Ca' Foscari University of Venice

Master's degree

in Environmental Sciences

Final Thesis

LCA of the urban bio-wastes conversion into bio-based polymers in a bio-refinery context

PHA-based bio-plastic

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1 Introduction

1.1 Context

In a future where the Circular Economy will be the only path to solve a lot of environmental problems tied with the production and management of waste and materials to be reused, the EU is moving towards these items with concrete researches and projects. The objective of the EU commitment is to implement the circular economy into every concept of the EU market and industry. To do this, it is necessary to improve resources recovery options from each step of the value chains, from the product design to waste recycle, in order to make a real End of Waste directive. Within these considerations, the resource recovery from the organic fraction of municipal solid waste (OFMSW) towards higher value products than energy is a concrete option in the urban environment because of the significant amount of organic residues originate from the separate collection. Even the waste activated sludge (WAS) generated by urban wastewater treatment plants (WWTP) is an important organic waste that could be considered in a resource recovery approach.

These two waste streams contain a valuable amount of organic carbon (around 100-120 g COD/inhabitant per day, for municipal wastewater and around 30-40% more for OFMSW) that can be transformed in high economic value bio-products. The main focus is that this two streams that historically were handled separately, will be treated together within this new approach, creating an interesting opportunity to identify the best strategies to convert the organic carbon in useful products or energy (Reis, Silvia, Valentino, Werker, & Majone, 2018). The integrated treatment called Anaerobic Co-digestion (AcoD) (Bolzonella, D., Battistoni P., Susini C., 2006) of WAS along with organic solid waste (like the OFMSW, garden and agro-industry waste) in a novel bio-refinery (Cavinato, Bolzonella, Pavan, Fatone, & Cecchi, 2013) is the key to implement a circular economy with several advantages in terms of economy, carbon recovery and environmental impacts. First of all, the production of biogas is doubled as we can see in the real case of Rovereto (Mattioli, Gatti, Mattuzzi, Cecchi, & Bolzonella, 2017), and then we have several advantages in terms of management approach because it is possible to handle both waste streams in a single plant. Last but not least, the conversions of the carbon into valuable bio-based products like PHA-based bio-plastic, bio-solvents and bio-fibres and so on. This approach is aimed to close the circle of a real circular economy in fact, before waste disposal, it is possible to obtain some valuable products that could be re-used in the society, with the advantage of reducing these outputs and the connected environmental, social and economic impacts. On the other hand, it is necessary to take into account the territorial conditions because the projects and the technologies have to be affordable for the society and the stakeholders to create a sustainable recovery cycle that can be closed within the territory itself. (Majone Mauro, 2017)

1.2 Thesis description and goal

The aim of this study was to evaluate the environmental impacts of the conversion of several types of urban bio-wastes into valuable bio-based products (like PHA-based bio-plastics, bio-based solvents, fibres for bio-composites) within a single facility, using one main technology chain for the conversion and minimizing any residual or consequent waste to be disposed of.

<u>The overall objective of the project was to determine the environmental impacts of the PHA production from bio-waste into a pre-exiting waste management system</u>

The goal of this study is to identify the potential life cycle environmental impacts of the PHA production process under the bio-waste treatment (i.e. sewage sludge, organic fraction of municipal solid waste) by using a LCA model for developing different scenarios to compare the results.
The study was conducted on the pilot plant of the municipal wastewater treatment plant of Treviso, Italy and different types of waste treatment plants in Copenhagen Metropolitan area (Denmark) and in the Province of Trento (Italy). Either way the overall target is to demonstrate that the process is relevant in other systems.

Specific objectives were:

- To characterize the waste streams of the chosen territorial clusters instead of the Person Equivalent (PE) installed and the outputs of their current bio-waste management systems;
- To characterize the chemical composition of the waste streams;
- To conduct a Mass Balance of the pilot plant;
- To conduct a LCA of the pilot plant and of the different territorial clusters;
- To quantify the PHA production in the chosen clusters;
- To explain the chosen technology and how to implement it in the clusters;
- To compare the results between different scenarios (AD, RES URBIS bio-refinery);
- To identify which parameters have influenced the results and the impacts the most.

For each cluster was built the Res Urbis scenario, that integrated the new technology in a new concept of bio-refinery, and the comparative scenarios to describe how the current technologies could manage the waste streams of a bio-refinery.

The waste streams and mass balance of the different clusters and scenarios were investigated by the Department of Environmental Engineering at the Danmark Techniske Universitat, the Department of Chemistry of La Sapienza University of Rome and the Department of Environmental Sciences, Informatics and Statistics of Ca' Foscari University of Venice based on the data collected in the pilot plant located in the wastewater treatment plant of Treviso.

2 Background

2.1 The RES URBIS project

"RESources from URban BIo-waSte" (RES URBIS) is a European project that begins in January 2017 financially supported by *EU Horizon 2020* framework programme.

The challenge of the project Res Urbis is to reduce the residual or consequent waste to be disposed of with the possibility of new outputs from the bio-refinery introducing bio-based products in the bio-industry sector in order to close the circle of recycling in a circular economy perspective. The project is mainly focused on integrating the waste bio-refinery into existing wastewater treatment plants or anaerobic digestion plants with the conversion of different types of the organic fraction from separate collection of municipal solid waste, such as food and kitchen waste from households, restaurants, caterers and retail premises, excess sludge from treatment of urban wastewater, garden and parks waste, and similar into valuable bio-products. The main purpose of the study is to obtain Polyhydroxyalkanoate (PHA) and related PHA-based bio-plastics; bio-based solvents and fibers for bio-composites (Figure 1). The application of this bio-based polymers are biodegradable commodity film, packaging interlayer film, electronics and/or interior design goods, premium slow C release system for groundwater remediation (Majone, 2016).

The feasibility of the proposed concept and scenarios will be investigated in territorial clusters, which have been selected in different European countries and present different characteristics:

- Province of Trento (Italy);
- Barcelona Metropolitan area (Spain);
- Lisbon Metropolitan area (Portugal);
- South Wales (United Kingdom);
- Copenhagen (Denmark).

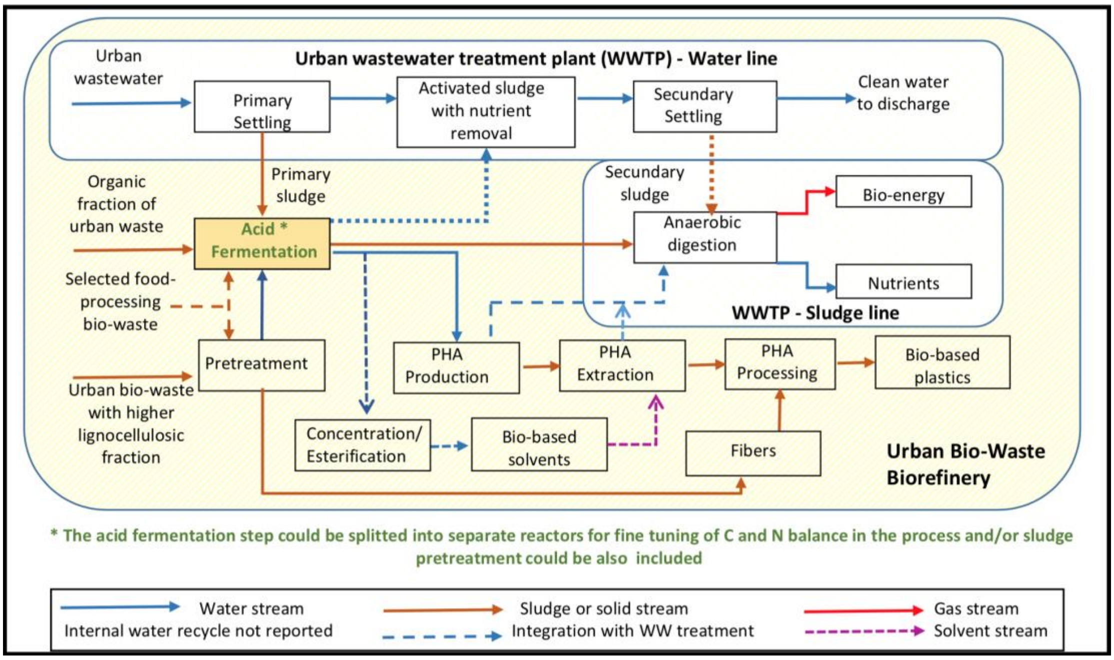

Figure 1 - Waste biorefinery scheme for urban bio-waste and possible integration with existing wastewater treatment plant

2.2 Definition of Biowaste

In EU Directive 2008/98/EC on waste, "Biowaste" is defined as follows: "biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises, comparable waste from food processing plants and other waste with similar biodegradability properties that is comparable in nature, composition and quantity".

The bio-waste in the urban areas can be identified as the potential organic waste generated in these complex contexts. The most important types are: food waste, referred to the stream generated from the whole food supply chain in the urban area; the garden and park waste generated during the maintenance of green areas and the wastewater sludge from the wastewater treatment plants. In this study it is important to specify that it considered the entire organic fraction from municipal solid waste (OFMSW) from household or residential, service, commercial and others, and both primary and secondary thickened sludge.

The key parameters of the considered bio-waste are the content of impurities, such as plastic, paper etc.; the physical characteristics of the individual waste types: water content, total solids (TS), volatile solids (VS), ash, volatile fatty acids (VFAs) and organic components like proteins, carbohydrates and lipids; the chemical characteristics like the content of heavy metals and the energy content in biochemical methane potential and heating values (Boldrin, Maklawe, Fantinel, & Bolzonella, 2017).

2.3 What is PHA? Why PHA? And its production

Polyhydroxyalkanoates (PHA) is a class of bio-polymers, made up of different esters, produced by numerous microorganisms (like the Polyphosphate accumulating bacteria (Poly-P)) as an internal energy storage. The bio-polyesters are converted by sugars and lipids to create a source of carbon storage within the cellular structure (Kourmentza, C., Placido, J., Venetsaneas, N., Burniol Figols, A., Varrone, C., Gavala, H. N. & Rei, 2017). There are two types of bacteria: those who accumulate PHAs during a phase of limitation of nutrients (such as nitrogen, phosphorous, oxygen) and those that accumulates PHAs during the growth phase without the lack of nutrients (Raza, Abid, & Banat, 2018).

There is a wide variety of esters in the family of PHA but only a few types of different PHAs will be interesting for future applications. The most investigated PHA is the homopolymer Poly(3-hydroxybutyrate) (PHB) for his proprieties and applications like bio-plastic, bio-solvents, bio-fibers and so on (Majone Mauro, 2017).

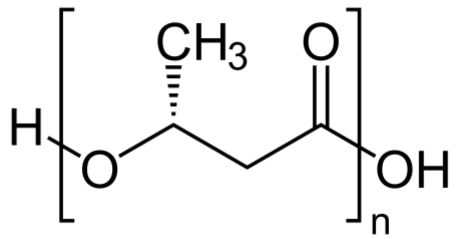

Figure 2 - Chemical structure of poly-(R)-3-hydroxybutyrate (P3HB), a polyhydroxyalkanoate

These kinds of polymers are studied because they are very similar to the fossil-based plastic and they could resolve one of biggest problem in the waste management such as the plastic biodegradation. In fact the PHAs are the most suitable bio-polymers for this purpose, because they are bio-based, produced from bacteria, non-toxic, bio-compatible and bio-degradable, a real “green” plastic (Raza et al., 2018).

Another important characteristic of this family of poly-esters is that can be produced in non-sterile conditions according to (Morgan-Sagastume et al., 2014) (mild conditions). In fact, this family of bio-esters can be produced using waste activated sludge microorganisms feed with a carbon sources obtained by organic waste fermentation. The process, based on Mixed Microbial Culture (MMC), improves the parameters' stabilization requiring less energy and low-cost feedstocks in an optic of non-sterile conditions. In the mixed microbial culture process, the culture selection is achieved under conditions of feast-famine (FF) regime with low ratio in a sequencing batch reactor (SBR) (Villano et al., 2014) using Volatile Fatty Acids (VFAs) as main substrates for the selective growth of PHA-storing organisms because they are efficiently converted in PHA (Morgan-sagastume et al., 2015). VFAs was produced from the acidogenic fermentation of the readily biodegradable chemical oxygen demand (rbCOD) of the OFMSW and WAS (Morgan-Sagastume et al., 2014). The main fact is that the bio-wastes introduced in the process can be strongly reduced by converting the organic solids into VFAs for the PHAs accumulation and production and into biogas with a minimization of the waste to be disposed of and the extraction of valuable products (Valentino et al., 2015).

The process is already used at Pilot Scale in a well understand, robust and tunable method that is integrated in the pilot plant of Treviso (and other realities)(Valentino et al., 2015) but the aim of Res Urbis is to make it ready for the industrial scale, analysing the full-scale impacts and socio-economic costs (Majone, 2016).

The production of PHAs requires several steps:

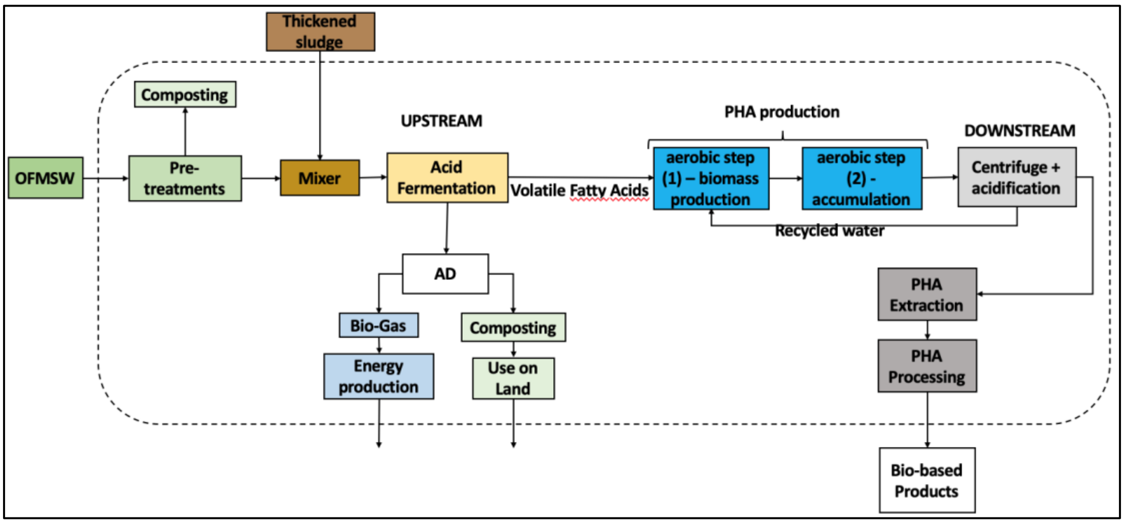

Figure 3 - PHA production process

The first step is to collect the carbon sources from the OFMSW, after the pre-treatment steps (mechanical opening, selection and pressing), and the excess thickened secondary sludge (SS) in a mixer. This is done to break the large molecules into smaller and most suitable compounds because they have to proceed in a reactor for the acidogenic fermentation.

In the second step there is the conversion of the rbCOD into the VFAs. The stream goes into a solid/liquid separation with an ultrafiltration to divide the liquid stream rich in VFAs, for the step of accumulation of PHAs, from the solid stream, that goes to be disposed of (generally Anaerobic Digestion).

The third step is the PHA production that can be dived into two phases requiring a sequencing batch reactor, the so called feast-famine conditions: the first phase is the growth of selected active biomass of microbes, the MMC, providing all the nutrients; then there is the phase of lack of nutrients (like nitrogen and phosphate), to create the regime of accumulation of the carbon sources into the bacteria within the internal storing cell being able to accumulate PHA up to 90% of cell dry weight (Valentino et al., 2015).

The downstream section includes the PHA extraction and processing. It includes a microfiltration, a high-pressure homogenization and centrifugation to increase the concentration of the PHA rich biomass, release the poly-esters and to separate it from the fluid. The extraction is done using different methods: i) extraction with solvents, like chloroform, 1,2-dichloroethane or acetone, but 1,2-propylene carbonate is preferred due to its lower toxicity; ii) the floatation method, a modification of the solvent extraction followed by the self-floatation of the cell debris; iii) the digested method, due to release the PHAs from the cells using a chemical or enzymatic digestion; iv) the supercritical fluid extraction (like supercritical carbon dioxide) recover the PHAs from the cells with low toxicity and costs; v) the aqueous two-phase extraction, that uses the water solvent to extract PHAs (Raza et al., 2018). The processing of PHA is possible thanks to the thermoplastic properties of these polyesters so they could be modelled in various products with different applications. The biocompatibility, biodegradability and greenness characteristics makes PHAs affordable for the medical sector like tissue engineering (bone, heart valve and so on) or bio-implant patches; for the pharmaceutical sector like in drug delivery carriers; or in the biofuel sector through the methyl esterification technique; or in other nanotechnology sectors as manufacturing of bio-composites, for protein chips for detection of hepatitis B virus, for film and nano-gels, nanofibers (Raza et al., 2018). But the most suitable sector is the packaging sector because PHAs can be used to produce bioplastic packaging in foam form. So, it can functionally replace over the 50% of the fossil-plastic used today. In addition to these attributes, PHAs are biodegradable in aquatic (oceans, rivers, and wetlands), soil, and municipal waste treatment environments, and they can be both hot and cold composted (Packaging & Serdp, 2010).

