the “waste bag typification” was composed of 26.9% organic waste, 4.9% garden waste, 15.7% paper and cardboard, 14.3% plastic, 7.4% of glass, 7.6% bulky wood waste, 4.9% textiles and 20.7% other materials. Considering the average characterization of the waste bag (31.8% of biowaste), the amount of biowaste per capita generated was 0.37 kg/inhabitant/day, corresponding to a total of 453,480.4 tonne/year of generated biowaste.

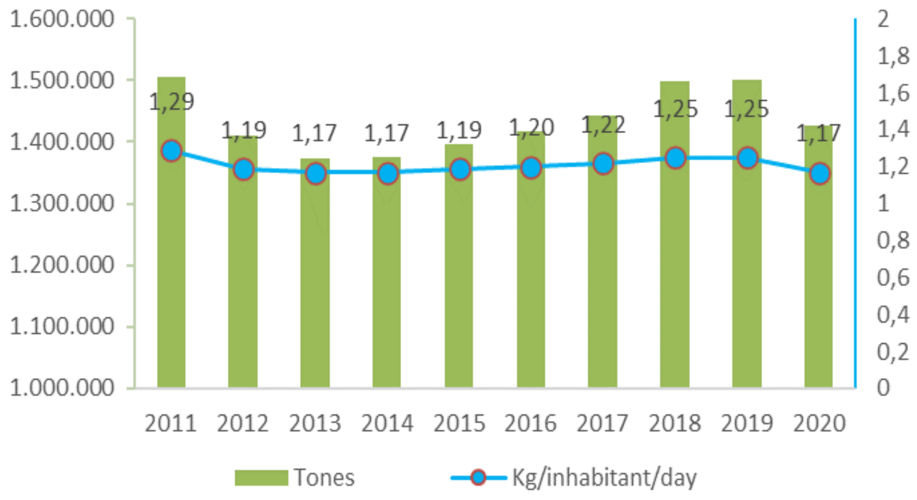


Figure 1 Evolution of waste generation at Metropolitan Area of Barcelona (2011-2020). Source: AMB.

Figure ***1*** shows that the average per capita production, calculated on the 36 municipalities of AMB, does not vary significantly in the last 10 years. However, a decrease is observed in the economic crisis years and in 2020. Of course, this reduction is unequal among the municipalities of the AMB (the biggest ones contributing more).

In 2020, the total amount of separately collected biowaste (considering all streams) was 184,284.3 tonne/year. That supposes a generation per capita of 42.8 kg/inhabitant/year[1], excluding garden waste, and 51.62 kg/inhabitant/year, including garden waste. Regarding food waste approximately 7,2% of the separately collected biowaste could be avoidable.

Table ***2*** summarizes data available for the amount of each stream of collected biowaste (tonne/yr), in 2020. It shows that the biowaste arriving at the metropolitan treatment plants is mainly from separate collection and municipal maintenance park services.

Table 2 Amount of biowaste collected (tonne/yr)

Type of collected biowaste stream	Tonne/year
Domestic	142,934.80
Non-domestic	11,899.50
Garden waste	29,450.00
TOTAL	184,284.30

Separately collected biowaste in the MAB mainly undergoes the following types of treatment:

- Composting, to obtain compost as the main output to be used in agriculture and gardening, as soil amendment and fertilizer.
- Anaerobic digestion coupled with composting tunnel, to obtain biogas as the main output for energy production. The digested material undergoes a composting process. Depending on its quality, it will be used or not in agriculture and gardening.

The amount of biowaste sent to each treatment is reported in *Table* ***7***.

[1] Calculation based on the total population and not on the served population, given the difficulties in knowing the actual number of inhabitants participating in the separate collection system.

Table 3 Amount of biowaste per treatment facility at Metropolitan Area of Barcelona. Source: AMB

FACILITY	TREATMENT	TONNE/YEAR
ECOPARC 1	Anaerobic digestion + composting	52,840.84
ECOPARC 2	Anaerobic digestion + composting	63,267.45
ECOPARC 4	Composting	26,947.37
Composting plant TORRELLES	Aerated windrow composting	5,569.02
Composting plant SANT CUGAT	Aerated windrow composting	9,831.86
Crushing plant CASTELLDEFELS	Pruning crushing of garden waste	18,517.93
Home composting[2]	Home composters	1,102.10
	Total treated biowaste	**176,974.47***

* There are approximately 7,300 tonnes of garden waste not treated in plants of the Metropolitan Area of Barcelona

Residual waste still contains a lot of organic waste as well as other recoverable materials. The main treatment it undergoes is MBT coupled with energy recovery and bio-stabilization or bio-drying, thus producing a generic combustible fraction delivered to Waste to Energy plants, and a fraction with stabilized organic matter intended for landfilling. The amount of residual waste sent to each treatment is reported in *Table* **4**.

Table 4 Amount of residual waste per treatment facility at Metropolitan Area of Barcelona.

FACILITY	TREATMENT	TONNE/YEAR
ECOPARC 1	MBT + biostabilization	168,224.84
ECOPARC 2	MBT + biostabilization / biodrying	173,506.68
ECOPARC 3	MBT + energy recovery (biogas) and biostabilization	187,785.14
ECOPARC 4	MBT + pre-SRF	235,883.41
Integrated system plant for residual waste valorization	Energy recovery (waste-to-energy)	189,302.84

The sustainability of MAB's urban bio-waste chain has been analyzed by the Biocircularcities (BCC) project. Biocircularcities (BCC) is a 3-year (2021-2023) project funded by the Bio-Based Industries Joint Undertaking (JU) and the European Union's Horizon 2020 Framework Program through "Funding & tender opportunities" (BBI-2020-SO4-S4 Type of action BBI-CSA). BCC aims at promoting sustainable circular practices for biowaste management across diverse contests in Europe. To this end, three different European pilot areas, including MAB, with as many biowaste chains were analyzed, in order to provide a range of case studies, for a greater replicability at European level. The biowaste chains were selected on the basis of the results from the local Living Labs and on the suggestions of the involved stakeholders.

In the BCC project, the environmental and economic performance of the current municipal biowaste management (business as usual – BaU – scenario) in the MAB, was evaluated using life cycle assessment LCA) and life cycle costing LCC) methodologies.

[2] Data retrieved from Catalan Waste Agency statistics (year 2020 for the whole 36 AMB municipalities) http://estadistiques.arc.cat/ARC/#

Additionally, an alternative scenario, aligned with circular economy principles, was analyzed and compared to the BaU scenario for identifying improvements in current management practices.

The analyses were conducted in collaboration with the local public administration Àrea Metropolitana de Barcelona (AMB), which was in charge of providing the necessary data.

Evaluating the sustainability performances allows for identifying and ranking the best available practices and therefore it is a fundamental step in promoting the transition toward a sustainable circular bioeconomy.

2 LIFE CYCLE ASSESSMENT (LCA) OF MUNICIPAL BIOWASTE MANAGEMENT IN THE METROPOLITAN AREA OF BARCELONA

Life Cycle Assessment (LCA) is a comprehensive methodology used to assess the environmental impacts of products or services throughout their entire life cycle. This approach helps to identify and quantify the energy and materials used (inputs) and the wastes released into the environment (outputs), thus highlighting opportunities to enhance environmental sustainability.

In this work, LCA was conducted in accordance with ISO Standards 14040 and 14044: 2006, as well as the recommendations from the International Reference Life Cycle Data System (ILCD, 2010) and the Product Environmental Footprint (PEF) guidelines issued by the European Commission (ISO 14040, 2006; ISO 14044, 2006; EC, 2010; Zampori & Pant, 2019).

According to the ISO standard procedures, the LCA comprises four stages (*Figure 2*):

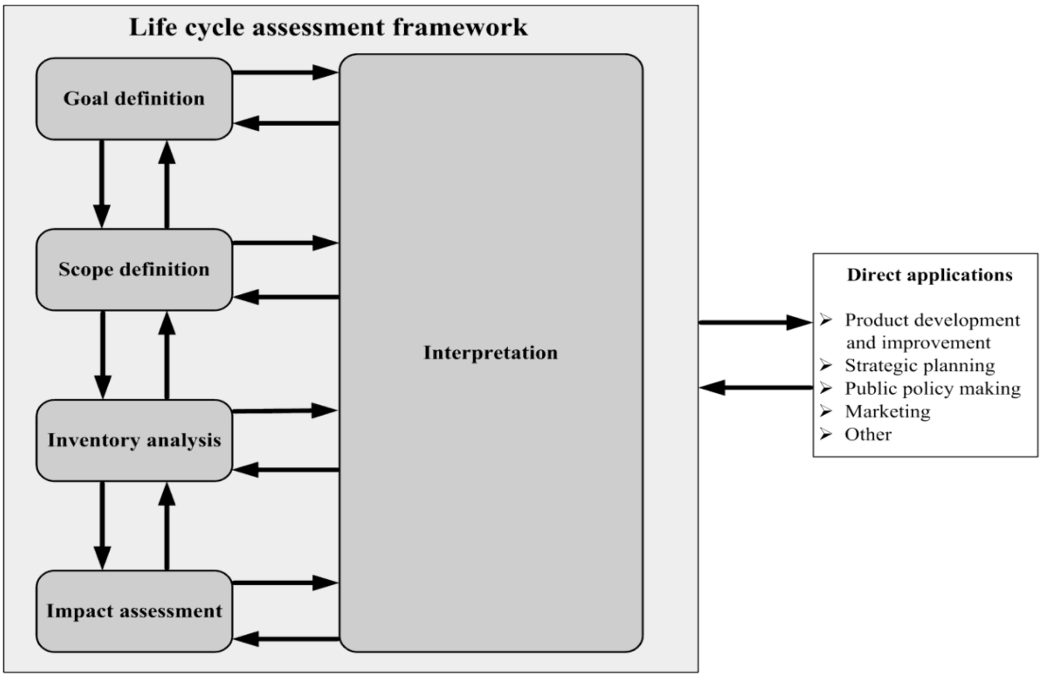


Figure 2 - Framework for Life Cycle Assessment (source: ISO 14040, 2006).