PHAs have some disadvantages in their chemical properties and purity compared to the fossil-based plastics: they lack of clear transparency and a narrow window; they are degraded at 120°C; they have a slow crystallization rate; there is sometimes an excess of heavy metals in some samples that justified the actual price and distribution in the market compared to “normal” plastic (Valentino, 2018).

In Res Urbis project it has been estimated that 56 Kg of PHAs are produced per TS tonne of mixed urban biowaste (Valentino, 2018).

In the actual tested conditions, the selling price of PHAs resins ranges from 2.2-5.0€/Kg according to (Valentino et al., 2017) depending on substrate costs and PHA yield on the substrate. The main problem remain that it costs 3-4 times more than the conventional petroleum-based polymers (1.00-1.55 €/Kg) according to (Kourmentza, C., Placido, J., Venetsaneas, N., Burniol Figols, A., Varrone, C., Gavala, H. N. & Rei, 2017).

2.4 Cluster description

The main purpose of this study is to evaluate the possibility of a full-scale implementation of this new technology into the chosen clusters. Copenhagen Metropolitan Area and the Province of Trento have been chosen to understand the introduction of the bio-refinery into different waste management systems.

2.4.1 Trentino cluster

The Province of Trento is located in the north of Italy and corresponds to an area of 6207 km^2 (Figure 4) with a population of 538,604 inhabitants living in 175 municipalities with a population density of 87 ab/km^2. It is the smallest cluster under the project of Res Urbis and the only Italian reality but in a very particular mountain territory. The most populated cities are Trento (with around 120,000 inhabitants) and Rovereto with around 40,000 inhabitants (Trento, 2019).

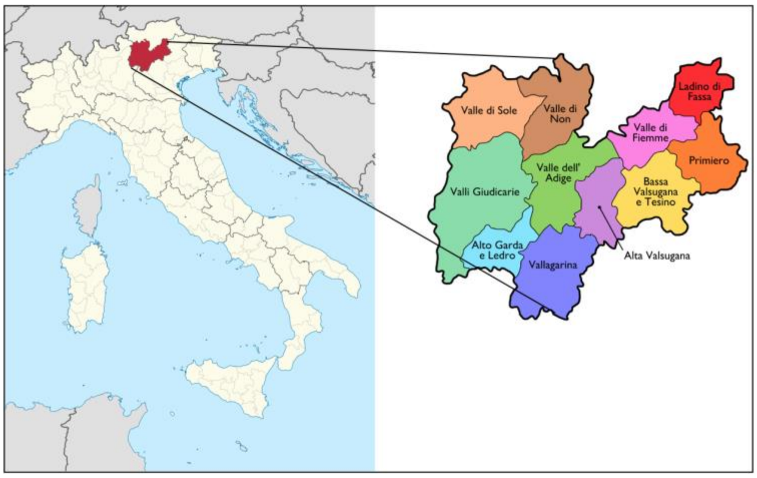

Figure 4 - The Province of Trento in Italy and the current local authority

The waste management is handled by different societies like Dolomiti Ambiente, ASIA (Special Agency for Environmental Hygiene), Comunità Val di Non etc. (Figure 4) that regulate different aggregations of municipalities (Trento, 2019).

Table 1 - Biowaste streams and their percentage of distributions in 2017 in the Province of Trento

Trento	OFMSW	SLUDGE	Tot
Tn/y	78,741	390,911	453,904
%	14%	86%	100.0%

In the current bio-waste management (Table 1), the total amount of waste considered was 453,904 tons. The total amount of the urban waste was 261,976 tn/y with 73,723 tn/y of source separated organic fraction that reached an efficiency of separate collection of 83% in 2016 with 136.9 kg/PE/2016. The residual waste was only 59,000 tons/year, 109.5 kg/PE/2016 based on the ISPRA data, that makes the Province of Trento one of the best in Italy. The organic fraction of municipal solid waste considered in the study was 78,741 tn/y (the 14% of the total) with 145.82 kg/PE/2016. These percentages are reached with the introduction of "pushed" collection systems, the construction of the collection points and the adoption of the punctual tariff. According to the provincial plan for waste management the organic fraction of the municipal solid waste is treated in 3 anaerobic digestion plants, and 4 composting plants. The minor capacity of the treatment plants beside the organic waste streams forces the stakeholders to send part of these waste outside the region to be managed (Majone, 2016).

The sludge produced and sent to the treatments was 390,911, the 86% of the total stream considered in this study. The municipalities served by the 70 WWTPs are 175 and the corresponding total population equivalent served is 839479 PE (including civil and industrial). In the project is considered only the civil stream with a total population equivalent served of 611,402 PE with 70 gTS/day/PE with the actual streams. Based on the collected data from the Province of Trento there are 3 wastewater treatment plants with Anaerobic Digestion and Dewatering. The biggest ones are Rovereto, one of first examples of cycle integration with joint processing of solid waste and sewage sludge through anaerobic co-digestion, Trento North and South and then there are other 67 smallest plants that sent the dewatered sludge to composting or AD.

Other destinations of the waste streams are different landfills already in activity in the territory.

The future plans and goals for the waste management in the Province of Trento are: the reduction of the landfilled waste and to became a “Landfill Free” Province and for the 2030 and the construction of a Waste to Energy plant (Marcazzan, 2014).

2.4.2 Copenhagen cluster

Denmark is located in the North of Europe and Copenhagen is the capital city of Denmark (Figure 5)and the most populated city. It is located in the South East in front of Sweden. In 2018 the city had a population of 777,218 with a population density of 4,400 inhab./km^2. The metropolitan area (or urban area) is a larger area with a section of 2,561 km^2 that includes 18 municipalities including the Copenhagen and Frederiksberg municipalities with a population of 1,280,371 inhabitants in 2018 and with a population density of 2,120 inhab./km^2 (Denmark, n.d.).

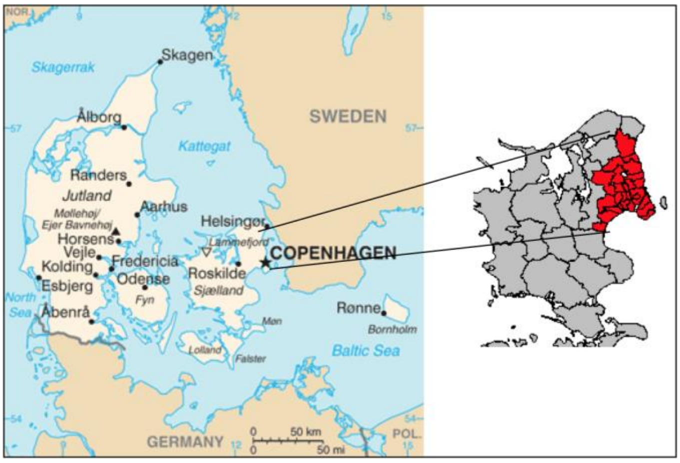

Figure 5 - City of Copenhagen in Denmark and a zoom to the Copenhagen metropolitan area with municipalities

The waste management considered in the study is handled by BIOFOS that provides the services for the wastewater treatments and the collection and transportation of the bio-waste in the area.

Table 2 - Biowaste streams and their percentage of distributions in 2017 in Copenhagen metropolitan area

Copenhagen	OFMSW	SLUDGE	Tot
Tn/y	207,567	1,152,506	1,360,073
%	15.3%	84.7%	100.00%

In the current bio-waste management (Table 2), the total amount of waste considered was 1,360,073 tn/y. The total amount of municipal food waste (OFMSW) was 207,567 tn/y, the 15.3% of the total, with 162.12 kg/day/inhab. Most of this stream is sent to incineration because in the metropolitan area there are two Waste-to-Energy plants, Copenhill (Amagerbakke) and Glostrup, provided by Vestforbrænding and Amager Resource Center and owned by the municipalities, that have capacities around 600,000 tn of waste per year and are both combined heat and power waste-to-energy producers sold to the national grid and reused. The bottom ash is reused for the construction industry and the fly ash is landfilled. Furthermore, the separation of household food waste began only in the 2018.

The sludge stream considered was 1,152,506 tn/y, the 84.7% of the total. The wastewater treatment is provided by the BIOFOS that operated in three large plants: Avedøre, Damhus˚aen and Lynetten. The actual Person Equivalent installed are 1,000,000 for Lynetten; 350,000 for Damhus˚aen and 400,000 for Avedøre based on the BIOFOS data for 2017. So, the total PE considered was 1,760,137 with 64.67 gTS/day/PE. In these wastewater plants there are primary and secondary settling and then the sludge is sent through an AD for the biogas production and later dewatered and send to incineration, except for Damhus˚aen.

In 2018 there was the inauguration of a third Waste-to-Energy plant, the biggest one, and for 2025 Copenhagen has the ambition of becoming a carbon neutral city.

3 Methodology and data processing

The life cycle assessment can be divided in several steps:

- Generalities of the LCA study
- Method, Assumptions and impact limitations
- Scope
  - Functional Unit
  - Impact assessment criteria
  - System boundaries
- Life Cycle Inventory
  - Data collection
  - Waste composition and Fractions used
  - Mass Flows, Scenarios and Material Flow Analysis
  - Technologies and transportation
  - Sensitivity

3.1 Generalities of LCA study

The intended application of this study is to compare different environmental impacts of the PHA production process under the bio-waste treatment in a new concept of bio-refinery. To highlight the environmental hotspots, it has been selected two European cities, Copenhagen metropolitan area and the Province of Trento, as described in the chapter 2, based on the data of the pilot plant of Treviso (the Scenario Res Urbis).

The commissioner of the study is the RES URBIS Consortium, in particular the department of Environmental Engineering at the Technical University of Denmark and the department of Environmental Science, Informatics and Statistics at the Ca' Foscari University of Venice. The first one stands for the LCA part and the second one stands for the process implementation part.

The results are intended to be used by the stakeholders (RES URBIS, Municipalities responsible for waste management and their publicly owned waste management companies) to understand if the RES URBIS scenario for the production of PHA-based polymers through the bio-wastes management plants has some environmental advantages compared to other waste management options (e.g. AD, Landfill, Compost, not included in this study) for the same types of wastes.

According to ILCD Handbook (EC-JRC & Commission, 2011), the decision-context is essential to determine the scope and the type of LCI model. Situation B refers to life cycle-based decision support with consequences that are so extensive that they overcome thresholds and result in additionally installed or additionally decommissioned equipment / capacity (e.g. production infrastructure) outside the foreground system of the analysed system. For this reason, this LCA is categorize as Situation B and the modelling approach can be defined as a consequential LCA.

3.2 Method, assumptions and impact limitations

The project was based on a pilot-scale plant in Treviso, for the PHA process implementation, and on full-scale plants in Copenhagen and the Province of Trento to compare the different scenarios. The first limitation of the project it is referred to the two different types of data that we used to run the scenario. For this reason, the study of the data representativeness, uncertainty, sensitivity and data quality is a key part in this LCA.

The software used was EASETECH, a specialised LCA model developed by DTU (Clavreul et al., 2014) and the study has been conducted according to the requirements of ISO 14044:2006 and the ILCD Handbook.

3.3 Scope

3.3.1 Functional unit

The functional unit of the system was 1m^3 of mixed bio-waste per year. This was composed by the 70% of thickened sludge, that come from the water line of the wastewater treatment plant, and the 30% of organic fraction of municipal solid waste considered after the pre-treatment steps; from 6 to 7% of the volatile solids of the 1m^3 of the mixed bio-waste became PHA at the end of bio refinery (Reis, Silvia, et al., 2018).

3.3.2 Impact Assessment Criteria and technologies

3.3.2.1 Impact Assessment Criteria

The Life Cycle Impact Assessment was based on the impact categories presented in Table 3. The LCIA impact assessment methods were selected among those recommended by the ILCD Handbook (EC-JRC & Commission, 2011). Results are presented as normalised impacts. In this study the European normalization factors for the year 2010 was used, based on Benini et al. (2014) and Sala et al., (2015). The unit for normalized potential impacts is the Person Equivalent (PE), which represent the average impact of a European citizen in 2010 while AE is Accumulated Exceedance; CTU_h is comparative toxic unit for humans and CTU_e is comparative toxic unit for ecosystem (Boldrin & Bassi Andreasi, 2017).

Table 3 - Characterization (midpoint) and normalization references utilized in the project. All the impact categories are based on the recommended impact categories in the ILCD Handbook (EC-JRC 2011) and the normalization references are based on the year 2010

Impact Category	**Acronyms**	**Characterization method**	**Normalization references**	**Units**
Climate change	CG	Baseline model of 100 years of the IPCC (Forster et al., 2007)	9.22E+03	kg CO2-eq./PE/year
Eutrophication Terrestrial	TE	Accumulated exceedance (Posch et al., 2008; Seppälä, Posch, Johansson, & Hettelingh, 2006)	1.76E+02	AE/PE/year
Eutrophication Freshwater	FE	EUTREND model as implemented in ReCiPe	1.48E+00	kg P-eq./person/year
Eutrophication Marine	ME	EUTREND model as implemented in ReCiPe	1.69E+01	kg N-eq./PE/year
Terrestrial acidification	AC	Accumulated exceedance (Posch et al., 2008; Seppälä et al., 2006)	4.73E+01	mol H+ eq. /PE/year
Particulate matter	PM	Compilation in Humbert, 2009 based on Rabl and Spadaro, 2004 and Greco et al., 2007	3.80E+00	kg $PM_{2.5}$ /PE/year
Human toxicity, cancer effects	HT-C	USEtox model v.1.01 (Rosenbaum et al., 2008)	3.69E-05	CTU_h*/PE/year
Human toxicity, non-cancer effects	HT-NC	USEtox model v.1.01 (Rosenbaum et al., 2008)	5.33E-04	CTU_h*/PE/year
Ecotoxicity freshwater	ET	USEtox model v.1.01 (Rosenbaum et al., 2008)	8.74E+03	CTU_e/PE/year
Abiotic depletion	ADP	CML 2002 (Guinée et al., 2002)	1.01E-01	kg Sb eq. /PE/year
Ionising radiation, hh	IOR	Human health effect model as developed by Dreicer et al. (1995) (ref. Frischknecht et al. 2000	1.13E+03	kBq U^{235} eq. (to air) /PE/year
Ozone depletion	ODP	Steady-state ODPs from the WMO assessment (latest WMO published ODP equivalents) (Montzka & Fraser, 1999) and the ReCiPe2008 data sets (v1.05).	2.16E-02	kg CFC-11 eq. /PE/year
Photochemical ozone formation, hh	POF	LOTOS-EUROS (van Zelm et al., 2008) as applied in ReCiPe 2008 v 1.05	3.17E+01	kg NMVOC eq. /PE/year

3.3.3 System Boundaries

The system boundaries of the model were based on the pilot plant of Treviso as shown in the Figure 6:

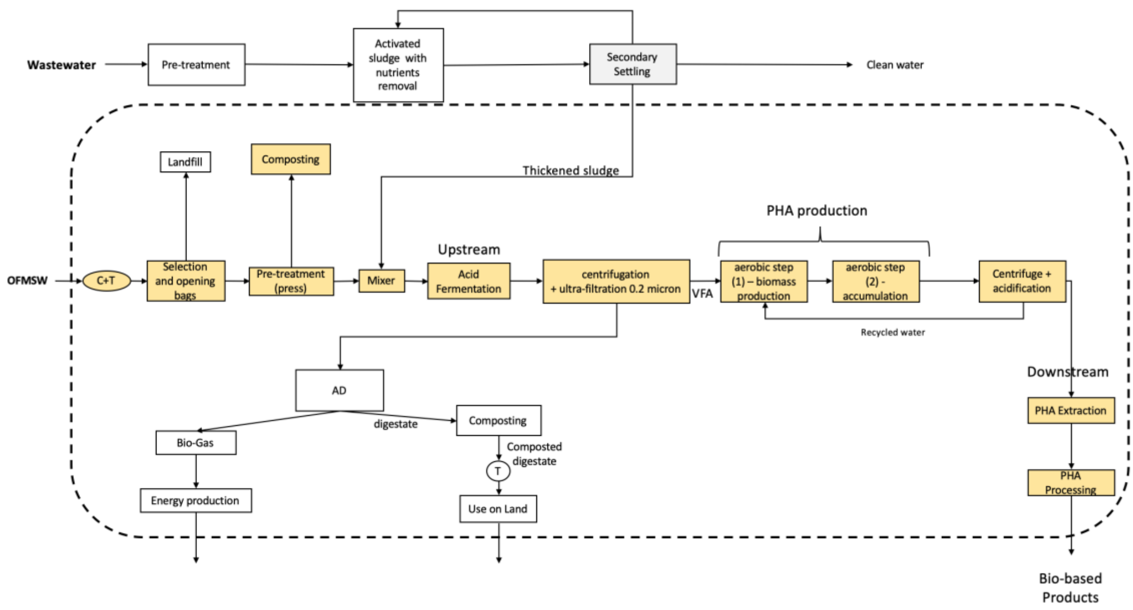

Figure 6 - System boundaries of the LCA study, C: collection; T: transportation

According to the preliminary LCA of Boldrin and Bassi Andreasi, (Boldrin & Bassi Andreasi, 2017) this study included:

- Collection and transportation;
- Opening of bags and selection of impurities;
- Pre-treatments: press;
- Composting;
- Mixer;
- Upstream: Acid Fermentation;
- Centrifugation and ultra-filtration;
- Anaerobic digestion;
- PHA production: i) aerobic step of biomass production, ii) aerobic step of PHA accumulation;
- Centrifugation;
- Downstream: PHA extraction and processing

The system boundaries involve the collection and transportation of the organic fraction of municipal solid waste with their capital goods. Moving inside the wastewater treatment plant there is the processes of bags' opening and selection of the impurities, that generate two streams. In the first one there are the impurities (like plastic or metals), that are sent to a landfill and, in the second one, there is the organic matter that goes to the pre-treatments. In this step there are several treatments that are not explained, except for the press that is important because generates two streams: the solid one goes to composting and the liquid one moves into the mixer. This step is the core of the process because combines two waste streams, the pre-treated organic fraction of municipal solid waste and the thickened sludge from the secondary settling of the water line of wastewater treatment plant.