Goal and Scope Definition: This phase involves setting the objectives of the LCA study and defining key parameters such as the functional unit, system boundaries, and data quality requirements. The functional unit quantifies the product's performance characteristics, providing a reference for inputs and outputs. The system boundary delineates which processes are included in the analysis. Data quality criteria ensure that the data collected meet the study's requirements.

Life Cycle Inventory (LCI) Analysis: This stage involves compiling an inventory of input and output flows for the system under study. It includes collecting primary data specific for the processes being analyzed, secondary data from literature, and representative background data from specialized databases, like EcoInvent. The collected data pertain to energy and material inputs, obtained products and co-products, waste, and environmental releases.

Life Cycle Impact Assessment (LCIA): This phase assesses the potential environmental impacts of the investigated product, process, or service by linking inventory data to selected environmental impact categories such as acidification, climate change, particulate matter, eutrophication, human toxicity, ozone depletion, and water use. LCIA identifies key contributors to each environmental impacts, thus highlighting areas for improvement.

Interpretation of Results: The final phase involves integrating findings from the inventory analysis and impact assessment to understand the significance of the environmental impacts. This phase provides conclusions, discusses limitations, suggests improvements, and offers recommendations, ensuring alignment with the defined goals and scope of the LCA study.

Each stage of the LCA process may be characterized by iterative revisions to ensure consistency and accuracy, ultimately aiming to provide a thorough evaluation of the environmental impacts and identify strategies for improvement.**Goal and Scope**

Separately collected municipal biowaste was selected as the biowaste chain to be investigated in detail, since it is the most abundant organic waste stream in the MAB pilot area. The environmental impacts generated from its management were quantified in this study in order to provide a basis for making decisions about the future biowaste management in Barcelona as well as in other urban contexts. Therefore, the **aim** was to provide decision-makers with potentially useful recommendations for local biowaste management planning.

In the reference year (2021), the produced biowaste represented 13.5% of the total amount of produced municipal solid waste (MSW, 1,478,128 tons). 46% of the produced biowaste, amounting to 199,628 tons, was separately collected and mainly consisted of domestic biowaste (74%). The impurities of this waste stream were around 15%.

The selected **Functional Unit** (FU) in the LCA analyses was 1 ton of separately collected municipal biowaste, transported to ECOPARC 2.

ECOPARC 2 is a MBT facility managing biowaste and residual waste of MSW: hence, there are two main treatment lines:

- **Biowaste line**: treating the separately collected organic fraction from MSW (brown containers), from markets and big producers as well as from municipal parks and gardens. Before being sent to biological treatment, the biowaste is pre-treated to remove non-organic fractions.
- **Residual waste line**: treating mixed municipal solid waste, collected in grey containers. This line first sorts out light packaging and other recoverable materials that have not been correctly separated at the origin, by placing them in the right container. Hence, this line separates materials by type: iron and aluminium cans, packaging and wraps of different types of plastic, etc.

In particular, the treatment processes at ECOPARC 2 are:

- **Mechanical treatment**: recyclable materials from both lines (biowaste and residual waste) are sorted out by machines and by hand. Organic matter, after pre-treatment, is transferred to the biological treatment. Other recyclable materials are packaged and delivered to various recyclers who will use them as secondary raw materials. The residual, unusable materials are compacted and sent to a final treatment (i.e. energy recovery or controlled landfilling).

- **Biological treatment**: depending on its origin, the organic matter undergoes a process of:
  - *Anaerobic digestion*, for the organic matter coming from separated waste collection (brown containers). The outcomes are biogas (mixture of methane and carbon dioxide) used to generate energy and digestate that is then separated into solid and liquid fractions. The solid digestate is sent to *composting* and refined to obtain good quality compost.
  - *Drying*, for the organic matter coming from residual waste (grey container). It leads to a bio-dried material used as biogenic fuel (energy recovery).

Therefore, overall, from biowaste and residual waste, in ECOPARC 2, the following products are obtained:

1. **Recoverable materials**, which have not been properly separated at source, such as metal, plastic, brick packaging, glass and cardboard.
2. **Biogas**, a renewable energy source that is generated from the degradation of biowaste and is used to produce electricity and heat.
3. **Digestate** (post-valorized as **compost** or pre-hygienized), organic amendment for agricultural application obtained from the biological treatment of the biowaste fraction.
4. **Bio-dried** and **bio-stabilized** obtained from the organic matter contained in the residual fraction and respectively used to produce energy in a dedicated plant and as material to cover mill's landfill.

2.1.1 Systems boundaries

Two scenarios referring to the selected biowaste chain were investigated and the process units included in this LCA analysis are described in Figure 3.

In the **BaU scenario**, representing the current situation, collection and treatment steps were accounted for.

In detail, the collection step included:

(i) the voluntary separate collection of biowaste (kitchen waste and small size green waste) in kerbside open containers, with a volume of 2,200 L;

(ii) the daily transportation of 77,244 tons of separately collected municipal biowaste to the local facility, namely ECOPARC 2, on an average distance of 10 km.

The treatment step included:

(i) the pre-treatment of separately collected municipal biowaste to remove non-organic fractions (impurities) together with 8,396 tons of biowaste from private or industrial origin. A total of 16,271 tons of biowaste is discarded and sent, partly, to incineration (63%) and, partly, to landfill (37%);

(ii) the anaerobic digestion (AD) of the remaining 69,369 tons of biowaste, producing biogas (9,954,367 m3) and digestate (20,062 tons);

(iii) the conversion of biogas into electricity by means of a Combined Heat and Power (CHP) plant: 20,569 MWh, out of a total annual production of 34,235 MWh, are currently fed into the national grid, whereas the remaining part is self-consumed by the AD plant;

(iv) the composting of digestate, leading to the production of 9,755 tons of compost: the digestate entering the composting process amounts to 10,307 tons, while the remaining part is disposed of in landfills (50%) or incinerated (50%).

An **Alternative scenario** was also designed, in light of the requirements and suggestions of local stakeholders, gathered during the first Living Lab, organized during the BCC project, in the MAB. In the Alternative scenario, a decrease of 5% in the production of biowaste was assumed as a consequence of the implementation of prevention measures. At the same time, alternative collection strategies were introduced to shift the biowaste separation from a voluntary to a more compulsory approach, allowing the identification of people who dispose of their waste. To this aim, door-to-door collection schemes and smart bins were proposed. The expected outcome is a higher capture and, at the same time, a better quality of collected biowaste. In detail, for the amount of collected biowaste, an increase of 30% was suggested by the local partner (AMB), according to other projects' results. Therefore, a net increase of 25% (plus 30% for the improved collection systems, minus 5% for the implemented prevention measures) was accounted for in the assessment, totaling 249,535 tons of separately collected biowaste. Regarding the quality of the collected biowaste, a reduction of impurities from 15% to 5% was assumed with the consequent increase of the amount of biowaste after pretreatment as input material for the anaerobic digestion plant.

As in the BaU scenario, also in the **Alternative scenario** collection and treatment steps were assessed separately.

In detail, the collection step included:

(i) the separate collection of biowaste (kitchen waste and small size green waste) in smart bins (50%) and in 10 L plastic bins (50%);

(ii) the transportation of MSW biowaste to the local facility, namely ECOPARC 2, on an average distance of 10 km, 4 days per week, for a total amount of 96,555 tons of biowaste.

The treatment step included:

(i) the pre-treatment of MSW biowaste, together with 8,396 tons of biowaste with a different origin (private or industry sources) to remove not organic fractions (impurities). In this scenario, the amount of residuals incinerated (63%) and landfilled (37%) is lower than in the BaU scenario, totalling 5,248 tons;

(ii) the anaerobic digestion of the remaining 99,704 tons of biowaste, with the production of biogas (14,307,424 m^3) and digestate (28,835 tons);

(iii) the purification of biogas into biomethane (by a mix of the most common technologies, namely amino washing, membrane technique, pressure swing adsorption in addition to biomethane production from synthetic gas by fluidised or fixed bed technology): considering a CH_4 content of 56%, the production of 8,012,157 m^3 of biomethane was accounted for. Since the entire amount of biogas was assumed to be upgraded to biomethane, the energy requirements of the AD plant were accounted for being taken from the national grid (Figure 3);

(iv) the composting of digestate, leading to the production of 14,021 tons of compost: the digestate entering the composting process amounts to 14,814 tons, while the remaining part is disposed of in landfills (50%) or incinerated (50%).