According to Valentino et al. (Valentino et al., 2017) after mixing step the two waste streams are sent to the first reactor where the process of acid fermentation, in mesophilic condition, converts organic biomass into volatile fatty acids (VFA). The effluent undergoes to a solid/liquid separation in an ultrafiltration system: the solid phase is sent to an anaerobic digester for biogas production, used for running a stationary engine to produce electrical energy, and the digestate, that is sent to composting. The composted digestate is used in a concept of use-on-land as mineral fertilizer substitution. The liquid phase of the Ultra-filtration, rich in VFA (acetic, propionic and butyric acids), is sent to the two steps bioreactors for PHA production.

In the two-aerobic-phase processes there is a first step of selection and production of Mixed Microbial Culture with high PHA storage ability and a second step of PHA accumulation; the section of production and accumulation takes place in SBRs (sequential batch reactors) using the feast-famine regime (Valentino et al., 2016). The last step is a chemical extraction and purification of the PHA to produce a biopolymer suitable for the plastic industry.

3.4 Life Cycle Inventory

3.4.1 Data collection

The study is based on the data collection from other sources, and it was the most time-consuming process because of the lack of data and the misunderstandings regarding the waste streams and the waste treatment technologies. Due to these facts, the construction of the mass flows analysis and the different scenarios were slowed down. Also, the back calculation of the mass balance of the pilot plant and the selection and integration of the process in the model took some time for indirect problems of the reliability of the data. Furthermore, the language barriers and the different classification of the parameters intensified the difficulties.

3.4.2 Waste composition and fractions used

To understand the data collected it has to be clear the waste composition and the specific characteristics used to build the system flows.

For the material fractions, in order to obtain a final inventory of the urban bio-waste treated in the system, it is considered:

- The physical characteristics:
  - Wet weight of the waste generation in the considered area per year
  - Total Solids of the generated streams composed by:
    - Volatile Solids (%TS);
    - Ashes (%TS);
  - Water content;
- Chemical composition:
  - Carbon, Nitrogen, Potassium, Phosphorous, heavy metals etc.;
- Energy content:
  - Lower heating value (LHV) or Biochemical methane potential (BMP).

The chemical composition and the energy content are selected from the data collected from the clusters and from the average values already included in the software.

The material fractions are different between the two bio-waste considered.

The streams considered in the study are: the organic fraction of municipal solid waste and the thickened sludge; each of them before any other treatment. All of the streams and fraction are calculated in tonnes per year.

Table 4 - Waste compositions of the substrate used in the models and mass flows

Substrate	Composition	Source
OFMSW	Material fractions from the cluster and an average chemical composition derived from the vegetable food waste and animal food waste of Easetech	Material fraction composition based on Edjabou et al. (2015). Chemical composition is based on Riber et al. (2009)
Wastewater sewage sludge	Material fractions from the cluster and chemical composition from Easetech	Chemical composition are based on Yoshida et al. (2017).

3.4.3 Mass Flows, Scenarios and Material Flow Analysis

The mass balance analysis is a core step of the life cycle inventory to fully comprehend the waste flows and the material fractions needed to implement a strong life cycle analysis.

3.4.3.1 Mass Flows and Scenarios

The current bio-waste flows conducted in the clusters are based on the back calculations and assumptions of the Treviso pilot plant. In fact, the system boundaries, the processes and the parameters of the selected clusters are founded on this real plant.
In the following sections is considered the mass balance of the material fractions named in the paragraph *Waste composition and fractions used*. The calculations were made in Excel.

i) Baseline Scenario: Res Urbis Scenario – Treviso

The baseline scenario is the *Res Urbis Scenario – Treviso* and it is built on the system boundaries presented in the section *System Boundaries*.
Table 5 and Table 6 show the waste streams and the compositions of the entering flows.

Table 5 - Res Urbis Scenario - Treviso OFMSW composition

OFMSW					
Fractions	Wet Weight	Water	TS	VS (%TS)	Ash (%TS)
kg	375	285	90	79.74	10.26
%	100%	100%	24%	89%	11%

Table 6 - Res Urbis Scenario - Treviso Sludge composition

THICKENED SLUDGE					
Fractions	Wet Weight	Water	TS	VS (%TS)	Ash (%TS)
kg	700	679	21	13.97	7.04
%	100%	97%	3%	67%	34%

The mass flow proceeds with the pre-treatments of the OFMSW that generates a flow of the 80% of the original wet weight that undergoes to the mixer, while the thickened sludge fits in as described in the Table 6.

The mixer sums the two streams to obtain the functional unit of $1m^3$ (Table 7).

Table 7 - Res Urbis Scenario - Treviso Mixer fractions

MIXER					
Fractions	Wet Weight	Water	TS	VS (%TS)	Ash (%TS)
kg	1000	919	81	64.85	16.16
%	100%	92%	8%	80%	20%

This flow proceeds to the acidogenic fermentation unit, where the organic fractions become volatile fatty acids and a little part of VS is degraded (4%) (Table 8).

Table 8 - Res Urbis Scenario - Treviso Acid fermentation fractions

ACID FERMENTATION					
Fractions	Wet Weight	Water	TS	VS (%TS)	Ash (%TS)
kg	996.76	919	77.76	62.25	15.51
%	100%	92%	8%	80%	20%

Then, there is a solid/liquid separation where approximately the 60% of the wet weight goes to the anaerobic digestion, that is called “solid flow”. The “liquid flow” goes to the PHA production section in SBR (Table 9).

Table 9 - Res Urbis Scenario - Treviso Liquid stream fractions

Liquid Stream					
Fractions	Wet Weight	Water	TS	VS (%TS)	Ash (%TS)
kg	402.96	390.51	12.44	11.50	0.94
%	100%	97%	3%	92%	8%

After the two aerobic phases the following stream (Table 10) is produced with a percentage of PHA of 1.13 on the wet weight.

Table 10 - Res Urbis Scenario - Treviso Liquid with PHA fractions

Liquid with PHA				
Fractions	Wet Weight	Water	TS ~ VS	PHA (%VS)
kg	402.96	390.51	10.81	4.54
%	100%	97%	3%	42%

The last step is the centrifugation of this stream that extracts the 87% of the water from the wet weight and concentrates the PHA in the stream (Table 11).

Table 11 - Res Urbis Scenario - Treviso Concentrated PHA fractions

Concentrated PHA to Downstream				
Fractions	Wet Weight	Water	TS ~ VS	PHA (%VS)
kg	60.04	49.23	10.81	4.54
%	100%	82%	18%	42%

This stream undergoes to the downstream process to extract the PHA.
The total production of PHA in this mass flow is 4.54 kg instead of 81 kg of TS in the mixer, so 0.056 kg of PHA per kg of TS or 0.07 kg of PHA per kg of VS.

Other Scenarios

The mass balance of the other scenarios is simplified for the study and took in considerations only the most important steps with the transfer coefficients calculated on the baseline scenario. The calculation of the percentage of the flows needed in the mixer is based on the 80% of the wet weight of the total OFMSW (the percentage after the pre-treatments), that is the 30% of the total wet weight needed in this step. Based on this value, it is calculated the other 70% of the total mass using the Sludge flow (Reis, Fernando, Valentino, Majone, & Werker, 2018).

ii) Res Urbis -Scenario Trento

The *Res Urbis -Scenario Trento* has the following mass flows

Table 12 shows the total mass flows of the cluster.

Table 12 - Res Urbis Scenario Trento mass flows and material fractions

%	SLUDGE (tn/y)	**TRENTO**	OFMSW (tn/y)	%
100%	390,912	Wet Weight	78,741	100%
96%	375,276	Water	59,843	76%
4%	15,637	TS	18,898	24%
80%	12,481	VS(%TS)	15,988	85%
20%	3,156	Ash(%TS)	2,911	15%

The mass flows needed in the mixer are shown in Table 13.

Table 13 - Res Urbis Scenario - Trento Waste streams needed for the mixer and the total sum in the mixer

%	SLUDGE (tn/y)	**TRENTO**	OFMSW (tn/y)	%	MIXER	SUM TOT	%
100%	146,983	Wet Weight	62,993	100%	Wet Weight	209,975	100%
96%	141,103	Water	50,331	80%	Water	191,434	91%
4%	5,879	TS	12,662	20%	TS	18,541	9%
80%	4,693	VS (%TS)	10,232	81%	VS (%TS)	14,925	80%
20%	1,187	Ash (%TS)	2,429	19%	Ash (%TS)	3,616	20%

Based on the transfer coefficient calculated on the baseline scenario the remaining amount of Volatile solids (that integrate the % of PHA), after the various steps, is 0.16 kg VS Downstream / kg VS Mixer.

So, the total VS in the downstream flow for the Trento Scenario is 2,488 tn/y.

Considering ongoing test carried out on the Treviso pilot scale, the amount of PHA at the end of the process ranges from 38 to 46% of the VS. So, the total production of PHA in this Scenario is 1,120 tn/y.

iii) Res Urbis -Scenario Copenhagen

The *Res Urbis -Scenario Copenhagen* has the following mass flows.

Table 14 shows the total mass flows of the cluster.

Table 14 - Res Urbis Scenario - Copenhagen Mass flows and material fraction

%	SLUDGE (tn/y)	**CPH**	OFMSW (tn/y)	%
100%	1,152,507	Wet Weight	207,567	100%
96%	1,110,957	Water	154,223	74%
4%	41,550	TS	53,345	26%
76%	31,703	VS(%TS)	48,011	90%
24%	9,848	Ash(%TS)	5,335	10%

The same line of thinking is done for the mass flows of Copenhagen Scenario.

The mass flows needed in the mixer are shown in Table 15.

Table 15 - Res Urbis Scenario – Copenhagen Waste streams needed for the mixer and the total sum in the mixer

%	SLUDGE (tn/y)	**CPH**	OFMSW (tn/y)	%	MIXER	SUM TOT	%
100%	166,054	Wet Weight	387,459	100%	Wet Weight	553,512	100%
78%	130,313	Water	373,490	96%	Water	503,803	91%
22%	35,741	TS	13,969	4%	TS	49,710	9%
86%	30,727	VS (%TS)	10,658	76%	VS (%TS)	41,385	83%
14%	5,015	Ash (%TS)	3,311	24%	Ash (%TS)	8,325	17%

The total VS in the downstream flow for the Copenhagen Scenario is 6,898 tn/y.

The total production of PHA in this Scenario is 3,104 tn/y.

3.4.3.2 *Material Flow Analysis*

Before the implementation of the Easetech model for the LCA it was necessary to verify the reliability of the calculations made in Excel with a material flow analysis.

Material flow analysis is a systematic assessment of the flows and stocks of materials in a defined system with a precise space and time. It is based on the mass conservations, so the inputs should be equal to the sum of the outputs and the stock changes of a process (Equation 1).

Equation 1

$$\frac{dm}{dt} = \sum_{i}^{input} m_i - \sum_{k}^{output} m_k$$

The other aspect of this method is the use of the transfer coefficients (TC) that describes the partitioning of a substance within a process and its transfer into a specific output. The total sum of the TC of a process must be 1 (Equation 2).

Equation 2

$$\sum_{i=0}^{k} TC_i = 1$$

It is a real decision-support tool that takes into account all the streams of the system to make an authentic material balance that can help to regulate the final results.

The applications in the waste management systems gives a solid understanding of the waste flows besides their material fractions and composition (Cencic & Rechberger, 2008).

In this project it is used a software called STAN (TU Wien, 2012) that supports the material flow analysis considering the uncertainties of the data. It is used to model the system in a graphic way with the predefined flows composed the material fractions and transfer coefficients. During data elaboration, the mean values of uncertain data are altered to resolve contradictions, to calculate unknown values and to decrease the absolute uncertainty of individual values. STAN uses a normal distribution and the error propagation as reconciliation method, based on the Gauss' Law (Cecchi, 2018).

The results obtained are divided into two layers for each scenario: the Total mass (goods) and the Volatile Solids (Figure 7, Figure 8).

i) *Res Urbis Scenario – Treviso*

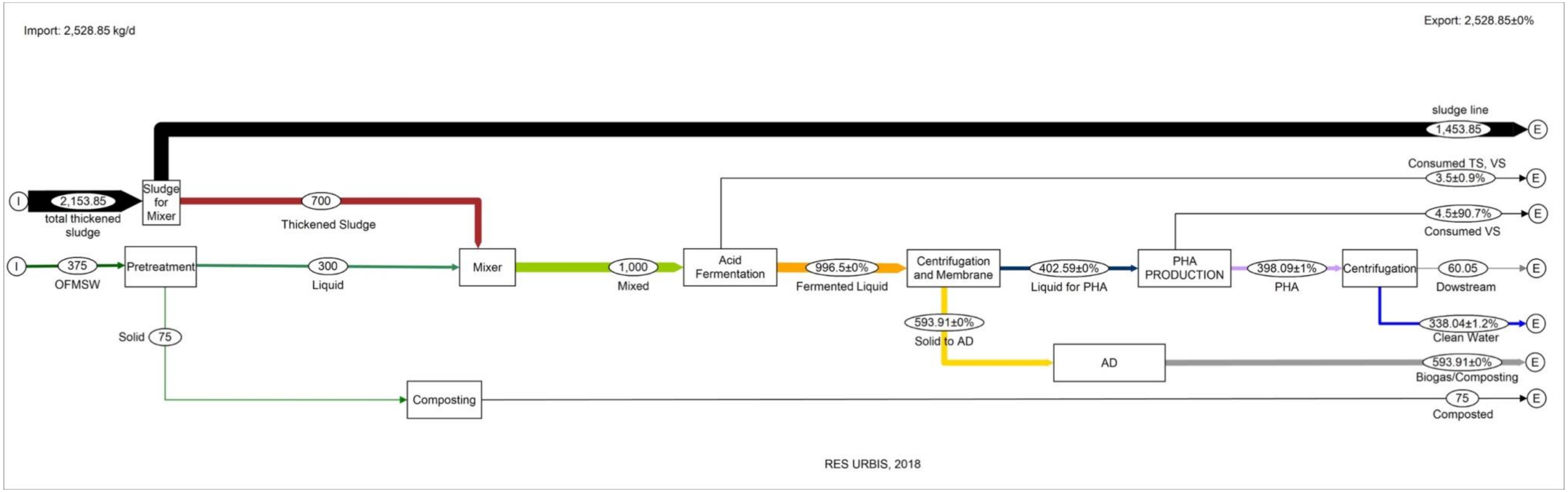

Figure 7 - Layer Goods of Res Urbis Scenario – Treviso

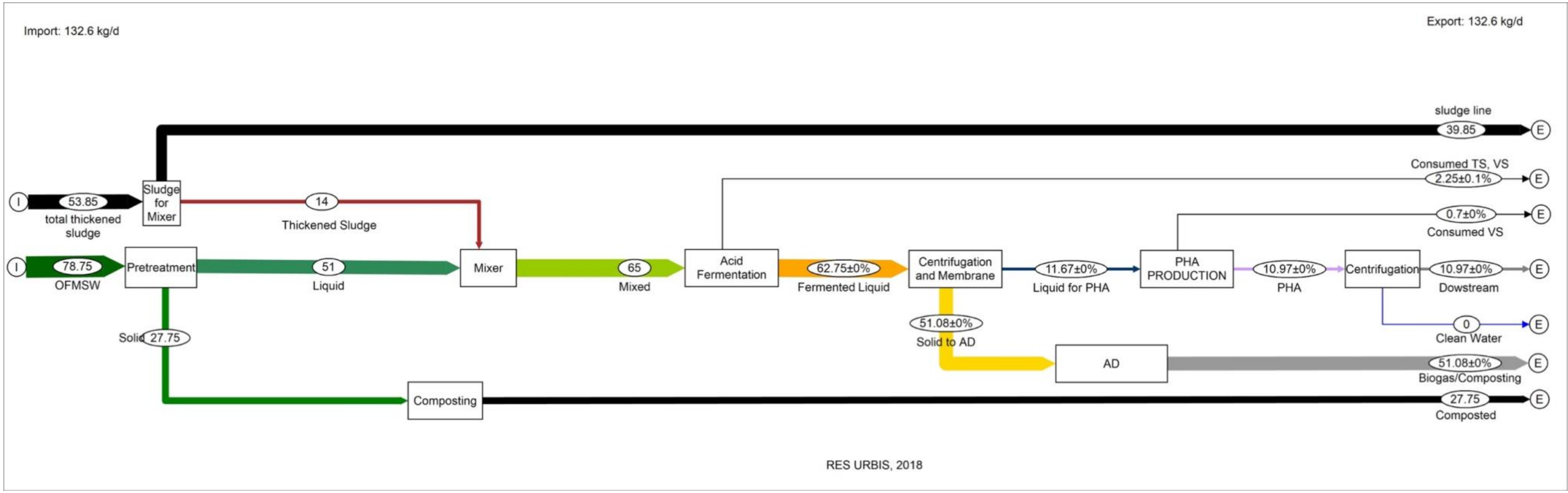

Figure 8 - Layer Volatile Solids of Res Urbis Scenario – Treviso

If comparing the total production of VS in the downstream flow (equal to 10.97 kg/d) with the excel mass balance, the difference obtained was less than 1%.
Based on the data calculated on the mass balance we know that the 42% of this flow is PHA, so it is produced 4.61 kg/d of PHA in this scenario.