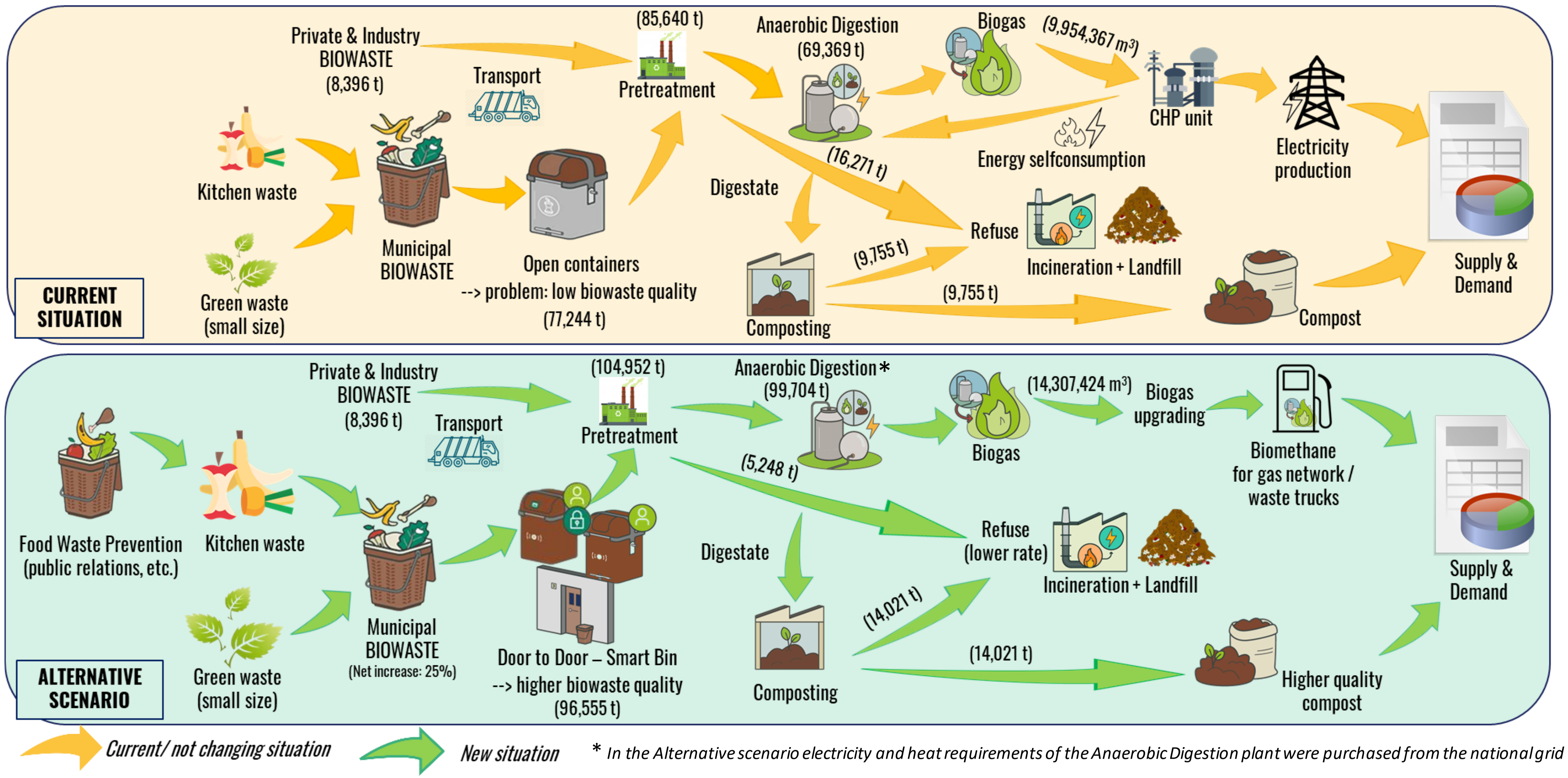


Figure 3. The municipal biowaste chain selected in the MAB pilot area.

2.1.2 Data sources

Primary data on resource consumption, waste production and management, as well as on the obtained products and by-products for the investigated scenarios, in the year 2021, were provided by the local BCC project partner, AMB. Data gaps were filled using information from scientific literature (background/secondary data) and the EcoInvent 3.8 database (https://ecoinvent.org/the-ecoinvent-database/data-releases/ecoinvent-3-8/). Average European or global data from EcoInvent 3.8 were also employed for background processes, such as infrastructures, power plants, energy grids, and the supply of energy, fuels, and auxiliaries. Specifically, the medium-voltage electric mix specific to Spain was used for the electrical supply.

2.1.3 Assumptions and limitations of the MAB case study

LCA applied to waste management systems, commonly called "waste LCA", has been widely addressed in the pertinent scientific literature (Ekvall and Finnveden, 2000) and many models have been developed over the years, generating further publications and sometimes leading to the inclusion of these models in the regulatory system in Europe (European Commission, 2005a; European Commission, 2005b). LCA methodology is worldwide recognised as an excellent tool for assessing different waste management systems, especially for comparisons between different treatment and disposal systems. These "Waste Life Cycle Assessments" have two different applications:

- Study of certain waste components: for example, there have been several studies comparing material recycling and energy recovery for paper versus plastic packaging. In these cases, the studied waste components are only a marginal part of the total waste stream. The methods used are equal to the methods used for product LCA.
- Study of waste management systems, where different treatment options (e.g. incineration versus landfilling) for different waste types (e.g. MSW), are compared. In these cases, the study comprises the total waste stream. The approach to handle this kind of system analysis slightly differs from the approach used for product LCA.

In the case of the MAB pilot area, the LCA was applied to the total waste stream. The assessment was specifically referred to the separately collected biowaste transported to ECOPARC 2 in order to take advantages of the availability of primary data from ECOPARC 2, provided by the local partner (AMB). In fact, the literature (Ripa et al., 2017) emphasizes the importance of avoiding streamlined and generalised analyses, in favour of linking the LCA results to local specificities, for accurately quantifying the environmental benefits. Therefore, the lack of primary data from the other waste treatment plants in the MAB would have affected the accuracy of the assessment. However, although the selected functional unit was 1 ton of separately collected municipal biowaste, transported to ECOPARC 2, this assessment can be extended to the whole municipal separately collected biowaste in the MAB, if it is assumed that the waste treatment conditions of ECOPARC 2 also apply to the other waste treatment plants.

Regarding the main calculations made in the BaU and Alternative scenarios, the following **assumptions** were made:

- The biowaste kerbside open containers (made of high density polyethylene, HDPE), with a volume of 2,200 L and a lifetime of 5 years, were emptied every day (only in the BaU scenario), at an occupation rate of 60%, considering a food waste density of 0.34 kg/L (data provided by AMB, on the basis of the results from the DECISIVE PROJECT[3]). The same features applied to the containers used in the door-to-door collection (Alternative scenario), with the only differences being a volume of 10 L and an emptying frequency of four times per week.

- Smart bins (Alternative scenario) had a volume of 2,250 L and a lifetime of 10 years. They were emptied four times per week, at an occupation rate of 95%, considering a food waste density of 0.34 kg/L. Each smart bin was equipped with a digital screen of 500 g.
- In both scenarios, 10-liter compostable bags of were thrown away, with an 80% occupancy of food waste having a density of 0.68 kg/L (data provided by AMB, according to the DECISIVE PROJECT).
- Heat produced in the CHP plant was completely used on site.
- The CH_4 content of the produced biogas was 56%.
- The electricity produced from biogas, in the BaU scenario, substituted the same amount of electricity from the national grid.
- In the Alternative scenario the produced biomethane replaced the same quantity of natural gas.

In order to calculate the avoided production of synthetic fertilisers in both scenarios, it was assumed that the compost produced in each scenario contains 1.2% nitrogen (N), 0.5% phosphorus (P) as P_2O_5, and 0.7% potassium (K) as K_2O (Gilbert and Siebert, 2022).

A **limitation** of this assessment is that the EcoInvent plant used for modelling the anaerobic digestion process has a yearly capacity of 10,000 tons, while the MAB plant has a capacity of 260,000 tons.

2.1.4 Impact assessment software and method

To conduct the LCA analyses of the three BCC case studies, the SimaPro 9.5.0.0 software (Pre-Consultants) was employed in conjunction with the Environmental Footprint (EF) 3.1 adapted V1.00 impact assessment method (Andreasi Bassi et al., 2023; Fazio et al., 2018). Developed by the European Commission, the EF method offers a standardized framework for evaluating the environmental performance of products, processes and services across Europe. By assessing multiple mid-point impact categories, including climate change, resource depletion, and water use, the EF method provides a comprehensive overview of potential impacts. The selected impact categories for this study are outlined in *Table 5*.

Table 5. Environmental Footprint impact categories selected for the LCA study (Andreasi Bassi et al., 2023).

Selected impact categories	Unit	Abbreviation
Acidification	mol H^+ eq	AC
Climate change	kg CO_2 eq	CC
Particulate matter	disease incidence	PM
Eutrophication, marine	kg N eq	EM
Eutrophication, freshwater	kg P eq	EF
Eutrophication, terrestrial	mol N eq	ET
Human toxicity, cancer	CTUh	HTc
Human toxicity, non-cancer	CTUh	HTnc
Ozone depletion	kg CFC_{11} eq	OD
Photochemical ozone formation	kg NMVOC eq	POF
Resource use, fossils	MJ	RUF
Resource use, minerals and metals	kg Sb eq	RUM
Water use	m^3 depriv.	WU

[3] https://www.decisive2020.eu/

2.2 Life Cycle Inventory (LCI) of the MAB pilot area

In this study, data from different sources were used. For the foreground system, mostly primary data were used, i.e. acquired directly from the local partner AMB. Conversely, secondary data from the EcoInvent v.3.8 database (allocation at point of substitution, dataset of unit processes), which includes average European data for most existing materials and energy supply processes and/or services, were used for background systems, including capital goods and infrastructures. The EcoInvent database was also used to model: (i) the organic waste treatment (both anaerobic digestion and industrial composting); (ii) the production of high voltage electricity in a heat and power co-generation plant and its transformation to medium voltage; (iii) the upgrading of biogas to biomethane; (iv) the disposal of residuals in a landfill and (v) residuals' incineration. The transport costs were also included and modelled using the EcoInvent dataset 'Municipal waste collection service by 21 metric ton lorry', whereas collection distances were calculated based on primary data, provided by the local partner (AMB), on the average distance from collection points to the treatment plant and on the frequency of collection events in the investigated scenarios. In the system expansion, the Spanish production mix of medium voltage electricity was used for crediting energy supply from CHP, whilst for crediting composting and biogas upgrading to biomethane, the avoided production of fertilizers and natural gas, respectively, was included.