ii) Res Urbis Scenario – Trento

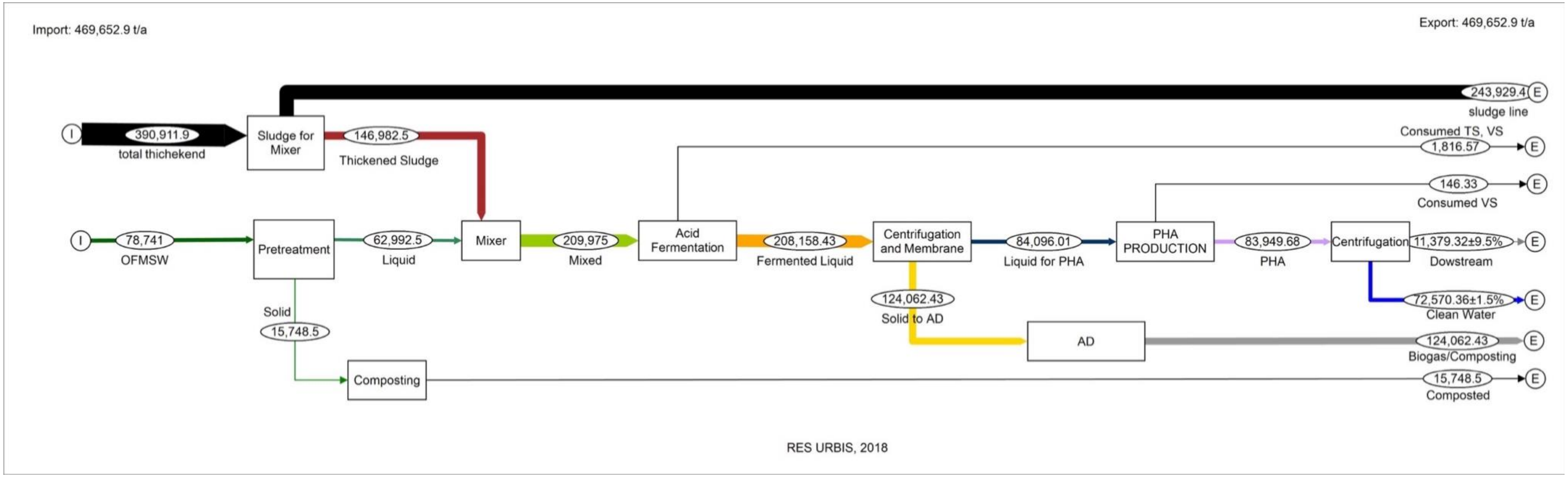

Figure 9 - Layer Goods of Res Urbis Scenario – Trento

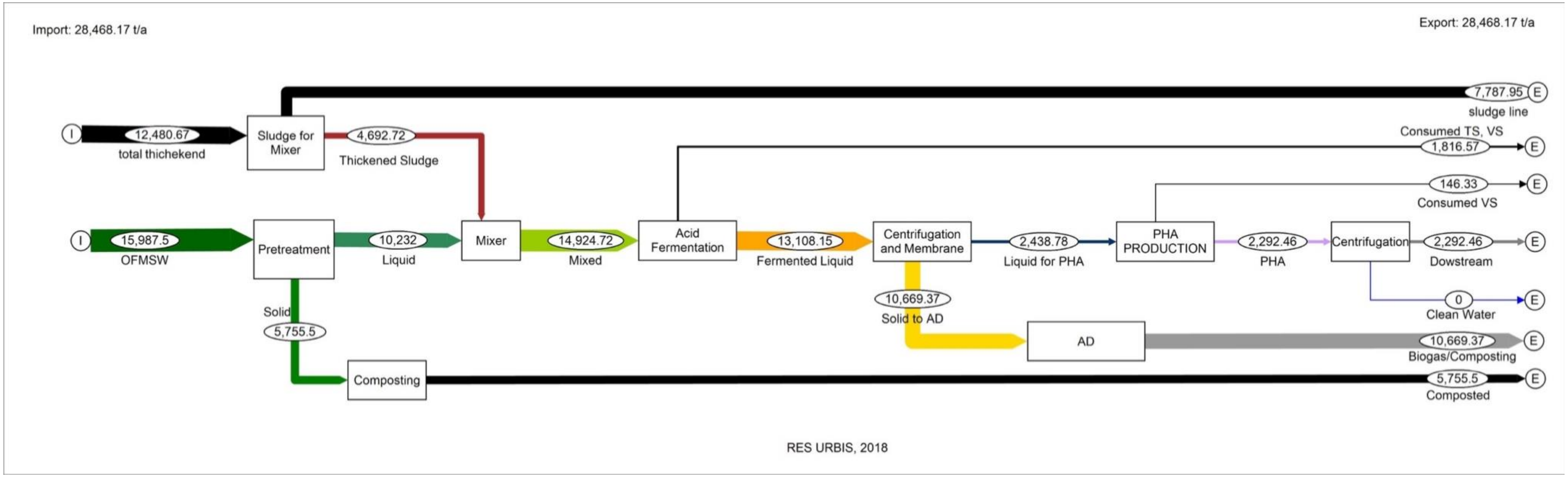

Figure 10 - Layer Volatile Solids of Res Urbis Scenario – Trento

The total VS in the downstream flow is 2,292.5 tn/y (Figure 10), that is only 10% lower than the Excel mass balance because the software has re-arranged the mass balance. Based on this value of VS, the 42% is PHA so 1,031.6 tn/y.

iii) Res Urbis Scenario – Copenhagen

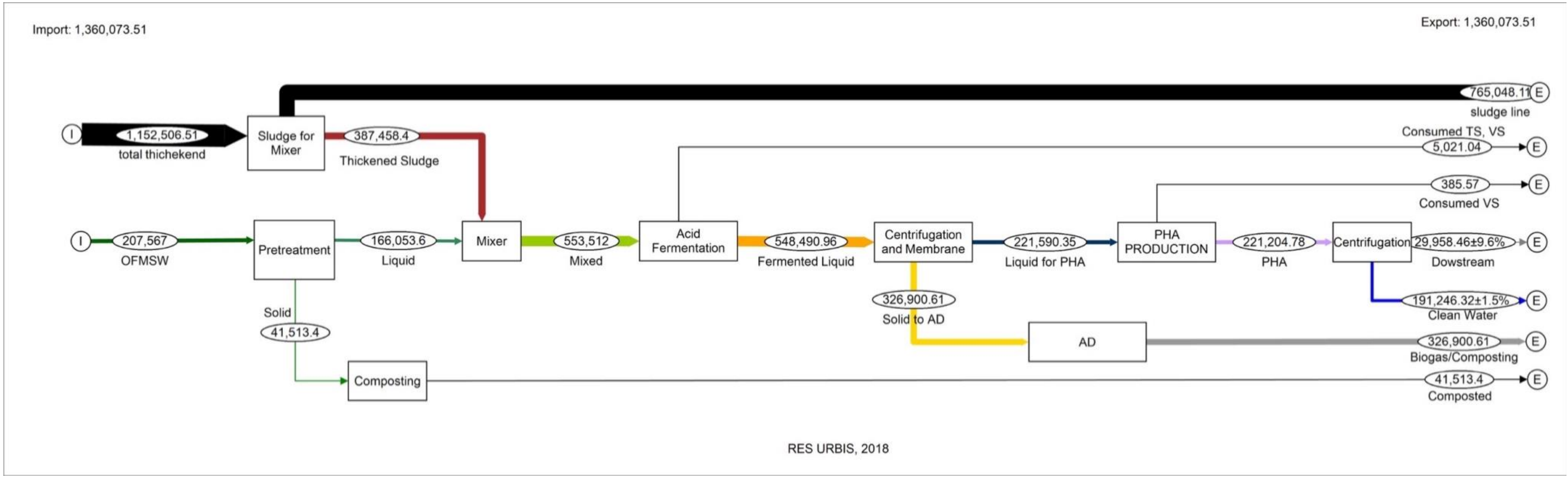

Figure 11 - - Layer Goods of Res Urbis Scenario – Copenhagen

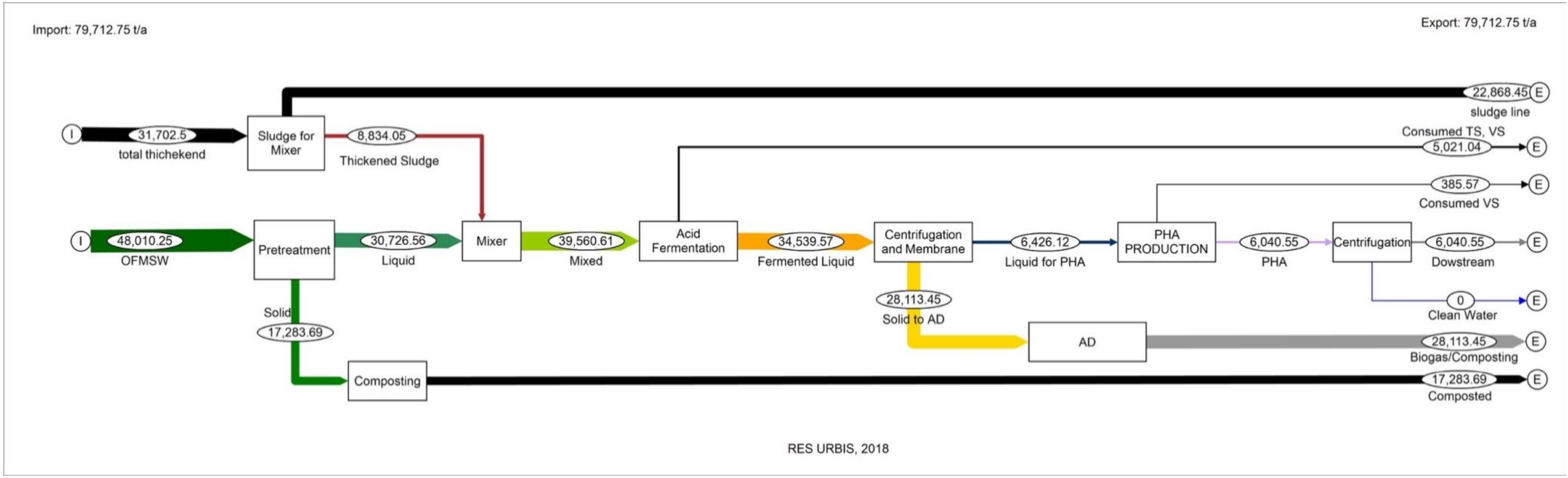

Figure 12 - Layer Volatile Solids of Res Urbis Scenario – Copenhagen

The total VS in the downstream flow is 6,040 tn/y (Figure 12), that is lower than the Excel calculation because the software has re-arranged the mass balance. Based on this value of VS, the 42% is PHA so 2,718 tn/y.

Sum Up

Therefore, to make a sum up of the information of the material flow analysis compared to the Excel calculations, we have made the following Diagram 1 where the production is normalized to tonnes per year for each cluster.

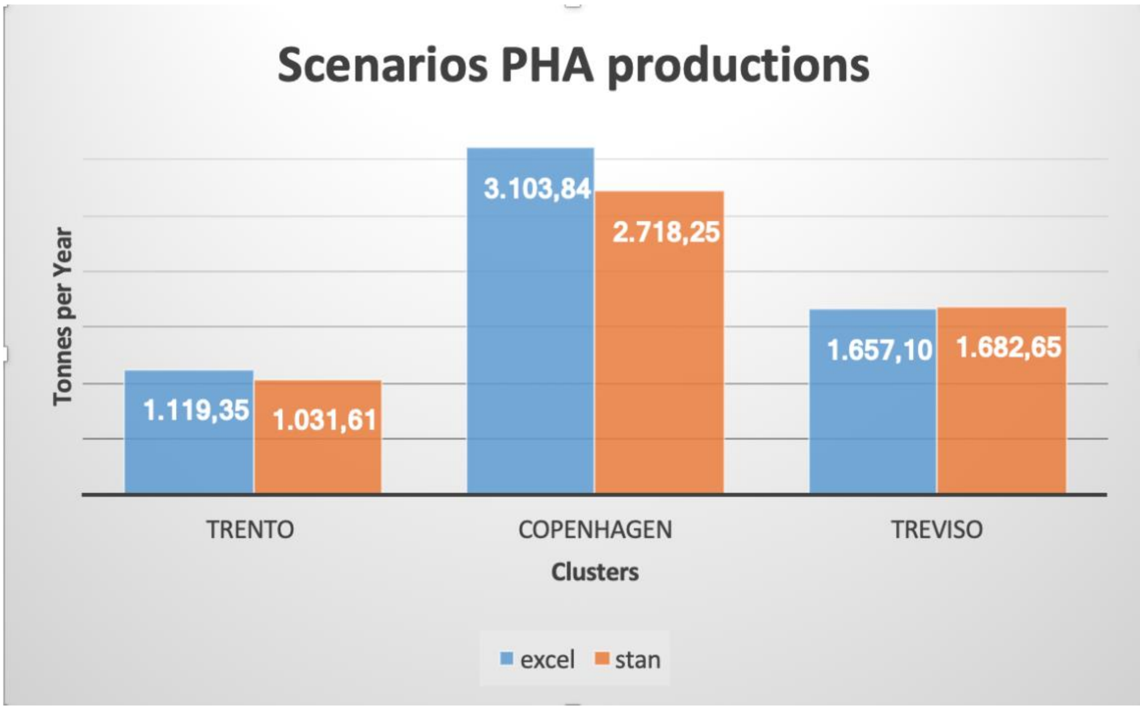

Diagram 1 - Comparisons of the PHA productions in the different scenarios

The total production of PHA in the different clusters shows that the mass balance and the elaboration with STAN are very similar, meaning that the calculations where basically correct. The focus of this comparison is to see how much PHA could be produced in tonnes per year in big territories besides their different bio-waste composition and management. We could assume that, with these total PHA productions, the future up-scaling of this technology is certainly a good objective.

3.4.4 Technologies and transportation

i) Transportation

The transportation of waste is considered in different steps in the model as it happens in the waste management chain of the area. All the scenarios are modelled using the same process for both waste collection and transport, as well as the same uncertainty range (Boldrin & Bassi Andreasi, 2017).

The collection process includes the diesel burnt by the collection trucks from the first stop until the last stop of the collection route (Larsen et al., 2009). All trucks are assumed being diesel fueled EURO3. The diesel consumption is modelled with the same consumption as residual waste in (Larsen et al., 2009).

Table 16 - Overview of the consumptions and km used in the project

Process	Data used in the baseline	Uncertainty
Collection		
Diesel consumption	3.07 E-03 l/ kg_{ww} [±20%]	Diesel consumption for the baseline (Larsen et al., 2009). Uncertainty range assumed by the authors.
Res Urbis		
Distance between households and the treatment plant	30 km	Uncertainty range assumed by the authors of 20%
Transport of compost and digestate from the compost plant to the use on land	12 km	Min: 10km; max: 200 km Adapted from (Andreasi Bassi, Christensen, & Damgaard, 2017)

ii) Treatment technologies

The treatment technologies used to model the processes in Easetech are presented in the following table Table 17.