Table 6 lists the main foreground input and output material and energy flows involved in the investigated scenarios, with reference to the selected functional unit (1 ton of separately collected biowaste transported to ECOPARC 2).

Table 6 *- Life Cycle Inventory for BaU scenario in the MAB pilot area, referred to the FU of 1 ton of separately collected biowaste transported to ECOPARC 2.*

Separately collected biowaste in the MAB pilot area			
BaU scenario - collection			
Inputs	**Unit**	**Value**	**Reference**
Container number (HDPE)	#	1.22E-03	AMB
Container volume	l/item	2.20E+03	AMB
Estimated lifetime	yrs	5	AMB
Compostable bags number	#	1.84E+02	AMB
Bag volume	l/item	10	AMB
Bag weight	kg/item	8.00E-03	AMB
Water (for the maintenance of the equipment)	m^3	1.29E-02	AMB
Average distance for transport	km/trip	10	AMB
Total running distance	km/yr	3.65E+03	Our calculation

Bau scenario – treatment				
Inputs		**Unit**	**Value**	**Reference**
Treatment by anaerobic digestion		tons	8.98E-01	AMB
Treatment by industrial composting		tons	1.33E-01	AMB
Conversion of biogas by CHP		m^3	1.29E+02	AMB
Outputs		**Unit**	**Value**	**Reference**
Electricity		MWh	34,235	AMB
Self-consumed		%	40	AMB
Sold to the grid		%	60	AMB
Compost		tons	1.26E-01	AMB
Waste to landfill		tons	1.40E-01	AMB/ENT
Waste to incineration		tons	1.96E-01	ENT

Alternative scenario - collection

Inputs	Unit	Value	Reference
Container number (HDPE)	#	2.35E-01	AMB
Container volume	l/item	10	AMB
Estimated lifetime	yrs	5	AMB
Smart bins	#	3.30E-04	AMB
Container volume	l/item	2.25E+03	AMB
Estimated lifetime	yrs	10	ENT
Compostable bags number	#	1.84E+02	AMB
Bag volume	l/item	10	AMB
Bag weight	kg/item	8.00E-03	AMB
Average distance for transport	km/trip	10	AMB
Total running distance	km/yr	2.09E+03	Our calculation

Alternative scenario - treatment

Inputs	Unit	Value	Reference
Treatment by anaerobic digestion	tons	1.03	Our calculation
Treatment by industrial composting	tons	1.53E-01	Our calculation
Purification of biogas	m^3	1.48E+02	Our calculation
Outputs	**Unit**	**Value**	**Reference**
Biomethane	m^3	8.30E+01	Our calculation
Compost	tons	1.45E-01	Our calculation
Waste to landfill	tons	9.2E-02	Our calculation
Waste to incineration	tons	1.08E-01	Our calculation

2.3 Life cycle impact assessment (LCIA) of the MAB pilot area

The current scenario (BaU) of biowaste management in the MAB pilot area was firstly assessed in order to model physical flows, resources consumption and emissions to the environment, with reference to the treatment of 1 ton of separately collected biowaste transported to ECOPARC 2, in the reference year 2021.

The characterized results of the impact assessment for the BaU scenario are summarized in ***TABLE 7***.

Table 7 - Characterized impacts of the BaU scenario, referred to the FU of 1 ton of separately collected biowaste transported to ECOPARC 2 (reference year 2021).

Impact category	Abbrev.	Unit	Total	Collection	Treatment
Acidification	AC	mol H^+ eq	3.15E+01	2.95E+01	1.97E+00
Climate change	CC	kg CO_2 eq	5.06E+03	4.63E+03	4.30E+02
Particulate matter	PM	disease inc.	6.74E-04	6.59E-04	1.52E-05
Eutrophication, marine	EM	kg N eq	1.26E+01	1.19E+01	7.92E-01
Eutrophication, freshwater	EF	kg P eq	5.47E-01	8.27E-02	4.65E-01
Eutrophication, terrestrial	ET	mol N eq	1.36E+02	1.30E+02	6.00E+00
Human toxicity, cancer	HTc	CTUh	8.60E-07	5.89E-07	2.71E-07
Human toxicity, non-cancer	HTnc	CTUh	1.75E-05	1.01E-05	7.36E-06
Ozone depletion	OD	kg CFC11 eq	1.06E-03	1.01E-03	4.53E-05
Photochemical ozone formation	POF	kg NMVOC eq	4.68E+01	4.58E+01	1.03E+00
Resource use, fossils	RUF	MJ	6.59E+04	6.35E+04	2.34E+03
Resource use, minerals and metals	RUM	kg Sb eq	4.53E-03	3.79E-03	7.38E-04
Water use	WU	m^3 depriv.	9.87E+02	5.77E+01	9.30E+02

All LCA results are disaggregated to visualize the contributions of each investigated phase (collection, including transportation, and treatment) to the environmental loads in all selected impact categories. The percentage values are also displayed in

Figure 4, in order to highlight the relative contribution of each investigated phase.

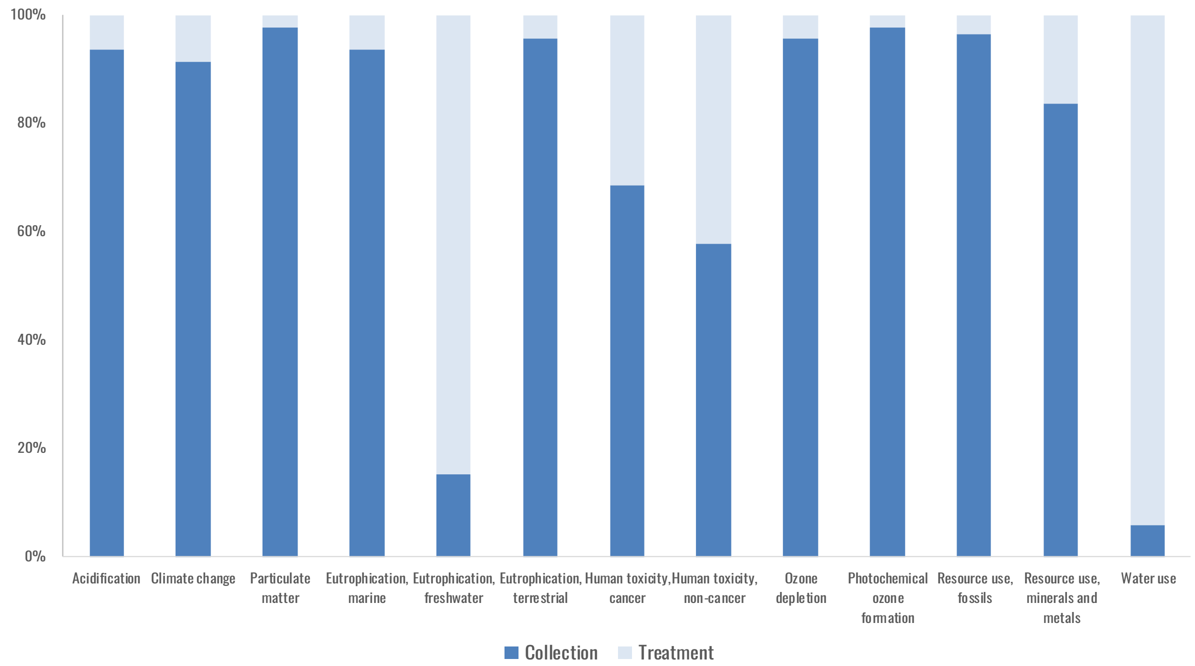


Figure 4 - Percentage contribution of each phase in the BaU scenario to the total impact of the analyzed impact categories, calculated on the basis of a FU of 1 ton of separately collected biowaste transported to ECOPARC 2 (reference year 2021).

Except for EF and WU impact categories, the highest contribution to the analyzed impact categories derives from the collection phase, that also includes transportation. This phase generates from 58% of total impacts, in HTnc impact category, up to 98%, in PM impact category. Only in EF and WU, the treatment phase is impacting more than the collection, generating 85% and 94% of total impacts, respectively. In these cases, the impacts were related to the wastewater produced in the AD plant (EF) and the water requirements of CHP plant (WU).

In deeper details, almost all the impacts generated by the collection phase are due to transportation, with contributions higher than 99% in all the investigated impact categories. Small impacts, ranging from 0.02% in POF to 1.11% in EF, come from the compostable bags, while the impacts from plastic containers as well as from water consumption for maintenance are negligible.

Regarding the treatment phase of the BaU scenario, the characterized impacts are detailed in Table 8, as absolute values, and in Figure 5, as percentage values.

Table 8 - Characterized impacts of the treatment phase in the BaU scenario, referred to the FU of 1 ton of separately collected biowaste transported to ECOPARC 2 (reference year 2021).

Impact categ.	Unit	Total	Anaerobic Digestion	Composting	CHP	Waste to landfill	Waste to incineration	Avoided electricity	Avoided N fertiliser	Avoided P fertiliser	Avoided K fertiliser
AC	mol H^+ eq	1.97E+00	2.95E-01	2.91E-01	2.11E+00	1.80E-02	6.27E-02	-7.27E-01	-5.18E-02	-1.19E-02	-1.98E-02
CC	kg CO_2 eq	4.30E+02	1.14E+02	6.31E+00	2.18E+02	8.44E+01	1.02E+02	-8.25E+01	-7.48E+00	-1.54E+00	-2.85E+00
PM	disease inc.	1.52E-05	5.59E-06	1.49E-06	1.01E-05	2.46E-07	5.26E-07	-2.00E-06	-4.25E-07	-1.07E-07	-2.26E-07
EM	kg N eq	7.92E-01	1.36E-01	1.18E-02	4.91E-01	2.50E-01	3.17E-02	-1.16E-01	-8.37E-03	-1.38E-03	-2.90E-03
EF	kg P eq	4.65E-01	2.17E-01	2.20E-04	2.73E-01	1.73E-03	7.66E-03	-3.17E-02	-1.62E-03	-4.77E-04	-6.24E-04
ET	mol N eq	6.00E+00	1.06E+00	1.29E+00	4.76E+00	5.47E-02	2.71E-01	-1.19E+00	-1.40E-01	-2.90E-02	-6.08E-02
HTc	CTUh	2.71E-07	9.42E-08	3.51E-09	1.82E-07	4.24E-09	2.89E-08	-3.42E-08	-4.94E-09	-1.05E-09	-1.86E-09
HTnc	CTUh	7.36E-06	2.45E-06	3.86E-08	4.71E-06	1.93E-07	1.02E-06	-9.04E-07	-9.62E-08	-2.01E-08	-3.63E-08
OD	kg CFC11 eq	4.53E-05	6.35E-06	4.34E-07	4.42E-05	4.72E-07	8.21E-07	-5.35E-06	-1.06E-06	-1.95E-07	-3.99E-07
POF	kg NMVOC eq	1.03E+00	3.02E-01	1.04E-02	9.59E-01	4.53E-02	6.71E-02	-3.22E-01	-1.72E-02	-3.79E-03	-8.05E-03
RUF	MJ	2.34E+03	4.34E+02	2.99E+01	3.96E+03	3.65E+01	6.68E+01	-1.99E+03	-1.28E+02	-2.34E+01	-4.33E+01
RUM	kg Sb eq	7.38E-04	1.57E-04	9.72E-06	9.75E-04	8.89E-06	8.96E-05	-2.58E-04	-1.60E-04	-2.95E-05	-5.57E-05
WU	m^3 depriv.	9.30E+02	2.33E+00	1.13E-01	9.75E+02	2.21E-01	1.64E+01	-5.56E+01	-6.91E+00	-7.07E-01	-1.23E+00

The main contribution, in the treatment phase, to the environmental loads comes from the production of electricity in the CHP plant, also including the transformation of produced electricity from high to medium voltage. This step of the treatment phase generates from 42% of the total impacts in CC impact category up to 98% in WU impact category. The step of anaerobic digestion produces over 43% of the total impacts in EF impact category (ranging from 0.23% to 31% in the other categories), while the composting process overcomes 10% of contribution only in AA and ET impact categories. The disposal of residuals in landfill mainly affects EM impact category (generating 27% of the total impacts in that category), whereas the incineration of residuals is responsible for 19% of the impacts in CC impact category. It is noteworthy that the avoided production of electricity (considering the average national electricity mix) and N, P and K synthetic fertilizers generates negative values of impacts, corresponding to environmental benefits. These benefits are mainly due to the production of electricity from biogas in the CHP plant and, at a minor extent, to the recovery of compost. In particular, due to the significant contribution of fossil resources used in the national electricity mix, the most relevant benefits regard the RUF and RUM impact categories, with savings of 2,180 MJ and 5.03E-04 kg Sb eq, respectively, corresponding to a reduction of 48% and 41% of the total impacts. The reduction of impacts in the remaining impact categories ranges from 7% in WU to 29% in AA.

As expected, the environmental gains achieved by avoiding the production of fossil electricity and of chemical fertilizers are insufficient to overcome the environmental loads generated by biowaste management. Nonetheless, the contribution to reducing overall impact is significant.

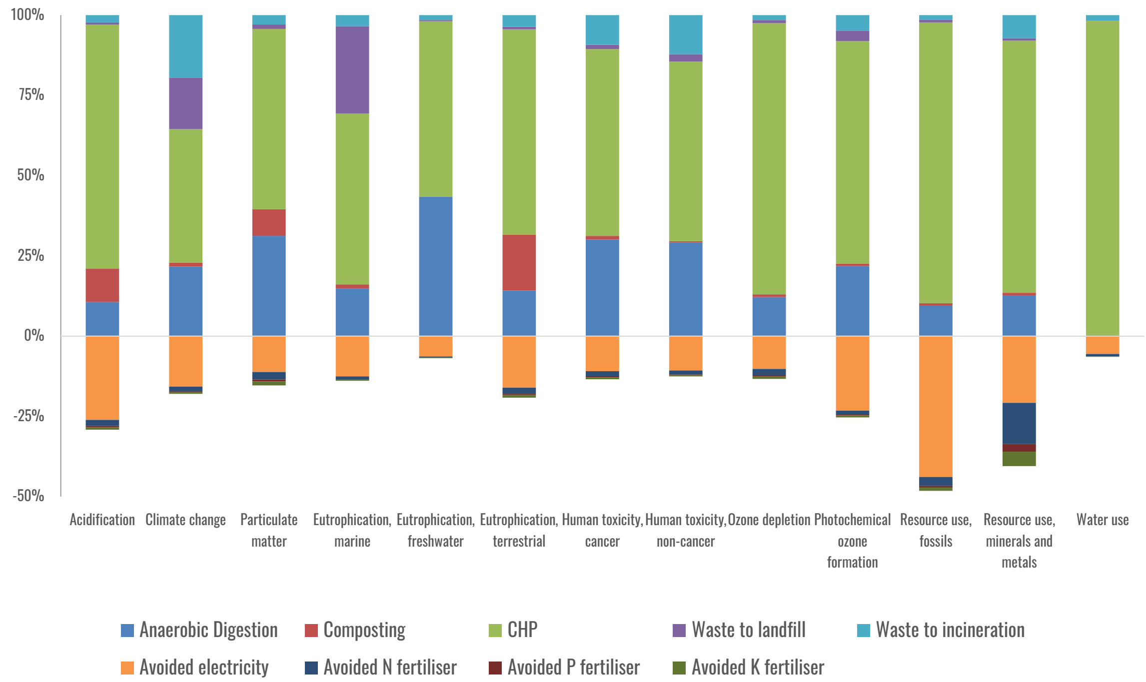


Figure 5 - Percentage contribution to the total impact of each analyzed impact category, calculated for the treatment phase in the BaU scenario, referred to the FU of 1 ton of separately collected biowaste transported to ECOPARC 2 (reference year 2021).

As far as the Alternative scenario is concerned, the characterized results are reported in *Table* ***9*** and *Figure* ***6***. The trend of the relative contribution of collection and treatment phases to the total impacts in the investigated impact categories is similar to the trend recorded for the BaU scenario: the collection phase, that also includes transportation, is responsible for most of the impacts generated in all the impact categories, with contributions always higher than 63%, except for EF where 84% of the total impacts is generated by the treatment phase. Unlike the BaU scenario, the treatment phase is less impactful than the collection phase in WU impact category, generating only 16% of the total impacts, due to the absence of CHP plant in the Alternative scenario. Moreover, the treatment phase generates environmental benefits in OD and RUF impact categories, saving respectively 2.32E-05 kg CFC11 eq and 3.05E+03 MJ.

Deepening the collection and treatment phases of the Alternative scenario, the collection phase is impacting essentially due to the inputs of transportation, responsible for 99%, as average value, of the total impacts. Also in this case, as already seen for the BaU scenario, the impacts of containers (both containers for door-to-door collection and smart bins) are irrelevant, while the compostable bags generate 0.5% of total impacts, on average.

Table 9 - Characterized impacts of the Alternative scenario, referred to the FU of 1 ton of separately collected biowaste transported to ECOPARC 2 (reference year 2021).

Impact category	Abbrev.	Unit	Total	Collection	Treatment
Acidification	AC	mol H^+ eq	1.75E+01	1.69E+01	5.96E-01
Climate change	CC	kg CO_2 eq	2.87E+03	2.65E+03	2.17E+02
Particulate matter	PM	disease inc.	3.84E-04	3.77E-04	7.73E-06
Eutrophication, marine	EM	kg N eq	7.09E+00	6.78E+00	3.12E-01
Eutrophication, freshwater	EF	kg P eq	2.99E-01	4.77E-02	2.52E-01
Eutrophication, terrestrial	ET	mol N eq	7.67E+01	7.44E+01	2.34E+00
Human toxicity, cancer	HTc	CTUh	4.57E-07	3.37E-07	1.20E-07
Human toxicity, non-cancer	HTnc	CTUh	9.26E-06	5.79E-06	3.47E-06
Ozone depletion	OD	kg CFC11 eq	5.56E-04	5.79E-04	-2.32E-05
Photochemical ozone formation	POF	kg NMVOC eq	2.65E+01	2.62E+01	3.01E-01
Resource use, fossils	RUF	MJ	3.33E+04	3.63E+04	-3.05E+03
Resource use, minerals and metals	RUM	kg Sb eq	2.38E-03	2.18E-03	1.99E-04
Water use	WU	m^3 depriv.	3.93E+01	3.32E+01	6.14E+00