Table 17 - Overview of the data used for modelling the processes in the scenarios

Process	Data used in the baseline	Uncertainty
Water content in the AD plant	77% (Møller, Christensen, & Jansen, 2011)	+- 5% (V. Bisinella, Brogaard, & Astrup, 2016)
Internal consumptions in the AD plant	Heat: heating up the substrate to 55 °C, starting from an average ambient temperature of 15°C. Electricity: 48.9 kWh/kg wet weight entering for pumps, ventilator, etc. Diesel for machineries	Average ambient temperature: min 8 °C; max 20°C Electricity and diesel consumption +- 20%
Biochemical methane potential (BMP) [m^3CH_4 / t_{VS}]	From partners: 500 m3CH4 / t VS	Uncertainty range from Fitamo et al. (2016)
Methane content in the biogas produced	63 % (EASETECH database, calculated based on elemental composition using Buswell formula)	Min.: 56%; max.: 63% (Fitamo et al., 2016)
CH_4 leaking from the AD plant	3% (Yoshida et al., 2017)	Min.: 1% (Bisinella et al., 2016), max.: 10% (CDM, 2012)
Efficiency of biogas engine	42.1% electricity 43.0% heat (GE Power, 2017)	+- 8% (GE Power, 2017)
Fate of C due to the direct emissions of the use on land – food and garden waste	Average of different types of soil and countries (Yoshida et al., 2016)	Max and min between sandy loam soil, coarse sand soil and heavy clay in Danish, German and Dutch soil (Yoshida et al., 2016)
Fate of N due to the direct emissions of the use on land – mixed sludge	Average of different types of soil and countries	Max and min 45between sandy loam soil, coarse sand soil and heavy clay in Danish, German and Dutch soil
Fate of P due to the direct emissions of the use on land – all types of waste	Average of different types of soil and countries (Klinglmair et al. 2015)	Max and min 45between sandy loam soil, coarse sand soil and heavy clay in Danish, German and Dutch soil (Klinglmair et al., 2015)
Pre-treatments	Press: solid/liquid separation, 80% of the streams goes to the mixer	Uncertainty of 10%
Acidogenic fermentation	hydrolysing and fermenting the organic content of SS-OFMSW mixture into mainly volatile fatty acids (VFA); it includes an anaerobic batch reactor (V=380 L) a Continuous Stirred Tank Reactor (CSTR), mechanically stirred and under temperature control by using a thermostatic jacket. The HRT (equal to SRT) was set at 6 days. (Reis, Fernando, et al., 2018)	Due to the degradation of VS the values of variation are: Min: 4% max 5% (Valentino, 2018)
Ultra-Filtration	The centrifugation unit is used for solid/liquid separation after fermentation. It is composed of coaxial centrifuge filter equipped with 5-10 m porosity nylon filter bag, allowing the removal of 80% of total suspended solids approximately.	Uncertainty: 5%
PHA Aerobic Phase	SBR reactor divided in two phases: -Aerobic Selection: inoculations with activated sludge. Operativity: 1.0 d of both HRT and SRT (which are the same having no biomass settling phase) and cycle length of 6 h (i.e. 4 cycles per day). Each operating cycle is divided into four aerobic phases: biomass withdrawal (0.5 min), regeneration (10 min), feeding (0.5 min), and reaction (349 min). The reactor is aerated by means of linear membrane blowers (Bibus EL-S-250), which allowed also for adequate stirring. The temperature and pH are continuously measured but not actively controlled. The medium temperature in the SBR changes seasonally between 15-18°C in March and October (as minimum), and 26-29°C in July-August (as maximum). The pH is maintained around 8.0 during the whole SBR cycle, having the fermented feedstock a good buffering capacity, due to the high level of alkalinity (4.4-5.9 g/L CaCO3). The SBR is fed with the fermented feedstock (after solid/liquid separation) and consequently, the applied OLR changes according to CODSOL and VFA concentrations in the feed: 3.17-6.19 gCODSOL/L d, and 1.17-5.04 gCODVFA/L d, as range of OLR variations. -Accumulation: The storage potential of the selected biomass is exploited through batch accumulation tests (V=50- 70 L), performed with both synthetic (acetic acid with no nutrient addition), and fermented feedstock, obtained from the three different fermentation conditions. The biomass (X) was loaded from the SBR (Reis, Fernando, et al., 2018)	Uncertainty: 5%

iii) Substituted products

The following table describes the compositions of the marginal electricity (Table 18) used for both electricity consumption and production. The mix is calculated based on the future energy forecasts for Italy, Spain, Portugal and UK (EC, 2016) as difference between 2030 and 2015. The datasets for individual countries and technologies are imported from the database Ecoinvent v 3.4 (Boldrin & Bassi Andreasi, 2017).

Table 18 - Composition of the marginal electricity used in all the scenarios

Source	**%**
Nuclear	10%
Solids	38%
Oil (including refinery gas)	1%
Gas (including derived gases)	1%
Biomass-waste	12%
Hydro (pumping excluded)	3%
Wind	24%
Solar	12%
Geothermal and other renewables	0%

The following Table 19 describes how the avoided processes are modelled in the scenarios.

Table 19 - Modelling of substitutions connected the avoided processes as a result of the waste management system

Process	**Data used in the baseline**	**Uncertainty**
Anaerobic digestion		
Substitution of electricity and heat owing to the production of energy in the biogas engine	It depends on the efficiency of the combustion engine.	N/A
Substitution of mineral fertilizer owing to use on land of compost.	N: 40%, K: 100% and P: 100% (Hansen, Bhander, Christensen, Bruun, & Jensen, 2006)	Bisinella et al. (2016) and Yoshida et al. (2017)
RES URBIS		
Substitution of traditional fossil ester resin thanks to the production of PHA.	45 kg PHA produced per ton of TS, corresponding to 9.4 kg PHA / t food waste and 1.5 kg PHA / t mixed sludge. We modelled the uncertainty of the quality of the produced PHA and the uncertainty of the material actually substituted in the market: 1 kg of PHA is assumed to substitute in the market 0.7 kg of traditional resin (called here substitution ratio).	The uncertainty of the substitution ratio is estimated by the authors [min: 0.4 kg; max: 1 kg] A conservative assumption for the substitution ratio was made because of the lack of information on the quality of PHA produced within the RES URBIS biorefinery.
Substitution of electricity and heat owing to the production of energy in the biogas engine	It depends on the efficiency of the combustion engine.	N/A
Substitution of mineral fertilizer owing to use on land of compost.	N: 40%, K: 100% and P: 100% (Hansen et al., 2006)	Bisinella et al. (2016) and Yoshida et al. (2017)

3.4.5 Sensitivity

The sensitivity analysis is made to understand the sensitivity inputs (Clavreul, Guyonnet, & Christensen, 2012) and to analyse how much the parameters and inputs influences the results (Laurent et al., 2013).

In this study the sensitivity of the individual parameters is linked to their uncertainty in order to identify the most important parameters with the focus on the isolation of the factors that have the largest contribution to the overall uncertainty of the results (Boldrin & Bassi Andreasi, 2017).

The uncertainty is estimated for individual parameters and assumed having uniform distribution when the parameter has one value, and triangular distribution when the parameters range from a min. and a max. Based on these assumptions, various variance-based techniques are used for uncertainty propagation that provides the results with a Monte Carlo simulation (Valentina Bisinella, Conradsen, Christensen, & Astrup, 2016).

The output of this simulation is a list of the most important parameters that contributes the most at the uncertainty of the results as shown in the tables and diagrams of the results chapter.

According to previous researches (Bassi, Christensen, & Damgaard, n.d.), the perturbation analysis calculates the sensitivity ratio (SR) in order to observe the effect of a small variation of a parameter on the final results. SR is the ratio between the relative change of the result and the relative change of the parameter. The Equation 3 of SR is the following:

Equation 3

$$SR = \frac{\frac{\Delta result}{\text{initial result}}}{\frac{\Delta parameter}{\text{initial parameter}}}$$

The following tables (Table 20, Table 21) show the parameters tested in the perturbation analysis and included in the Excel for the calculation of the Monte Carlo analysis of the LCA model.

Table 20 - Parameter tested in the perturbation analysis with the type of uncertainty (TD: triangular; UD: uniform)

Parameter name	Value	Unit	% of uncertainty	Min (manual)	Max (manual)	Type uncertaint y
heat	0.5			0.25	0.75	TD
R_CG_colAD_Al	0.00000917	kg/kg tot wet weight	20%			UD
R_colltruck_diesel	0.00009	l/kg tot wet weight	20%			UD
R_colltruck_km	30	km	20%			UD
R_Pre_Treat_water_liquid	84	%	10%			UD
R_Pre_Treat_VS_liquid	64	%	5%			UD
R_sludge_thickened_water_mixe r	33	%	20%			UD
R_sludge_thickened_VS_mixer	26	%	20%			UD
R_CG_AD_CrSt	0.000168	kg/kg tot wet weight	20%			UD
AD_water_content	77	%	5%			UD
AD_AD_yield	24.8	%	10%			UD
AD_AD_CH4_biogas	63	%		56	63	TD
AD_AD_e	0.049	kWh / kg tot wet weight	20%			UD
T	15	l / kg tot wet weight		8	20	TD
AD_AD_wheel	0.0009	MJ / kg tot wet weight	20%			UD
AD_biogas_leakingCH4	3	%	10%	1	10	TD
AD_biogas_engine_eff_e	0.36375	%	20%			UD
AD_comp_degr_e	0.053	kWh / kg tot wet weight	20%			UD
AD_truck_comp_km	12	km		10	200	TD
AD_UOL_direct_C_CH4	0.01	% C		0.01	0.05	TD
AD_UOL_direct_N_N2O	3.4	% N		1.7	5.1	TD
AD_UOL_direct_N_NH3	1.6	% N	20%			UD
AD_UOL_direct_N_NO3_l	37.3	% N		8.8	65.8	TD
AD_UOL_direct_N_NO3_r	12.35	% N		0.9	23.8	TD
AD_UOL_direct_N_st	15.85	% N		1.7	30	TD
AD_UOL_P_l	24.125	%P		0.55	47.7	TD
AD_UOL_direct_emiss_Cr	1	kg / kg Cr		0.8	1	TD
AD_UOL_direct_emiss_Cu	1	kg / kg Cu		0.8	1	TD
AD_UOL_direct_emiss_Pb	1	kg / kg Pb		0.8	1	TD
AD_UOL_direct_emiss_Zn	1	kg / kg Zn		0.8	1	TD
AD_UOL_Subst_P	1	kg / kgP		0.67	1	TD
AD_UOL_indirect_N_N2O	1.3	%N		0.2	2.4	TD

AD_UOL_indirect_N_NO3_l	33.25	%N		6	60.5	TD
AD_UOL_indirect_N_NO3_r	30.3	%N		0.5	60.1	TD
AD_UOL_indirect_N_plant	35.2	%N		1.3	69.1	TD
AD_UOL_sludge_direct_N_N2O	3.1	%N		1.86	4.34	TD
AD_UOL_sludge_direct_N_NH3	6.71	%N	20%			UD
AD_UOL_sludge_direct_N_NO3_l	40.88	%N		16.72	65.04	TD
AD_UOL_sludge_direct_N_NO3_r	14.28	%N		5.47	23.09	TD
AD_UOL_sludge_direct_emiss_Cr	1	kg / kg Cr		0.8	1	TD
AD_UOL_sludge_direct_emiss_Cu	1	kg / kg Cu		0.8	1	TD
AD_UOL_sludge_direct_emiss_Zn	1	kg / kg Zn		0.8	1	TD
PHA_e	22.4	kWh/kg tot wet weight				UD
R_AF_mix_degradation_VS	4.5	%		4	5	TD
R_mixer_mixed_waste	1000	kg	0			UD
R_UF_liquid_water	96.9	%	5%			UD
R_UF_liquid_vs	2.9	%	5%			UD
R_PHA_Prod_vs	2.7	%	5%			UD
R_PHA_Centrifuge_ash	1.55	%	5%			UD
R_PHA_reusable_water	85	%	20%			UD
Subst_ratio_PHA	0.7			0.4	1	TD
Prod_PHA	0.42	kg / kg VS	20%			UD
Mech_dew_e	0.0082	kg / kg TS	20%			UD
Mech_dew_chem	0.054	kWh / kg TS	20%			UD

Table 21 - Uncertainty, Variance and Standard deviation input of the parameters for the Monte Carlo analysis

PARAMETER UNCERTAINTY ---> MONTE CARLO					
Parameter name	**Average % uncertainty around mean (calculated)**	**Min (calculated)**	**Max (calculated)**	**Variance input (analytical)**	**Standard deviation input**
heat	0.5	0.25	0.75	0.010416667	0.102062073
R_CG_colAD_Al	0.2	0.000007336	0.000011004	0%	1.05886E-06
R_colltruck_diesel	0.2	0.000072	0.000108	0%	1.03923E-05
R_colltruck_km	0.2	24	36	1200%	3.464101615
R_Pre_Treat_water_liquid	0.1	75.6	92.4	2352%	4.849742261
R_Pre_Treat_VS_liquid	0.05	60.8	67.2	341%	1.847520861
R_sludge_thickened_water_mixer	0.2	26.4	39.6	1452%	3.810511777

R_sludge_thickened_VS_mixer	0.2	20.8	31.2	901%	3.0022214
R_CG_AD_CrSt	0.2	0.0001344	0.0002016	0%	1.9399E-05
AD_water_content	0.05	73.15	80.85	494%	2.222798536
AD_AD_yield	0.1	22.32	27.28	205%	1.431828668
AD_AD_CH4_biogas	0.055555556	56	63	2.722222222	1.649915823
AD_AD_e	0.2	0.0392	0.0588	0%	0.005658033
T	0.4	8	20	6.055555556	2.460803843
AD_AD_wheel	0.2	0.00072	0.00108	0%	0.000103923
AD_biogas_leakingCH4	0.1	1	10	372%	1.92930615
AD_biogas_engine_eff_e	0.2	0.291	0.4365	0%	0.042002232
AD_comp_degr_e	0.2	0.0424	0.0636	0%	0.006119913
AD_truck_comp_km	7.916666667	10	200	1984.666667	44.54959783
AD_UOL_direct_C_CH4	2	0.01	0.05	8.88889E-05	0.00942809
AD_UOL_direct_N_N2O	0.5	1.7	5.1	0.481666667	0.694022094
AD_UOL_direct_N_NH3	0.2	1.28	1.92	3%	0.184752086
AD_UOL_direct_N_NO3_l	0.764075067	8.8	65.8	135.375	11.63507628
AD_UOL_direct_N_NO3_r	0.927125506	0.9	23.8	21.85041667	4.674442926
AD_UOL_direct_N_st	0.892744479	1.7	30	33.37041667	5.77671331
AD_UOL_P_l	0.977202073	0.55	47.7	92.63010417	9.624453448
AD_UOL_direct_emiss_Cr	0.1	0.8	1	0.002222222	0.047140452
AD_UOL_direct_emiss_Cu	0.1	0.8	1	0.002222222	0.047140452
AD_UOL_direct_emiss_Pb	0.1	0.8	1	0.002222222	0.047140452
AD_UOL_direct_emiss_Zn	0.1	0.8	1	0.002222222	0.047140452
AD_UOL_Subst_P	0.165	0.67	1	0.00605	0.077781746
AD_UOL_indirect_N_N2O	0.846153846	0.2	2.4	0.201666667	0.44907312
AD_UOL_indirect_N_NO3_l	0.819548872	6	60.5	123.7604167	11.12476592
AD_UOL_indirect_N_NO3_r	0.98349835	0.5	60.1	148.0066667	12.16579906
AD_UOL_indirect_N_plant	0.963068182	1.3	69.1	191.535	13.83961705
AD_UOL_sludge_direct_N_N2O	0.4	1.86	4.34	0.256266667	0.50622788
AD_UOL_sludge_direct_N_NH3	0.2	5.368	8.052	60%	0.774804061

AD_UOL_sludge_direct_N_NO3_l	0.590998043	16.72	65.04	97.28426667	9.863278698
AD_UOL_sludge_direct_N_NO3_r	0.616946779	5.47	23.09	12.93601667	3.596667439
AD_UOL_sludge_direct_emiss_Cr	0.1	0.8	1	0.002222222	0.047140452
AD_UOL_sludge_direct_emiss_Cu	0.1	0.8	1	0.002222222	0.047140452
AD_UOL_sludge_direct_emiss_Zn	0.1	0.8	1	0.002222222	0.047140452
PHA_e	0	22.4	22.4	0	0
R_AF_mix_degradation_VS	0.111111111	4	5	0.041666667	0.204124145
R_mixer_mixed_waste	0	1000	1000	0	0
R_UF_liquid_water	0.05	92.055	101.745	782%	2.797262054
R_UF_liquid_vs	0.05	2.755	3.045	1%	0.083715789
R_PHA_Prod_vs	0.05	2.565	2.835	1%	0.077942286
R_PHA_Centrifuge_ash	0.05	1.4725	1.6275	0%	0.044744646
R_PHA_reusable_water	0.2	68	102	9633%	9.814954576
Subst_ratio_PHA	0.428571429	0.4	1	0.015	0.122474487
Prod_PHA	0.2	0.336	0.504	0%	0.048497423
Mech_dew_e	0.2	0.00656	0.00984	0%	0.000946854
Mech_dew_chem	0.2	0.0432	0.0648	0%	0.006235383

4 Results and Discussion

In a LCA optic the best way to present the results is to make a contribution and uncertainty analysis.

In the following sections is provided an overview of the results obtained by the LCA modelling. The results are analysed as normalized environmental impacts due to the fact that each impact category has its own unit, so to compare the results it was necessary to proceed in a normalization way.

4.1 Contribution Analysis

The contribution analysis shows the contribution of the most important process and parameters for each impact category to understand how much they affect the model and the environment.

The results are showed in the Diagram 2, Diagram 3, Diagram 4 where the environmental impacts of the most important processes of the model are compared in the normalized impact categories. Each colour represents a process composed by a sum of the impacts of the parameters included.

The most important processes used in the LCA model are listed in the following Table 22.

Table 22 - Processes used in the model and their descriptions

Processes	Description
Acid fermentation	First step of the organics transformations (Valentino, 2018)
Biogas production, Thermophilic	Anaerobic digestion reactor
Capital goods Anaerobic digestion plant	Durable goods for the production and management of the plant (Brogaard & Christensen, 2016)
Capital goods Composting plant	Durable goods for the production and management of the plant (Brogaard & Christensen, 2016)

Capital goods Waste collection truck	Durable goods of the collection truck for the composted digestate (Brogaard & Christensen, 2016)
CG collection truck	Durable goods of the collection truck for the residual waste (Brogaard & Christensen, 2016)
Collection (as residual waste, curbside)	Curbside collection of residual waste, fuel consumption per tonne of wet waste from the 1st stop of the route to the final stop (Larsen et al., 2009)
Emissions to the environment	Emission of the degradation of the VS, C, N in the AD plant (Pavan, 2017)
Energy substitution	Substitution of energies like heat and electricity in the AD plant with CH4
Fugitive emissions CH4	Emissions of the CH4 productions
VS, C, N degradation Treviso	Degradation of substances in the plant (Pavan, 2017)s
Mineral fertilizer, Use on land	use on land of the compost and substitution of chemical fertilizers (Yoshida et al., 2016)
PHA Aerobic Phase	PHA aerobic phases of selection and accumulation
PHA Centrifugation	Solid/liquid separation
PHA extraction	Chemical extraction
PHA substitution	Substitution of fossil plastic with PHA
Pre-treatment OFMSW	Operations of pre-treatments in plant
Road, Truck, highway	Route on km from treatment plant for the transportation of the compost; moving one kg of goods in 1km in a truck with weight of 7.5t-12t; combustion emissions of a truck with a full weight driving 80km/h on average on motorway (euro5) (Chiang, Lai, & Chang, 2012)
Sewage sludge, composted, direct emission	Emissions to air, surface water, groundwater and soil accumulation from land application of dewatered anaerobically digested sludge on a sandy loam soil with N application rate below the maximum plant uptake (Bruun et al., 2016), (Yoshida, Nielsen, Scheutz, & Jensen, 2015)
Stationary engines, biogas per m3 CH4	Stationary engine combustion plant for the use of biogas to avoid energies (Aarhus University, 2018)
Transport	collection truck of residual waste, fuel consumption per tonne of wet waste from the 1st stop of the route to the final stop (Larsen et al., 2009)
Ultra-Filtration and centrifugation	Solid/liquid separation

The normalised results of the diagrams are expressed in units of person-equivalents (PE) for each process and the net total value. The processes included in the waste management can represent both environmental loads (positive impacts) and savings (negative impacts).