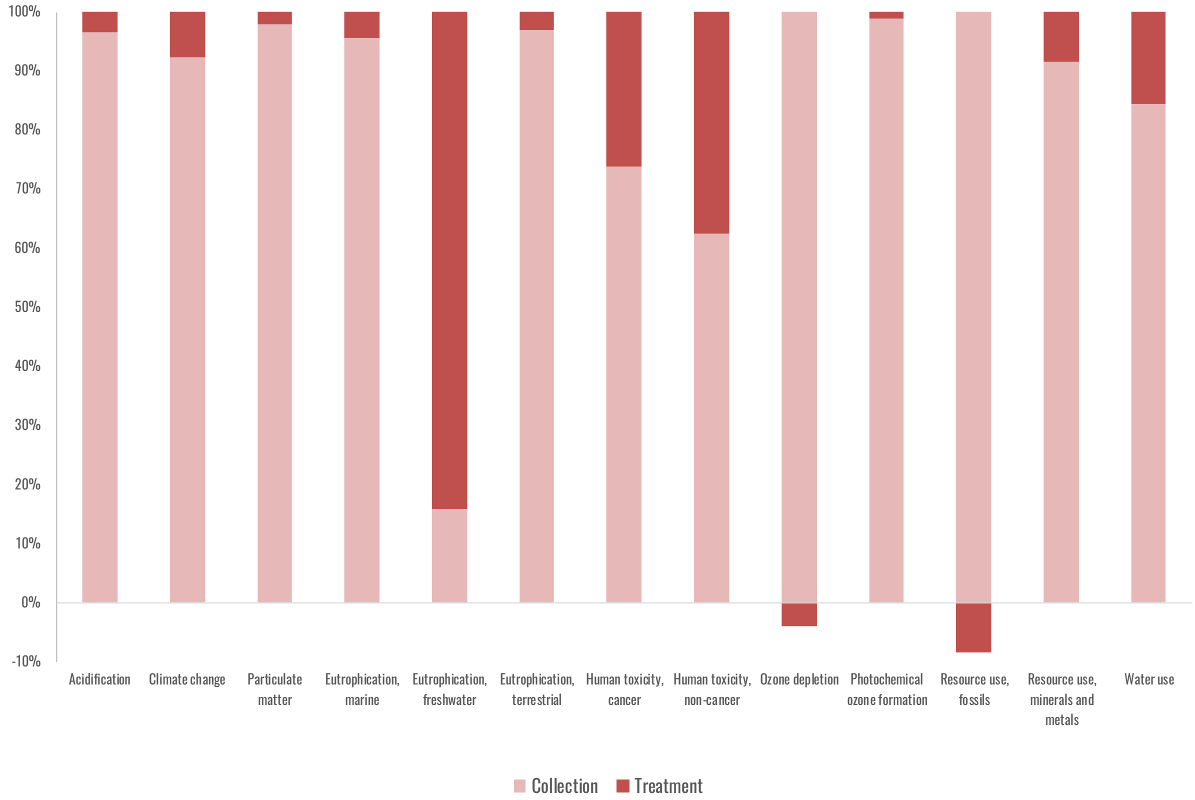


Figure 6 - Percentage contributions of each phase in the Alternative scenario to the total impact of the analyzed impact categories, referred to the FU of 1 ton of separately collected biowaste transported to ECOPARC 2 (reference year 2021).

Regarding the treatment phase of the Alternative scenario, the characterized impacts are shown in *Table* ***10*** and in *Figure* **7**. The main relative contribution to environmental loads comes from anaerobic digestion, that generates up to 97% of the total impacts in EF and 77% in HTc impact categories. The impacts of composting and of biogas purification to biomethane are definitely lower, being limited to 50% in ET and 49% in RUM, respectively. The impacts coming from the disposal of residual waste in landfill are significant only in a few impact categories (namely, EM and CC with contributions of 45% and 20% respectively), while the highest impact on WU, corresponding to 52% of the total impacts, comes from incineration of residual waste.

The environmental benefits (corresponding to negative net values of impacts), achieved by avoiding the supply of fossil-origin natural gas, are particularly relevant in the OD and RUF impact categories, with net savings of 2.32E-05 kg CFC11 eq is and 3.05E+03 MJ, respectively. Significant advantages are also produced in RUM and WU, thanks to the avoided production of synthetic fertilizers generating a reduction of 56% and 60% of the total impacts, respectively.

Table 10 - Characterized impacts of the treatment phase in the Alternative scenario, referred to the FU of 1 ton of separately collected biowaste transported to ECOPARC 2 (reference year 2021).

Impact categ.	Unit	Total	Anaerobic Digestion	Composting	Biogas upgrading	Waste to landfill	Waste to incineration	Avoided natural gas	Avoided N fertiliser	Avoided P fertiliser	Avoided K fertilizer
AC	mol H^+ eq	5.96E-01	3.40E-01	3.35E-01	6.94E-02	1.18E-02	3.43E-02	-9.90E-02	-5.95E-02	-1.37E-02	-2.28E-02
CC	kg CO_2 eq	2.17E+02	1.31E+02	7.34E+00	2.11E+01	5.53E+01	5.59E+01	-3.93E+01	-8.60E+00	-1.77E+00	-3.28E+00
PM	disease inc.	7.73E-06	6.44E-06	1.71E-06	4.98E-07	1.61E-07	2.88E-07	-4.93E-07	-4.88E-07	-1.23E-07	-2.60E-07
EM	kg N eq	3.12E-01	1.57E-01	1.37E-02	8.93E-03	1.64E-01	1.74E-02	-3.33E-02	-9.63E-03	-1.59E-03	-3.33E-03
EF	kg P eq	2.52E-01	2.49E-01	3.28E-04	2.12E-03	1.13E-03	4.19E-03	-2.22E-03	-1.86E-03	-5.49E-04	-7.18E-04
ET	mol N eq	2.34E+00	1.22E+00	1.48E+00	8.42E-02	3.58E-02	1.48E-01	-3.61E-01	-1.62E-01	-3.33E-02	-7.00E-02
HTc	CTUh	1.20E-07	1.08E-07	4.20E-09	9.38E-09	2.78E-09	1.58E-08	-1.15E-08	-5.68E-09	-1.20E-09	-2.14E-09
HTnc	CTUh	3.47E-06	2.82E-06	4.83E-08	1.94E-07	1.26E-07	5.61E-07	-1.07E-07	-1.11E-07	-2.31E-08	-4.17E-08
OD	kg CFC11 eq	-2.32E-05	7.33E-06	5.17E-07	2.49E-06	3.09E-07	4.49E-07	-3.24E-05	-1.21E-06	-2.24E-07	-4.58E-07
POF	kg NMVOC eq	3.01E-01	3.47E-01	1.22E-02	3.17E-02	2.97E-02	3.68E-02	-1.24E-01	-1.98E-02	-4.36E-03	-9.25E-03
RUF	MJ	-3.05E+03	5.07E+02	4.09E+01	2.92E+02	2.39E+01	3.66E+01	-3.72E+03	-1.48E+02	-2.69E+01	-4.98E+01
RUM	kg Sb eq	1.99E-04	1.88E-04	1.71E-05	2.45E-04	5.82E-06	4.90E-05	-2.47E-05	-1.84E-04	-3.39E-05	-6.41E-05
WU	m^3 depriv.	6.14E+00	2.76E+00	1.98E-01	5.04E+00	1.45E-01	8.95E+00	-7.83E-01	-7.95E+00	-8.13E-01	-1.41E+00

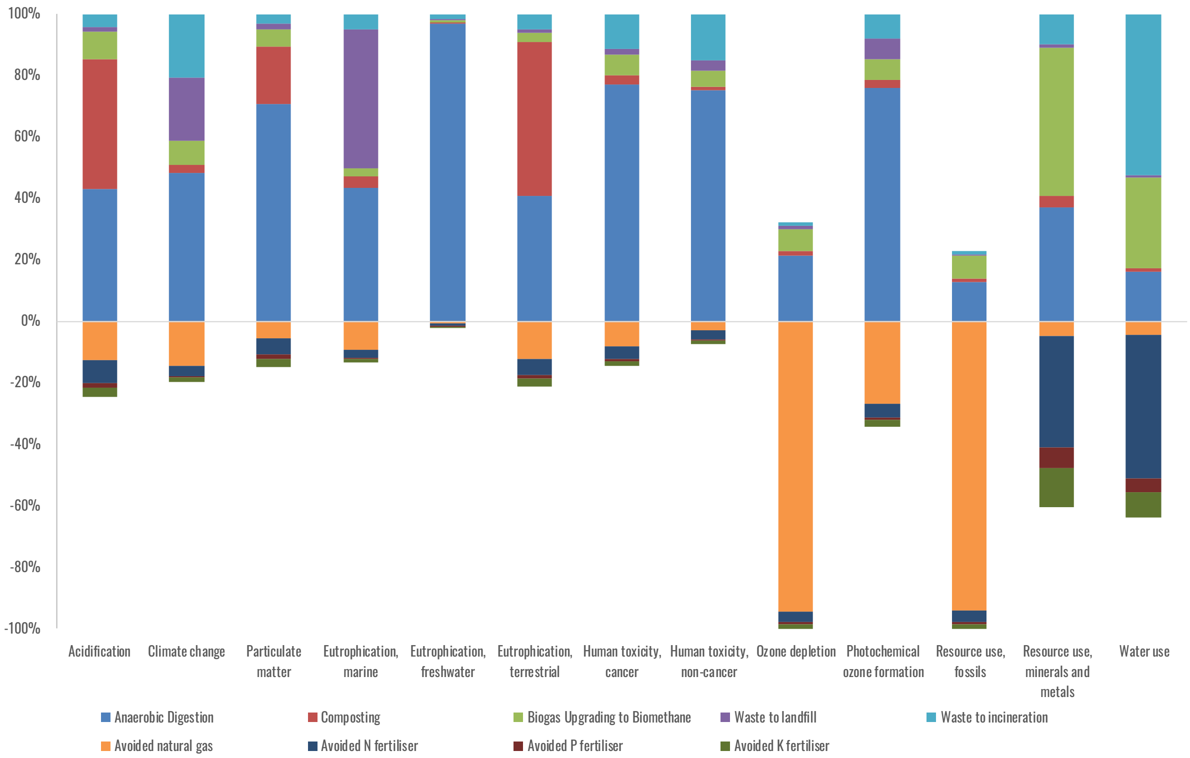


Figure 7 - Percentage contribution to the total impact of each analyzed impact category, calculated for the treatment phase in the Alternative scenario, referred to the FU of 1 ton separately collected biowaste transported to ECOPARC 2 (reference year 2021).