There are some deviations among the scenarios due to the differences of each territorial cluster but the trend of the data in each category is similar with some expectations beside the total waste considered.

i) Res Urbis Scenario - Treviso

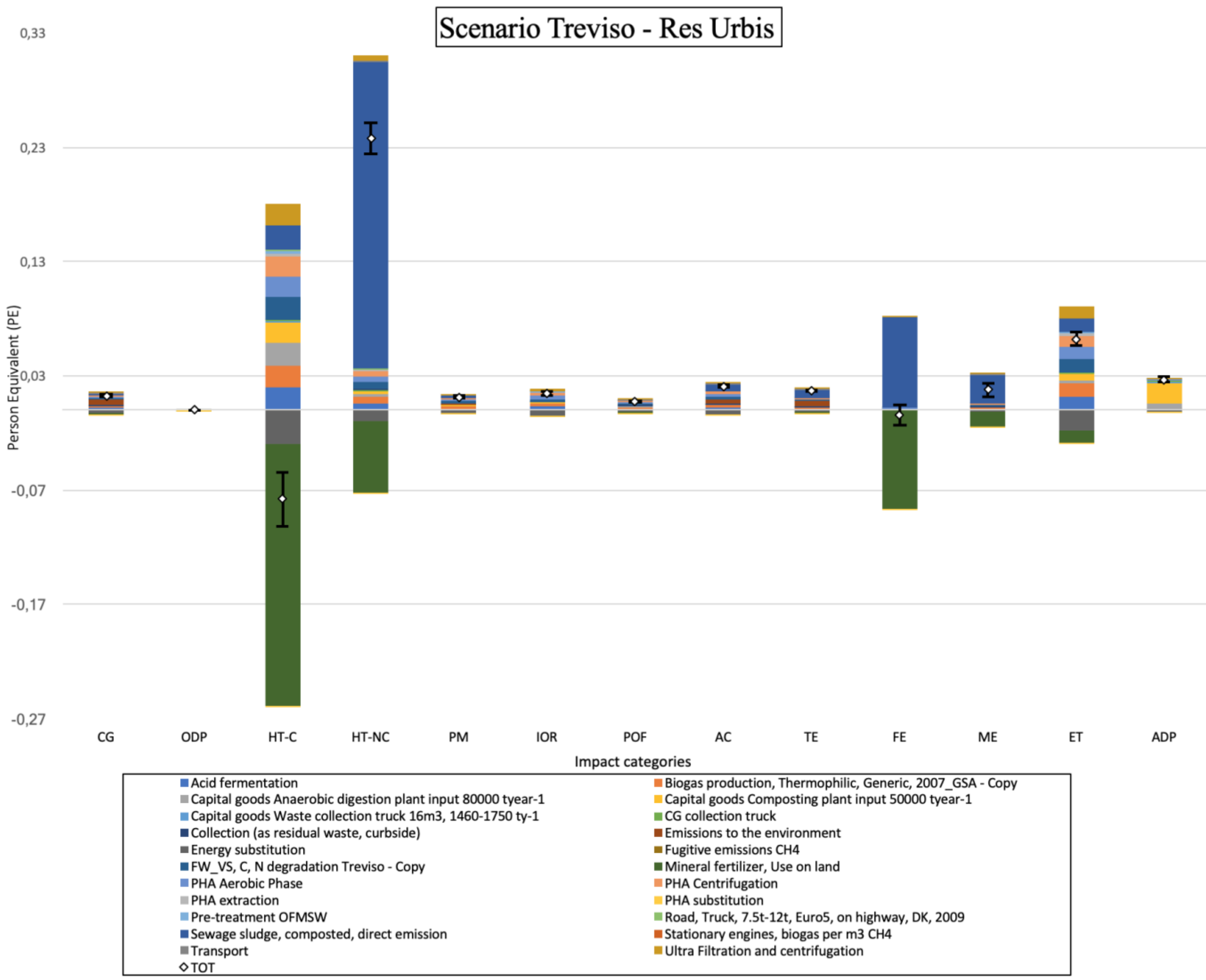

Diagram 2 - Potential environmental impacts in Person Equivalent (PE) for Res Urbis Scenario - Treviso for OFMSW and sludge

The following Table 23 and Table 24 show the processes and their contribution to the normalized environmental impact category in the Res Urbis Scenario – Treviso.

Table 23 –a) Processes and their contribution analysis in the normalized environmental impact categories in the Res Urbis Scenario – Treviso

Normalized Impact category and ILCD Method utilized	ILCD2011, Climate change with LT; midpoint; GWP100; IPPC2007 kg CO2-Eq	ILCD2011, Ozone depletion with LT, ODP with LT kg CFC-11 eq.	ILCD2011, Human toxicity, cancer effects, with LT, USEtox CTUh	ILCD2011, Human toxicity, non-cancer effects with LT, USEtox CTUh	ILCD2011, Particulate matter with LT, from Humbert 2009, PM kgPM2.5-eq	ILCD2011, Ionising radiation human health with LT, IRP100 with LT, ReCiPe 1.05 midpoint (H) kBq U235 eq
Sum	0.012730501	7.89155E-05	-0.077971967	0.237720146	0.011690445	0.01460879
Acid fermentation	0.001746844	1.90832E-05	0.019940532	0.005428423	0.001470095	0.003018251
Biogas production, Thermophilic, Generic, 2007_GSA - Copy	0.001496646	2.16444E-05	0.019220543	0.006739375	0.001595913	0.002904261
Capital goods Anaerobic digestion plant input 80000 tyear-1	0.000153843	7.07591E-06	0.01920461	0.001645375	0.000501641	0.000113167
Capital goods Composting plant input 50000 tyear-1	0.000218163	1.01235E-05	0.018695341	0.002724806	0.000642301	0.000400138
Capital goods Waste collection truck 16m3, 1460-1750 ty-1	3.00334E-05	-4.44259E-06	0.000604629	0.000264783	2.87076E-05	0.000103793
CG collection truck	9.92374E-05	-1.44922E-05	0.001849015	0.000616369	9.53786E-05	0.000338984
Collection (as residual waste, curbside)	0.000377587	5.90144E-08	4.88631E-05	0.00131301	0.000739366	4.44884E-06
Emissions to the environment	0.004664911	0	0	0	0.001163134	0
Energy substitution	-0.002102556	-3.35344E-05	-0.029519576	-0.009761647	-0.002370867	-0.004458807
Fugitive emissions CH4	0.000339607	0	0	0	0	0

FW_VS, C, N degradation Treviso - Copy	0.00147289	1.8636E-05	0.019723212	0.005835622	0.001510844	0.003005871
Mineral fertilizer, Use on land	-0.001271403	-6.92353E-09	-0.229087346	-0.062863096	-0.000384226	-5.21935E-07
PHA Aerobic Phase	0.001191751	1.66592E-05	0.017611428	0.004793874	0.001294431	0.00268873
PHA Centrifugation	0.001191482	1.66555E-05	0.01760745	0.004792791	0.001294139	0.002688123
PHA extraction	0.000177896	2.48677E-06	0.002628903	0.000715594	0.000193223	0.000401354
PHA substitution	-4.82742E-05	-2.26607E-06	-0.000468269	-0.000168023	-7.51286E-05	-2.01421E-05
Pre-treatment OFMSW	0.000179349	2.50709E-06	0.002650382	0.00072144	0.000194802	0.000404633
Road, Truck, 7.5t-12t, Euro5, on highway, DK, 2009	8.62593E-05	1.32356E-08	3.06462E-05	0.000422905	1.93624E-05	9.97774E-07
Sewage sludge, composted, direct emission	0.001056912	3.71668E-09	0.021448974	0.267966944	0.001672761	2.80184E-07
Stationary engines, biogas per m3 CH4	2.79404E-07	0	9.10254E-09	5.10236E-08	2.00983E-07	0
Transport	0.000334321	5.22522E-08	0.000114453	0.001162566	0.000654645	3.93907E-06
Ultra-Filtration and centrifugation	0.001334723	1.86578E-05	0.019724234	0.005368984	0.001449722	0.003011291

Table 24 - b) Processes and their contribution analysis in the normalized environmental impact categories in the Res Urbis Scenario – Treviso

Normalized Impact category and ILCD Method utilized	ILCD2011, Photochemical ozone formation, human health with LT, POCP kg NMVOC	ILCD2011, Terrestrial acidification, Accumulated Exceedance mol H+ eq.	ILCD2011, Eutrophication Terrestrial, Accumulated Exceedance mol N eq.	ILCD2011, Eutrophication Freshwater, FEP ReCiPe 1.05 midpoint (H) kg P eq.	ILCD2011, Eutrophication Marine with LT, ReCiPe2008 1.05 kg N eq.	ILCD2011, Ecotoxicity freshwater with LT, USEtox CTUe	ILCD2011, Depletion of abiotic resources, mineral fossil & renewable kg Sb eq.
Sum	0.007693803	0.020973274	0.017201223	-0.004367327	0.017860771	0.062193399	0.026698669
Acid fermentation	0.001312976	0.002193262	0.000822884	0.000405799	0.000835079	0.011720167	0.000709118
Biogas production, Thermophilic, Generic, 2007_GSA - Copy	0.001441075	0.002263126	0.000998926	0.000427089	0.000964342	0.011370972	0.000709208
Capital goods Anaerobic digestion plant input 80000 tyear-1	0.000191221	0.000210589	0.000113116	5.51719E-05	0.000176744	0.003060574	0.004438802
Capital goods Composting plant input 50000 tyear-1	0.000294564	0.000348466	0.000262929	0.000103236	0.000268732	0.005271227	0.018077709
Capital goods Waste collection truck 16m3, 1460-1750 ty-1	1.73685E-05	2.76008E-05	1.10502E-05	2.69787E-05	2.70565E-05	0.000407404	0.000358153
CG collection truck	5.62489E-05	8.9518E-05	3.63383E-05	6.92428E-05	4.87987E-05	0.00098995	0.001034106
Collection (as residual waste, curbside)	0.001008359	0.000530485	0.000728547	2.04533E-06	0.000681241	4.34512E-05	3.09904E-05
Emissions to the environment	0	0.00423281	0.005073853	0	0.000360898	0	0
Energy substitution	-0.001759609	-0.003223223	-0.001190538	-0.000658188	-0.00115767	-0.017453842	-0.001075148
Fugitive emissions CH4	4.48373E-05	0	0	0	0	0	0
FW_VS, C, N degradation	0.001393102	0.002279374	0.000935908	0.00040411	0.00093807	0.011667777	0.000706091

Treviso - Copy							
Mineral fertilizer, Use on land	-0.000580966	-0.00096552	-0.000686123	-0.085307122	-0.013219764	-0.011470935	-0.000306653
PHA Aerobic Phase	0.000958496	0.001878823	0.000617988	0.000360989	0.000634524	0.010428392	0.000621569
PHA Centrifugation	0.00095828	0.001878399	0.000617848	0.000360907	0.000634381	0.010426036	0.000621428
PHA extraction	0.000143077	0.000280457	9.22487E-05	5.38857E-05	9.47171E-05	0.001556673	9.27832E-05
PHA substitution	-4.14963E-05	-3.95E-05	-1.7682E-05	-1.26456E-05	-1.77955E-05	-0.00025605	-0.000145509
Pre-treatment OFMSW	0.000144246	0.000282748	9.30024E-05	5.4326E-05	9.54909E-05	0.001569391	9.35413E-05
Road, Truck, 7.5t-12t, Euro5, on highway, DK, 2009	8.08439E-05	5.4161E-05	6.31076E-05	4.58722E-07	5.74459E-05	2.48355E-05	6.95044E-06
Sewage sludge, composted, direct emission	6.3017E-05	0.006076838	0.007289383	0.078880283	0.025123348	0.011117867	1.95174E-06
Stationary engines, biogas per m3 CH4	1.86119E-06	9.3859E-07	1.24297E-06	0	1.18203E-06	4.61245E-10	0
Transport	0.000892816	0.0004697	0.000645066	1.81097E-06	0.000603302	4.00447E-05	2.74393E-05
Ultra-Filtration and centrifugation	0.001073485	0.002104221	0.000692127	0.000404296	0.000710647	0.011679464	0.000696137

The most relevant processes in the Res Urbis Scenario – Treviso are the direct emissions to air, surface water, groundwater and soil accumulation from land application of dewatered anaerobically digested sludge on a soil (Sewage sludge, composted, direct emission) that contributes the most particularly in Human toxicity, non-cancer effects **(**HT-NC) and Freshwater Eutrophication (FE) and Marine Eutrophication (ME) compared to the others processes. Other important processes are the emissions to the environment, the acidogenic fermentation of the bio-waste, the anaerobic digestion reactor for the biogas production (Biogas Production, Thermophilic) and the PHA aerobic phases and centrifugation.
At the contrary the savings are mainly due to the substitution of chemical fertilizers with mineral fertilizers (Mineral fertilizers, use on land) in Human toxicity, cancer effects (HT-C), Human toxicity, non-cancer effects **(**HT-NC), Freshwater Eutrophication (FE), Marine Eutrophication (ME) and Freshwater eco-toxicity (ET). And in lower measure to the substitution of energy and virgin polyester (PHA substitution).
Focusing on the unusual results, the capital goods of the collection truck and of the waste collection truck have some savings in the environmental impact category of ozone depletion (ODP), that is strange because it has to be positive impacts, so loads, and not the contrary.

ii) Res Urbis Scenario – Trento

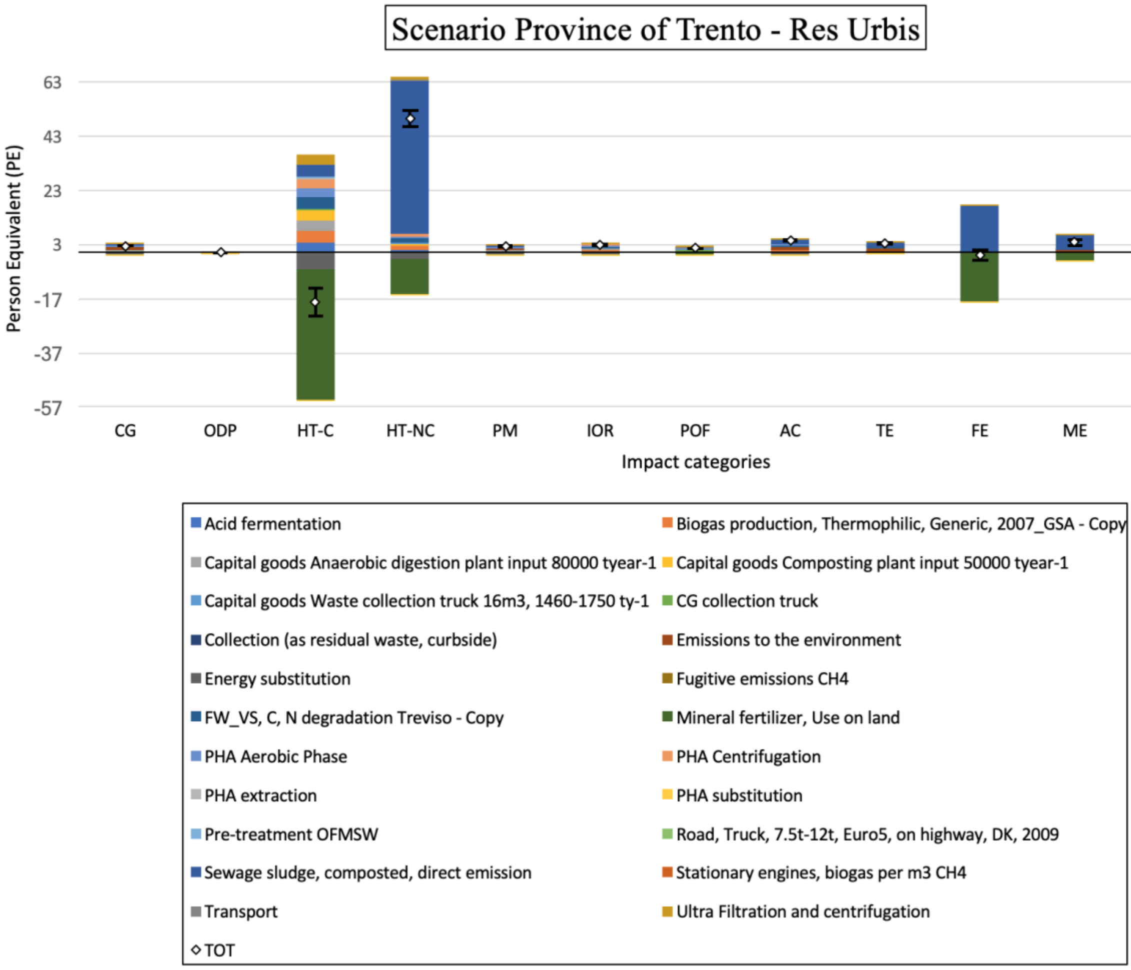

Diagram 3 - Potential environmental impacts in Person Equivalent (PE) for Res Urbis Scenario - Trento for OFMSW and sludge

The following Table 25 and Table 26 show the processes and their contribution to the normalized environmental impact category in the Res Urbis Scenario – Trento.