Finally, as shown in

Figure 8, from a comparison between BaU and Alternative scenarios reveals that the latter is environmentally more advantageous. The overall impacts in the Alternative scenario show decreases, compared to the BaU scenario, ranging from 43%, in PM and CC, up to 96%, in WU. The difference between the two scenarios is strictly linked to the reduction of the main hotspot, namely transportation: in the Alternative scenario, biowaste is collected 4 times per week, whereas in the BaU scenario biowaste is daily collected.

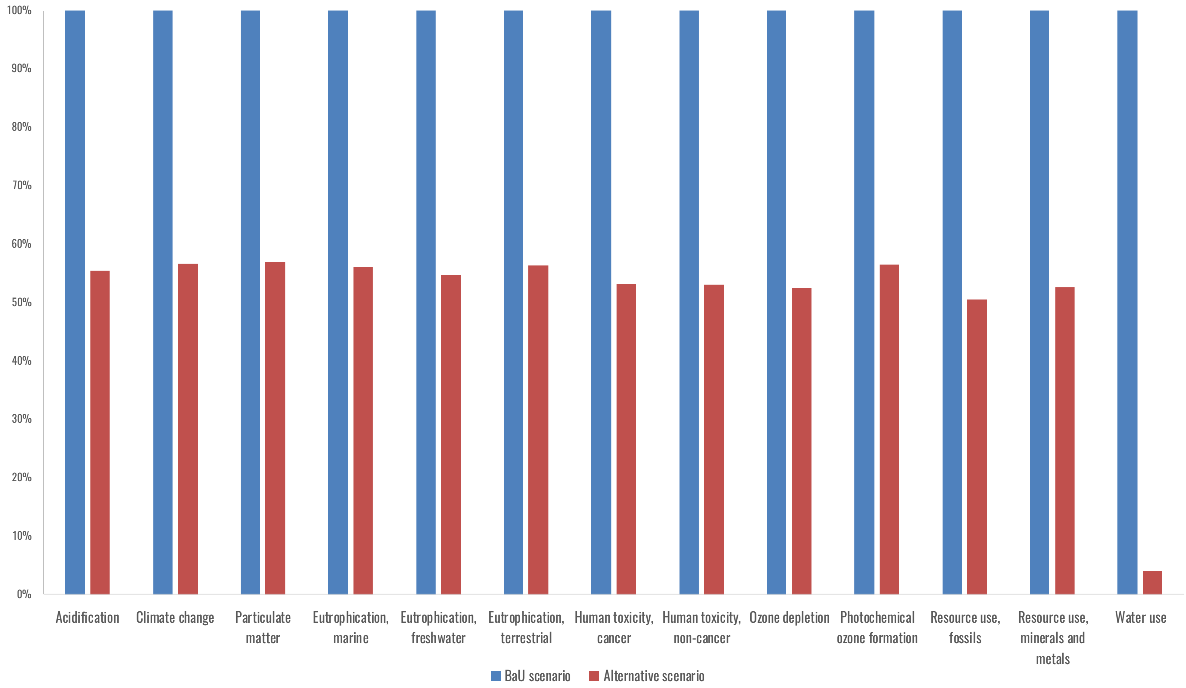


Figure 8 – Comparison between the characterized impacts from BaU and Alternative scenarios, referred to the FU of 1 ton of separately collected biowaste transported to ECOPARC 2 (reference year 2021).

3 LIFE CYCLE COSTING (LCC) OF THE BIOWASTE MANAGEMENT SYSTEMS IN THE MABPILOT AREAS

Life Cycle Costing (LCC) is a methodology applied for estimating the total expenditures and revenues of a system over its entire life cycle. on all resources consumed by the product or process system, during its lifetime.

Three types of LCC can be defined (Figure 9): conventional LCC (cLCC), environmental LCC (eLCC) and social LCC (sLCC). Conventional LCC (cLCC) focuses on all the costs related to an item from its conception and fabrication, including the initial investment, operating and maintenance, replacement and disposal (White and Ostwald, 1976; Bagg, 2013; Hin and Zmeureanu, 2014). Such costa are known as **internal costs**. Environmental LCC (eLCC) , eLCC, in addition to internal costs, also takes into account the costs, sustained or avoided, linked to environmental impacts, such as those due to climate change and resource depletion. These costs are referred to as **external costs** or **externalities** or environmental costs (Stern, 2006; Bierer et al., 2015). They are the costs usually, not directly paid by the responsible, but that are "externalized" on the environment. Social LCC (sLCC), compared to eLCC, also includes **social costs**. These are the economic damages, direct and indirect, suffered, presently or later on, by third parties or by the community due to the investigated system (Hunkeler et al., 2008).

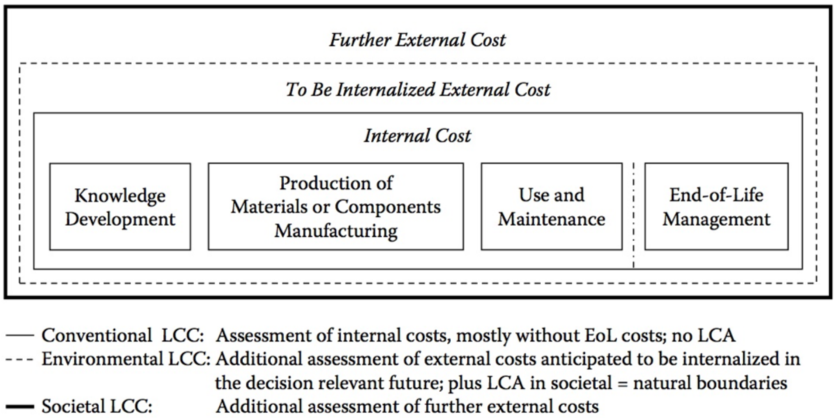


Figure 9 - Boundaries of conventional, environmental and social LCC.

In this study, the LCC was carried out considering the internal and environmental costs of the investigated systems, in order to effectively support policymakers.

3.1 Environmental Priority Strategies (EPS) methodology

The Environmental Priority Strategies (EPS) is an impact assessment method adhering to ISO standards 14040 and 14044, used to monetize the potential environmental impacts of emissions and resource use. Environmental impacts are translated into monetary values, expressed as Environmental Load Units (ELU), where one ELU equals one Euro of environmental damage. These costs reflect the willingness of an average OECD-inhabitant to pay for avoiding an environmental damage. Therefore, the EPS method provides a clear and standardized way to assess and compare environmental damage economic costs, thus aligning economic evaluations with environmental priorities and facilitating informed decision-making in sustainability efforts. In this study, the EPS 2015dx version (Medina-Salgado et al., 2021) was applied, focusing on impacts affecting five areas of protection, also referred to as Safeguard Subjects: Ecosystem Services (ES), Access to Water (AW), Abiotic Resources (AR), Human Health (HH), and Biodiversity (BD).

3.2 Goal and scope

The LCC analysis was conducted from the perspective of a political decision-maker or entrepreneur seeking to promote or invest in economically sustainable biowaste disposal systems, in line with the principles of circular bioeconomy. The objective of this LCC study is to provide biowaste managers and politicians of the MAB pilot area with information useful for evaluating the economic feasibility of the investigated biowaste management systems.

This LCC is consistent with LCA and follows a steady-state modelling approach, which lacks any temporal specification, assuming all technologies will remain constant in time.

System boundaries: For the studied systems, the boundaries and the related assumptions were the same as defined for the LCA studies (for deeper details, see Section 2).

Functional unit: In order to make the results comparable, the same functional unit for both LCA and LCC analyses was adopted.

3.3 Internal costs of the MAB pilot area

The internal costs for the BaU and the Alternative scenarios in the MAB pilot area, included in the LCC analysis and referring to the selected FU (1 ton of municipal biowaste collected and transported to ECOPARC 2, in the reference year 2021), are reported in *Table **11***.

Table 11 - Internal costs of the BaU and Alternative scenarios in the MAB pilot.

Phase	Internal cost/FU	Unit	Reference
BaU scenario			
Collection	-35	€	Personal communication from 3rd Peer Review Session of BCC project
Treatment	-86	€	Primary data - AMB
Total internal costs	**-121**	**€**	
Alternative scenario			
Collection	-35	€	Personal communication from 3rd Peer Review Session of BCC project
Treatment	-80	€	Personal communication from 3rd Peer Review Session of BCC project
Total internal costs	**-115**	**€**	

As shown in *Table **11***, the internal costs for the Alternative scenario resulted slightly lower than for the BaU scenario. Unfortunately, for the two analyzed phases (collection and treatment) only aggregated data were provided, not allowing to deeper investigate the single involved flows. The lack of data split into the investigated phases and flows (plastic containers, bags, transport for the collection, personnel, infrastructures, treatment in the anaerobic digestion and in the CHP plant, biogas upgrading, revenues for the products sold to the market, etc.) prevented a thorough examination.

Moreover, it is important to highlight that the internal costs (related to expenditures and revenues) for both scenarios are not primary data, but rather average European data. Indeed, streamlined and generalized analyses should be avoided or used with caution. Therefore, this LCC analysis should be considered indicative. A more reliable assessment would require site-specific data, given the complexity of a local municipal waste management system as well as the significant influence of context and local specificities on LCC results.

3.4 External costs (Externalities) of the MAB pilot area

The environmental damage costs of the two investigated scenarios, for each safeguard subject, are reported in *Table **12***.