Table 25 - a) Processes and their contribution analysis in the normalized environmental impact categories in the Res Urbis Scenario – Trento

Normalized Impact category and ILCD Method utilized	ILCD2011, Climate change with LT; midpoint; GWP100; IPPC2007 kg CO2-Eq	ILCD2011, Ozone depletion with LT, ODP with LT kg CFC-11 eq.	ILCD2011, Human toxicity, cancer effects, with LT, USEtox CTUh	ILCD2011, Human toxicity, non-cancer effects with LT, USEtox CTUh	ILCD2011, Particulate matter with LT, from Humbert 2009, PM kgPM2.5-eq	ILCD2011, Ionising radiation human health with LT, IRP100 with LT, ReCiPe 1.05 midpoint (H) kBq U235 eq
Sum	2.53944372	0.015931027	-18.27912169	49.3685308	2.330993837	2.812587416
Acid fermentation	0.328737311	0.003591252	3.752593493	1.021570841	0.276655981	0.568002322
Biogas production, Thermophilic, Generic, 2007_GSA - Copy	0.320236909	0.004631266	4.112609306	1.442015475	0.341476079	0.62142341
Capital goods Anaerobic digestion plant input 80000 tyear-1	0.029471556	0.001355518	3.67901084	0.315202364	0.096098841	0.021679148
Capital goods Composting plant input 50000 tyear-1	0.04671409	0.002167684	4.003136421	0.583448578	0.13753256	0.085679445
Capital goods Waste collection truck 16m3, 1460-1750 ty-1	0.001458293	-0.000215713	0.029358197	0.012856743	0.00139392	0.005039741
CG collection truck	0.020837479	-0.003043008	0.388248706	0.12942267	0.02002722	0.0711786
Collection (as residual waste, curbside)	0.079284173	1.23916E-05	0.010260068	0.275700627	0.15524913	0.000934149

Emissions to the environment	0.979519391	0	0	0	0.244230276	0
Energy substitution	-0.441486294	-0.007041411	-6.198402493	-2.049711637	-0.497825219	-0.936242414
Fugitive emissions CH4	0.07130925	0	0	0	0	0
FW_VS, C, N degradation Treviso - Copy	0.315375264	0.003990331	4.22312514	1.249523128	0.323501491	0.64361574
Mineral fertilizer, Use on land	-0.266964081	-1.45378E-06	-48.10284456	-13.19974154	-0.080678273	-0.000109594
PHA Aerobic Phase	0.223429186	0.00312327	3.301786522	0.898754317	0.242679699	0.504082462
PHA Centrifugation	0.223273063	0.003121088	3.299479373	0.898126306	0.242510125	0.50373023
PHA extraction	0.033061264	0.000462157	0.48857197	0.132990478	0.035909802	0.074590092
PHA substitution	-0.005629502	-0.000264258	-0.054607314	-0.019594051	-0.008761134	-0.002348874
Pre-treatment OFMSW	0.037659025	0.000526428	0.556516652	0.151485186	0.040903703	0.08496318
Road, Truck, 7.5t-12t, Euro5, on highway, DK, 2009	0.004188384	6.42665E-07	0.001488049	0.020534471	0.000940158	4.84477E-05
Sewage sludge, composted, direct emission	0.218067671	1.80466E-07	4.502563489	56.25360103	0.349408922	1.36045E-05
Stationary engines, biogas per m3 CH4	5.86682E-05	0	1.91131E-06	1.07137E-05	4.22015E-05	0
Transport	0.070199355	1.09717E-05	0.024032451	0.244110881	0.137459829	0.000827109
Ultra-Filtration and centrifugation	0.250643264	0.00350369	3.703950082	1.008224216	0.272238525	0.565480616

Table 26 - b) Processes and their contribution analysis in the normalized environmental impact categories in the Res Urbis Scenario – Trento

Normalized Impact category and ILCD Method utilized	ILCD2011, Photochemical ozone formation, human health with LT, POCP kg NMVOC	ILCD2011, Terrestrial acidification, Accumulated Exceedance mol H+ eq.	ILCD2011, Eutrophication Terrestrial, Accumulated Exceedance mol N eq.	ILCD2011, Eutrophication Freshwater, FEP ReCiPe 1.05 midpoint (H) kg P eq.	ILCD2011, Eutrophication Marine with LT, ReCiPe2008 1.05 kg N eq.	ILCD2011, Ecotoxicity freshwater with LT, USEtox CTUe	ILCD2011, Depletion of abiotic resources, mineral fossil & renewable kg Sb eq.
Sum	1.504799317	4.21953837	3.538269215	-0.952894618	3.672789272	12.04998582	5.498315565
Acid fermentation	0.247087936	0.412748316	0.15485787	0.07636695	0.157152886	2.205609284	0.133448372
Biogas production, Thermophilic, Generic, 2007_GSA - Copy	0.30834519	0.484239363	0.213738794	0.091383944	0.206339071	2.433040535	0.151748903
Capital goods Anaerobic digestion plant input 80000 tyear-1	0.03663186	0.040342156	0.021669473	0.01056918	0.033858602	0.586310564	0.85033697
Capital goods Composting plant input 50000 tyear-1	0.063073378	0.074615207	0.056299703	0.022105464	0.057542209	1.128700396	3.870886064
Capital goods Waste collection truck 16m3, 1460-1750 ty-1	0.000843339	0.001340175	0.000536552	0.001309968	0.001313746	0.019781793	0.017390397
CG collection truck	0.011810911	0.018796641	0.007630166	0.014539336	0.010246562	0.207865824	0.217137462
Collection (as residual waste, curbside)	0.211731225	0.111389223	0.152977344	0.000429471	0.143044349	0.009123708	0.006507231

Emissions to the environment	0	0.888788536	1.065387433	0	0.075779854	0	0
Energy substitution	-0.369475622	-0.676799465	-0.249984389	-0.138203654	-0.243082817	-3.664887911	-0.225755193
Fugitive emissions CH4	0.009414752	0	0	0	0	0	0
FW_VS, C, N degradation Treviso - Copy	0.298292031	0.488059362	0.200397462	0.086527776	0.200860288	2.498298991	0.151187961
Mineral fertilizer, Use on land	-0.121989009	-0.202735951	-0.144069305	-17.91244828	-2.775833097	-2.408621022	-0.064389785
PHA Aerobic Phase	0.179698694	0.35224132	0.115860253	0.067678074	0.118960472	1.955112499	0.11653159
PHA Centrifugation	0.179573128	0.351995189	0.115779295	0.067630784	0.118877347	1.953746349	0.116450162
PHA extraction	0.026590376	0.052121854	0.017144074	0.01001446	0.01760282	0.289301916	0.017243413
PHA substitution	-0.004839102	-0.004606297	-0.002061993	-0.001474674	-0.002075226	-0.029859265	-0.016968596
Pre-treatment OFMSW	0.030288244	0.059370331	0.019528264	0.01140715	0.020050807	0.329534528	0.019641418
Road, Truck, 7.5t-12t, Euro5, on highway, DK, 2009	0.003925433	0.002629827	0.003064234	2.22736E-05	0.002789329	0.001205907	0.000337484
Sewage sludge, composted, direct emission	0.004349535	1.271034924	1.52383239	16.56294551	5.268984961	2.334064473	9.47684E-05
Stationary engines, biogas per m3 CH4	0.000390805	0.000197081	0.000260994	0	0.000248197	9.68503E-08	0
Transport	0.187469892	0.09862563	0.135448356	0.00038026	0.126678839	0.008408426	0.005761597
Ultra-Filtration and centrifugation	0.201586319	0.395144949	0.129972242	0.075921386	0.133450072	2.193248732	0.130725348

Despite the higher mass flows, the different material fractions and chemical compositions of the bio-wastes, the most relevant processes in the Res Urbis Scenario – Trento are the same for the savings, the loads and the unusual results of the Res Urbis Scenario – Treviso.

iii) Res Urbis Scenario – Copenhagen

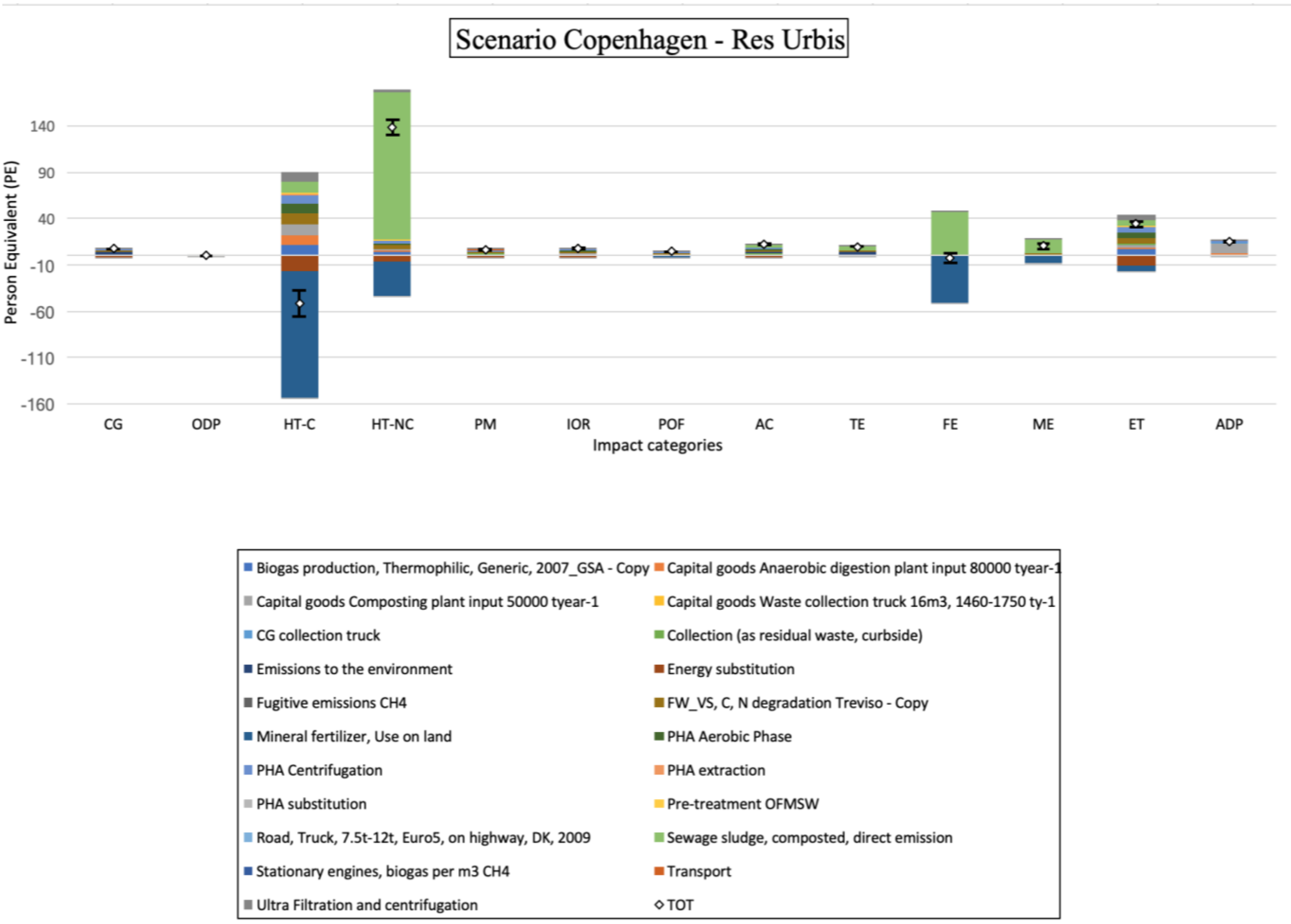

Diagram 4 - Potential environmental impacts in Person Equivalent (PE) for Res Urbis Scenario - Copenhagen for OFMSW and sludge

The following Table 27 and Table 28 show the processes and their contribution to the normalized environmental impact category in the Res Urbis Scenario – Copenhagen.

Table 27 - a) Processes and their contribution analysis in the normalized environmental impact categories in the Res Urbis Scenario – Copenhagen

Normalized Impact category and ILCD Method utilized	ILCD2011, Climate change with LT; midpoint; GWP100; IPPC2007 kg CO2-Eq	ILCD2011, Ozone depletion with LT, ODP with LT kg CFC-11 eq.	ILCD2011, Human toxicity, cancer effects, with LT, USEtox CTUh	ILCD2011, Human toxicity, non-cancer effects with LT, USEtox CTUh	ILCD2011, Particulate matter with LT, from Humbert 2009, PM kgPM2.5-eq	ILCD2011, Ionising radiation human health with LT, IRP100 with LT, ReCiPe 1.05 midpoint (H) kBq U235 eq
Sum	7.129779722	0.045646537	-51.80218996	139.1811185	6.514961022	7.91758311
Acid fermentation	0.934217099	0.010205746	10.66425042	2.90313547	0.786210569	1.614168711
Biogas production, Thermophilic, Generic, 2007_GSA - Copy	0.894801534	0.012940607	11.49139849	4.029263381	0.954148287	1.736372948
Capital goods Anaerobic digestion plant input 80000 tyear-1	0.083373948	0.003834715	10.40776851	0.891695448	0.271859881	0.061329493
Capital goods Composting plant input 50000 tyear-1	0.130477121	0.006054559	11.18116008	1.629630186	0.384142185	0.239311254
Capital goods Waste collection truck 16m3, 1460-1750 ty-1	0.003084039	-0.000456196	0.062087526	0.027189795	0.002947901	0.010658183
CG collection truck	0.05492911	-0.00802159	1.023451812	0.341167566	0.052793208	0.187631965
Collection (as residual waste, curbside)	0.208998843	3.26652E-05	0.027046285	0.726766895	0.409247992	0.002462486

Emissions to the environment	2.764981959	0	0	0	0.689411882	0
Energy substitution	-1.246225087	-0.019876457	-17.49681653	-5.785914756	-1.405258295	-2.642819945
Fugitive emissions CH4	0.201291359	0	0	0	0	0
FW_VS, C, N degradation Treviso - Copy	0.880881208	0.011145485	11.79570779	3.490069433	0.90357914	1.797697925
Mineral fertilizer, Use on land	-0.753584743	-4.10371E-06	-135.7844455	-37.26015795	-0.227738185	-0.000309361
PHA Aerobic Phase	0.636662624	0.008899775	9.408457832	2.561005092	0.691517063	1.436385591
PHA Centrifugation	0.636211041	0.008893463	9.401784432	2.559188577	0.691026571	1.435366766
PHA extraction	0.094094037	0.001315321	1.390500625	0.37849765	0.102201118	0.212287189
PHA substitution	-0.01474518	-0.000692164	-0.14303124	-0.05132209	-0.022947766	-0.006152334
Pre-treatment OFMSW	0.099271929	0.001387702	1.467018351	0.399325961	0.107825133	0.22396912
Road, Truck, 7.5t-12t, Euro5, on highway, DK, 2009	0.008857711	1.35912E-06	0.003146968	0.043426868	0.001988272	0.000102458
Sewage sludge, composted, direct emission	0.61473851	3.81654E-07	12.70954884	158.7895821	0.985919696	2.87712E-05
Stationary engines, biogas per m3 CH4	0.000165608	0	5.39525E-06	3.02427E-05	0.000119126	0
Transport	0.185050602	2.89222E-05	0.063351287	0.643494029	0.362354102	0.002180321
Ultra-Filtration and centrifugation	0.712246449	0.009956346	10.52541868	2.865044551	0.773613141	1.606911569

Table 28 - b) Processes and their contribution analysis in the normalized environmental impact categories in the Res Urbis Scenario – Copenhagen

Normalized Impact category and ILCD Method utilized	ILCD2011, Photochemical ozone formation, human health with LT, POCP kg NMVOC	ILCD2011, Terrestrial acidification, Accumulated Exceedance mol H+ eq.	ILCD2011, Eutrophication Terrestrial, Accumulated Exceedance mol N eq.	ILCD2011, Eutrophication Freshwater, FEP ReCiPe 1.05 midpoint (H) kg P eq.	ILCD2011, Eutrophication Marine with LT, ReCiPe2008 1.05 kg N eq.	ILCD2011, Ecotoxicity freshwater with LT, USEtox CTUe	ILCD2011, Depletion of abiotic resources, mineral fossil & renewable kg Sb eq.
Sum	4.160456186	11.85918096	9.923696039	-2.694509521	10.30658881	33.92299034	15.3580482
Acid fermentation	0.702183073	1.17296249	0.44008047	0.217022248	0.446602526	6.267977008	0.379238215
Biogas production, Thermophilic, Generic, 2007_GSA - Copy	0.861574765	1.35305566	0.597226712	0.255343871	0.576550411	6.798369858	0.424014795
Capital goods Anaerobic digestion plant input 80000 tyear-1	0.103630202	0.114126454	0.06130216	0.029899836	0.095784762	1.658649545	2.405568671
Capital goods Composting plant input 50000 tyear-1	0.176170248	0.20840773	0.157250697	0.061742771	0.160721139	3.152573003	10.81177161
Capital goods Waste collection truck 16m3, 1460-1750 ty-1	0.001783516	0.002834239	0.001134715	0.002770357	0.002778346	0.041835083	0.036777692
CG collection truck	0.031134421	0.049549312	0.020113672	0.038326746	0.027010684	0.547949423	0.572390134
Collection (as residual waste, curbside)	0.558138901	0.293630088	0.4032594	0.001132116	0.377075303	0.024050756	0.017153534
Emissions to the environment	0	2.508867398	3.007369797	0	0.213910956	0	0