Table 12 - Comparison among the externalities of the BaU and Alternative scenarios in the MAB pilot area, referred to the selected FU (1 ton of separately collected biowaste transported to ECOPARC 2, in the reference year 2021).

Safeguard subject	Unit*	BaU scenario	Alternative scenario
Ecosystem services	ELU	2.01E+01	1.12E+01
Access to water	ELU	1.14E+00	6.34E-01
Biodiversity	ELU	6.55E-02	3.65E-02
Human health	ELU	9.73E+02	5.43E+02
Abiotic resources	ELU	1.68E+03	8.80E+02
Total	**ELU**	2.67E+03	1.44E+03

**1 ELU: 1 Euro*

Both investigated scenarios determine environmental damage costs, amounting to 2674 ELU in the BaU scenario *versus* 1435 ELU in the Alternative one. Overall, the Alternative scenario results to be more advantageous, with a total environmental damage cost almost halved in comparison with the BaU scenario. For both scenarios, the highest costs are related to Abiotic Resources safeguard subject (62% of the total damage costs, on average) and to Human Health safeguard subject (37% of the total damage costs, on average). The environmental damage costs related to the Ecosystem services represent only 1%, whereas the costs of the remaining safeguard subjects result irrelevant.

In order to understand which flows mainly contribute to the externalities, the environmental damage costs of the analyzed phases (namely, collection and treatment phases), for each investigated safeguard subject, are reported in *Table **13*** and *Table **14***, for the BaU scenario, and in *Table **15*** and *Table **16***, for the Alternative scenario.

Table 13 - Externalities of the Collection phase of BaU scenario in the MAB pilot, referred to the selected FU (1 ton of MSW biowaste collected and transported to ECOPARC 2, in the reference year 2021).

Safeguard subject	Unit*	Total	Plastic Containers	Bags	Transport	Water
Ecosystem services	ELU	1.90E+01	1.18E-08	9.89E-03	1.90E+01	1.26E-08
Access to water	ELU	1.07E+00	7.12E-10	6.24E-04	1.07E+00	7.64E-10
Biodiversity	ELU	6.11E-02	4.12E-11	3.90E-05	6.10E-02	4.19E-11
Human health	ELU	9.23E+02	5.54E-07	5.75E-01	9.23E+02	6.15E-07
Abiotic resources	ELU	1.51E+03	2.41E-06	3.45E+00	1.50E+03	2.27E-06
Total	**ELU**	**2.45E+03**	**2.97E-06**	**4.04E+00**	**2.44E+03**	**2.90E-06**

**1 ELU: 1 Euro*

Table 14 - Externalities of the Treatment phase of BaU scenario in the MAB pilot, referred to the selected FU (1 ton of separately collected biowaste transported to ECOPARC 2, in the reference year 2021).

Safeguard subject	Unit*	Total	Anaer. Digestion	Composting	CHP plant	Waste to landfill	Waste to incineration	Avoided Electricity	Avoided fossil fertilisers
Ecosystem services	ELU	1.06E+00	2.19E-01	-1.60E-02	7.85E-01	2.51E-02	4.10E-01	-3.19E-01	-4.43E-02
Access to water	ELU	6.63E-02	1.28E-02	6.42E-04	4.76E-02	1.46E-03	2.56E-02	-1.89E-02	-2.88E-03
Biodiversity	ELU	4.41E-03	7.25E-04	2.29E-04	2.96E-03	3.82E-04	1.34E-03	-1.06E-03	-1.76E-04
Human health	ELU	5.00E+01	1.03E+01	4.81E-01	4.14E+01	2.37E+00	1.42E+01	-1.68E+01	-1.86E+00
Abiotic resources	ELU	1.74E+02	2.14E+01	1.51E+00	2.00E+02	1.30E+00	8.40E+00	-3.15E+01	-2.71E+01
Total	**ELU**	**2.26E+02**	**3.19E+01**	**1.97E+00**	**2.43E+02**	**3.70E+00**	**2.30E+01**	**-4.86E+01**	**-2.90E+01**

**1 ELU: 1 Euro*

In the **BaU scenario**, 92% of the total environmental damage costs is generated by the collection phase and 8% by the treatment phase. In the collection phase, transport is the main contributor, totaling over 2,400 ELU. The total damage cost of the treatment phase is 226 ELU. Although the biogas treatment in the CHP plant alone generates damage costs of 243 ELU, the overall damage cost is reduced to 226 ELU, thanks to the savings from avoiding electricity generation from fossil sources (approximately 49 ELU) and synthetic fertilizers production (29 ELU, primarily in the Abiotic resources safeguard subject). Composting also brings savings in the Ecosystem services safeguard subject, even if of minor extent.

Table 15 - Externalities of the Collection phase of Alternative scenario in the MAB pilot, referred to the selected FU (1 ton of separately collected biowaste transported to ECOPARC 2, in the reference year 2021).

Safeguard subject	Unit*	Total	Plastic containers	Smart bins	Bags	Transport
Ecosystem services	ELU	1.09E+01	4.99E-04	3.36E-06	9.89E-03	1.09E+01
Access to water	ELU	6.13E-01	3.02E-05	2.06E-07	6.24E-04	6.13E-01
Biodiversity	ELU	3.49E-02	1.75E-06	1.18E-08	3.90E-05	3.49E-02
Human health	ELU	5.28E+02	2.35E-02	2.69E-04	5.75E-01	5.27E+02
Abiotic resources	ELU	8.62E+02	1.02E-01	1.86E-03	3.45E+00	8.58E+02
Total	ELU	**1.40E+03**	**1.26E-01**	**2.13E-03**	**4.04E+00**	**1.40E+03**

**1 ELU: 1 Euro*

Table 16 - Externalities of the Treatment phase of Alternative scenario in the MAB pilot, referred to the selected FU (1 ton of separately collected biowaste transported to ECOPARC 2, in the reference year 2021).

Safeguard subject	Unit*	Total	Anaerobic Digestion	Composting	Biogas Upgrading	Waste to landfill	Waste to incineration	Avoided Natural gas	Avoided fossil fertilisers
Ecosystem services	ELU	3.20E-01	2.52E-01	-1.81E-02	5.84E-02	1.64E-02	2.24E-01	-1.62E-01	-5.10E-02
Access to water	ELU	2.11E-02	1.48E-02	7.58E-04	3.57E-03	9.58E-04	1.40E-02	-9.62E-03	-3.31E-03
Biodiversity	ELU	1.57E-03	8.35E-04	2.65E-04	1.91E-04	2.50E-04	7.35E-04	-5.05E-04	-2.02E-04
Human health	ELU	1.54E+01	1.18E+01	5.71E-01	2.22E+00	1.55E+00	7.76E+00	-6.41E+00	-2.14E+00
Abiotic resources	ELU	1.83E+01	2.52E+01	2.27E+00	2.12E+01	8.50E-01	4.60E+00	-4.74E+00	-3.11E+01
Total	**ELU**	**3.40E+01**	**3.73E+01**	**2.82E+00**	**2.35E+01**	**2.42E+00**	**1.26E+01**	**-1.13E+01**	**-3.33E+01**

**1 ELU: 1 Euro*

An analogous trend can be observed also in the **Alternative scenario.** The collection phase is responsible for most of the total environmental damage costs (98%), the transport being the main contributor, with total damage costs of 1,397 ELU (61% in Abiotic resources and 38% in Human Health). Regarding the treatment phase, 47% of total damage costs arise from biowaste treatment in the anaerobic digestion plant. Biogas upgrading ranks second, accounting for 30% of the total damage costs, followed by residual waste incineration, at 16%. A total of 45 ELU are saved, primarily due to the avoided production of synthetic fertilizers (31 ELU are saved only in the Abiotic resources safeguard subject), which are replaced with the obtained compost. Additionally, avoiding the use of fossil natural gas saves over 6 ELU, in the Human health safeguard subject. As a result, the overall damage cost decreases to 34 ELU.

In *Table* ***17***, the Total Life Cycle costs for the two investigated scenarios in the MAB pilot are shown. These costs were obtained by summing the internal and external costs. The results highlight that the Alternative scenario is more convenient than the BaU scenario, producing a net saving of 1,236 €/FU.

However, it is important to keep in mind that this LCC analysis can only be considered indicative and it would be necessary to rely the evaluation on site-specific primary data.

Table 17 - Total Life Cycle Costs (LCC) for BaU and Alternative scenarios in the MAB pilot, referred to the selected FU (1 ton of separately collected biowaste transported to ECOPARC 2, in the reference year 2021).

Category	Unit	BaU	Alternative
Net INTERNAL costs	€/FU	-121	-115
Net EXTERNAL costs	€/FU	-2,67	-1,44
Total	**€/FU**	**-2,79**	**-1,56**

4 CONCLUSIONS

Based on the obtained LCA/LCC results for the MAB pilot area, the following conclusions have been drawn for the analysed biowaste chain:

- The proposed solutions (prevention measures, different collection systems, and treatment) in the Alternative MAB scenario proved to be more sustainable than the current solutions described in the BaU scenario, both environmentally and economically.
- The environmental and economic impacts generated by collection activities in both scenarios are greater than those generated by treatment processes.
- The greatest environmental and economic benefits come from biomethane production which consequently avoids the need for fossil methane production.
- The Ozone Depletion and Resource Use (Fossils) impact categories record a net benefit from the proposed alternative solution.
- The Alternative MAB scenario allows for an average reduction of 70% in environmental impacts and about 46% in external costs.

Therefore, the environmental impacts due to bioproduct generation are compensated by the benefits of avoiding the use of fossil-based alternatives. However, due to the numerous assumptions made to replace missing primary data, the obtained results should only be considered indicative.

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