Energy substitution	-1.042953757	-1.910465815	-0.70565456	-0.390120517	-0.686172842	-10.34522548	-0.637260519
Fugitive emissions CH4	0.02657591	0	0	0	0	0	0
FW_VS, C, N degradation Treviso - Copy	0.833164745	1.363208946	0.55973355	0.241682718	0.561026361	6.978056324	0.422286516
Mineral fertilizer, Use on land	-0.344349904	-0.572281931	-0.406678042	-50.56316066	-7.835606426	-6.799042198	-0.181759131
PHA Aerobic Phase	0.51205236	1.00371347	0.330144394	0.192849024	0.338978483	5.571103214	0.33205737
PHA Centrifugation	0.511689162	1.003001538	0.329910223	0.192712236	0.338738046	5.567151642	0.331821842
PHA extraction	0.075677559	0.148341443	0.048792905	0.028501662	0.050098518	0.823367935	0.049075628
PHA substitution	-0.012674908	-0.012065131	-0.005400913	-0.003862567	-0.005435575	-0.078209443	-0.044445315
Pre-treatment OFMSW	0.079842013	0.15650451	0.051477925	0.030070078	0.052855384	0.868676971	0.051776206
Road, Truck, 7.5t-12t, Euro5, on highway, DK, 2009	0.008301614	0.00556163	0.006480327	4.71048E-05	0.005898949	0.002550285	0.00071372
Sewage sludge, composted, direct emission	0.010386234	3.58681514	4.300025422	46.75378723	14.87191694	6.588492994	0.000200419
Stationary engines, biogas per m3 CH4	0.001103163	0.00055632	0.000736733	0	0.00070061	2.73388E-07	0
Transport	0.494184264	0.259984331	0.357051712	0.001002392	0.333934629	0.022165222	0.015187987
Ultra-Filtration and centrifugation	0.572842603	1.122873132	0.369338741	0.215743829	0.379221602	6.232497918	0.371478823

Despite the higher mass flows, the different material fractions and chemical compositions of the bio-wastes, the most relevant processes in the Res Urbis Scenario – Copenhagen are the same for the savings, the loads and the unusual results of the other two scenarios.

This is possible due to the fact of using the same average chemical composition in this study but with different material fractions.

The main differences between the scenarios are the total mass (wet weight) of the two bio-waste stream, as results of the different PE served and the fact that for the scenario of Treviso the stream are considered in kg/d and for the other two in tn/y. But we can see from the comparison of these three scenarios that it is not affecting the final results.

4.2 Uncertainty contribution analysis

The chapter describes the most important parameters in each scenario based on the uncertainty and sensitivity analysis described in the Sensitivity paragraph. Notwithstanding that the study was done with 195 parameters, at the end, the LCA model was built with less than 60 parameters, due to the fact that the calculations of the perturbation analysis for the different scenarios, with the Monte Carlo simulation technique, was too problematic for the instruments used and the calculations crashed the software.

The following Table 29 shows the parameters, that are inside the construction of the processes, divided per impact category and scenario, that contribute the most to the overall uncertainty.

Table 29 - List of the most important parameters for all the scenarios

Impact Categories	Treviso	% Contribution	Trento	% Contribution	Copenhagen	% Contribution
Climate change (CG)	R_Pre_Treat_water_liquid	1%	R_Pre_Treat_water_liquid	1%	R_Pre_Treat_water_liquid	1%
	R_sludge_thickened_water_mixer	32%	R_sludge_thickened_water_mixer	26%	R_sludge_thickened_water_mixer	28%
	AD_water_content	32%	R_sludge_thickened_VS_mixer	1%	AD_water_content	35%
	AD_AD_yield	1%	AD_water_content	36%	AD_AD_yield	1%
	AD_AD_e	3%	AD_AD_yield	1%	AD_AD_e	3%
	AD_biogas_engine_eff_e	9%	AD_AD_e	4%	AD_biogas_engine_eff_e	9%
	AD_comp_degr_e	3%	AD_biogas_engine_eff_e	9%	AD_comp_degr_e	4%
	AD_UOL_indirect_N_N2O	2%	AD_comp_degr_e	4%	AD_UOL_indirect_N_N2O	2%
	AD_UOL_sludge_direct_N_N2O	13%	AD_UOL_indirect_N_N2O	2%	AD_UOL_sludge_direct_N_N2O	14%
	R_UF_liquid_water	1%	AD_UOL_sludge_direct_N_N2O	14%	R_UF_liquid_water	1%
	R_PHA_reusable_water	2%	R_UF_liquid_water	1%	R_PHA_reusable_water	1%
			R_PHA_reusable_water	1%		
Ozone depletion (ODP)	R_Pre_Treat_water_liquid	1%	R_Pre_Treat_water_liquid	1%	R_Pre_Treat_water_liquid	1%
	R_sludge_thickened_water_mixer	33%	R_sludge_thickened_water_mixer	26%	R_sludge_thickened_water_mixer	28%
	AD_water_content	43%	R_sludge_thickened_VS_mixer	1%	R_sludge_thickened_VS_mixer	1%
	AD_AD_yield	3%	AD_water_content	48%	AD_water_content	46%
	AD_AD_e	3%	AD_AD_yield	3%	AD_AD_yield	3%
	AD_biogas_engine_eff_e	12%	AD_AD_e	4%	AD_AD_e	4%
	AD_comp_degr_e	4%	AD_biogas_engine_eff_e	12%	AD_biogas_engine_eff_e	12%
	R_UF_liquid_water	1%	AD_comp_degr_e	4%	AD_comp_degr_e	4%
	R_PHA_reusable_water	1%	R_UF_liquid_water	1%	R_UF_liquid_water	1%
			R_PHA_reusable_water	1%	R_PHA_reusable_water	1%
Human	R_sludge_thickened_water_mixer	11%	R_sludge_thickened_water_mixer	8%	R_sludge_thickened_water_mixer	9%

toxicity, cancer effects (HT-C)	R_CG_AD_CrSt	1%	R_CG_AD_CrSt	1%	R_CG_AD_CrSt	1%
	AD_water_content	13%	AD_water_content	14%	AD_water_content	14%
	AD_AD_yield	1%	AD_AD_yield	1%	AD_AD_yield	1%
	AD_AD_e	1%	AD_AD_e	1%	AD_AD_e	1%
	AD_biogas_engine_eff_e	2%	AD_biogas_engine_eff_e	2%	AD_biogas_engine_eff_e	2%
	AD_comp_degr_e	1%	AD_comp_degr_e	1%	AD_comp_degr_e	1%
	AD_UOL_Subst_P	71%	AD_UOL_Subst_P	72%	AD_UOL_Subst_P	72%
Human toxicity, non-cancer effects (HT-NC)	R_sludge_thickened_water_mixer	2%	R_sludge_thickened_water_mixer	1%	R_sludge_thickened_water_mixer	1%
	AD_water_content	3%	AD_water_content	3%	AD_water_content	3%
	AD_biogas_engine_eff_e	1%	AD_biogas_engine_eff_e	1%	AD_biogas_engine_eff_e	1%
	AD_UOL_Subst_P	11%	AD_UOL_Subst_P	11%	AD_UOL_Subst_P	11%
	AD_UOL_sludge_direct_emiss_Zn	83%	AD_UOL_sludge_direct_emiss_Zn	84%	AD_UOL_sludge_direct_emiss_Zn	84%
Particulate matter (PM)	R_colltruck_diesel	1%	R_colltruck_diesel	1%	R_colltruck_diesel	1%
	R_colltruck_km	1%	R_colltruck_km	1%	R_colltruck_km	1%
	R_Pre_Treat_water_liquid	1%	R_Pre_Treat_water_liquid	1%	R_Pre_Treat_water_liquid	1%
	R_sludge_thickened_water_mixer	32%	R_sludge_thickened_water_mixer	25%	R_sludge_thickened_water_mixer	28%
	AD_water_content	40%	R_sludge_thickened_VS_mixer	1%	R_sludge_thickened_VS_mixer	1%
	AD_AD_yield	3%	AD_water_content	44%	AD_water_content	43%
	AD_AD_e	3%	AD_AD_yield	3%	AD_AD_yield	3%
	AD_biogas_engine_eff_e	10%	AD_AD_e	4%	AD_AD_e	4%
	AD_comp_degr_e	4%	AD_biogas_engine_eff_e	10%	AD_biogas_engine_eff_e	10%
	AD_UOL_sludge_direct_N_NH3	5%	AD_comp_degr_e	4%	AD_comp_degr_e	4%
	R_UF_liquid_water	1%	AD_UOL_sludge_direct_N_NH3	5%	AD_UOL_sludge_direct_N_NH3	5%
	R_PHA_reusable_water	1%	R_UF_liquid_water	1%	R_UF_liquid_water	1%
			R_PHA_reusable_water	1%	R_PHA_reusable_water	1%
Ionising	R_Pre_Treat_water_liquid	1%	R_Pre_Treat_water_liquid	1%	R_Pre_Treat_water_liquid	1%

radiation (IOR)	R_sludge_thickened_water_mixer	38%	R_sludge_thickened_water_mixer	30%	R_sludge_thickened_water_mixer	33%
	AD_water_content	35%	R_sludge_thickened_VS_mixer	1%	AD_water_content	38%
	AD_AD_yield	3%	AD_water_content	40%	AD_AD_yield	3%
	AD_AD_e	4%	AD_AD_yield	3%	AD_AD_e	5%
	AD_biogas_engine_eff_e	11%	AD_AD_e	5%	AD_biogas_engine_eff_e	11%
	AD_comp_degr_e	5%	AD_biogas_engine_eff_e	12%	AD_comp_degr_e	5%
	R_UF_liquid_water	1%	AD_comp_degr_e	5%	R_UF_liquid_water	1%
	R_PHA_reusable_water	3%	R_UF_liquid_water	1%	R_PHA_reusable_water	2%
			R_PHA_reusable_water	2%		
Photochemical ozone formation (POF)	R_colltruck_diesel	2%	R_colltruck_diesel	2%	R_colltruck_diesel	2%
	R_colltruck_km	2%	R_colltruck_km	2%	R_colltruck_km	2%
	R_Pre_Treat_water_liquid	1%	R_Pre_Treat_water_liquid	1%	R_Pre_Treat_water_liquid	1%
	R_sludge_thickened_water_mixer	30%	R_sludge_thickened_water_mixer	23%	R_sludge_thickened_water_mixer	26%
	AD_water_content	45%	R_sludge_thickened_VS_mixer	1%	R_sludge_thickened_VS_mixer	1%
	AD_AD_yield	2%	AD_water_content	50%	AD_water_content	49%
	AD_AD_e	3%	AD_AD_yield	2%	AD_AD_yield	2%
	AD_biogas_engine_eff_e	9%	AD_AD_e	3%	AD_AD_e	3%
	AD_comp_degr_e	3%	AD_biogas_engine_eff_e	9%	AD_biogas_engine_eff_e	9%
	AD_truck_comp_km	1%	AD_comp_degr_e	4%	AD_comp_degr_e	3%
	R_UF_liquid_water	1%	R_UF_liquid_water	1%	R_UF_liquid_water	1%
	R_PHA_reusable_water	1%	R_PHA_reusable_water	1%	R_PHA_reusable_water	1%
Terrestrial acidification (AC)	R_Pre_Treat_water_liquid	1%	R_Pre_Treat_water_liquid	1%	R_Pre_Treat_water_liquid	1%
	R_sludge_thickened_water_mixer	26%	R_sludge_thickened_water_mixer	20%	R_sludge_thickened_water_mixer	22%
	AD_water_content	28%	AD_water_content	31%	AD_water_content	30%
	AD_AD_yield	2%	AD_AD_yield	2%	AD_AD_yield	2%
	AD_AD_e	3%	AD_AD_e	3%	AD_AD_e	3%

	AD_biogas_engine_eff_e	7%	AD_biogas_engine_eff_e	8%	AD_biogas_engine_eff_e	8%
	AD_comp_degr_e	3%	AD_comp_degr_e	3%	AD_comp_degr_e	3%
	AD_UOL_sludge_direct_N_NH3	26%	AD_UOL_sludge_direct_N_NH3	28%	AD_UOL_sludge_direct_N_NH3	28%
	R_UF_liquid_water	1%	R_UF_liquid_water	1%	R_UF_liquid_water	1%
	R_PHA_reusable_water	1%	R_PHA_reusable_water	1%	R_PHA_reusable_water	1%
Eutrophication Terrestrial (TE)	R_colltruck_diesel	1%	R_colltruck_diesel	1%	R_colltruck_diesel	1%
	R_colltruck_km	1%	R_colltruck_km	1%	R_colltruck_km	1%
	R_sludge_thickened_water_mixer	6%	R_sludge_thickened_water_mixer	5%	R_sludge_thickened_water_mixer	5%
	AD_water_content	11%	AD_water_content	12%	AD_water_content	12%
	AD_AD_yield	1%	AD_AD_yield	1%	AD_AD_yield	1%
	AD_AD_e	1%	AD_AD_e	1%	AD_AD_e	1%
	AD_biogas_engine_eff_e	2%	AD_biogas_engine_eff_e	2%	AD_biogas_engine_eff_e	2%
	AD_comp_degr_e	1%	AD_comp_degr_e	1%	AD_comp_degr_e	1%
	AD_UOL_sludge_direct_N_NH3	76%	AD_UOL_sludge_direct_N_NH3	77%	AD_UOL_sludge_direct_N_NH3	77%
Eutrophication Freshwater (FE)	AD_UOL_Subst_P	100%	AD_UOL_Subst_P	100%	AD_UOL_Subst_P	100%
Eutrophication Marine (ME)	AD_UOL_indirect_N_NO3_l	7%	AD_UOL_indirect_N_NO3_l	7%	AD_UOL_indirect_N_NO3_l	7%
	AD_UOL_indirect_N_NO3_r	36%	AD_UOL_indirect_N_NO3_r	36%	AD_UOL_indirect_N_NO3_r	36%
	AD_UOL_sludge_direct_N_NO3_l	37%	AD_UOL_sludge_direct_N_NO3_l	37%	AD_UOL_sludge_direct_N_NO3_l	37%
	AD_UOL_sludge_direct_N_NO3_r	19%	AD_UOL_sludge_direct_N_NO3_r	20%	AD_UOL_sludge_direct_N_NO3_r	20%
Ecotoxicity freshwater (ET)	R_Pre_Treat_water_liquid	1%	R_Pre_Treat_water_liquid	1%	R_Pre_Treat_water_liquid	1%
	R_sludge_thickened_water_mixer	35%	R_sludge_thickened_water_mixer	28%	R_sludge_thickened_water_mixer	30%
	AD_water_content	40%	R_sludge_thickened_VS_mixer	1%	R_sludge_thickened_VS_mixer	1%
	AD_AD_yield	2%	AD_water_content	44%	AD_water_content	43%
	AD_AD_e	4%	AD_AD_yield	3%	AD_AD_yield	3%
	AD_biogas_engine_eff_e	9%	AD_AD_e	4%	AD_AD_e	4%

	AD_comp_degr_e	4%	AD_biogas_engine_eff_e	10%	AD_biogas_engine_eff_e	10%
	AD_UOL_Subst_P	2%	AD_comp_degr_e	5%	AD_comp_degr_e	4%
	R_UF_liquid_water	1%	AD_UOL_Subst_P	2%	AD_UOL_Subst_P	2%
	R_PHA_reusable_water	1%	R_UF_liquid_water	1%	R_UF_liquid_water	1%
			R_PHA_reusable_water	1%	R_PHA_reusable_water	1%
Depletion of abiotic resources (ADP)	R_sludge_thickened_water_mixer	3%	R_sludge_thickened_water_mixer	2%	R_sludge_thickened_water_mixer	3%
	R_sludge_thickened_VS_mixer	1%	R_sludge_thickened_VS_mixer	1%	R_sludge_thickened_VS_mixer	1%
	R_CG_AD_CrSt	2%	R_CG_AD_CrSt	2%	R_CG_AD_CrSt	2%
	AD_water_content	92%	AD_water_content	93%	AD_water_content	93%
	R_PHA_reusable_water	1%	R_PHA_reusable_water	1%	R_PHA_reusable_water	1%

The parameters that are contributing the most to the uncertainty range in this analysis are:

- the separation process of the thickened sludge (R_sludge_thickened_water_mixer);
- the water content in the anaerobic digestor (AD_water_content);
- the fate of N and P when the composted mixed digestate is spread on land (AD_UOL_subst_P; AD_UOL_sludge_direct_N_NH3; AD_UOL_indirect_N_NO3_r; AD_UOL_sludge_direct_N_NO3_l; AD_UOL_sludge_direct_N_NO3_r), fate of heavy metals as Zinc (AD_UOL_sludge_direct_emission_Zn).

It should be noted that the uncertainty of the substitution of the PHA produced in the scenarios is not relevant for the overall uncertainty.

The most important parameters and processes remains the same of the screening-LCA (Boldrin & Bassi Andreasi, 2017), that were the water content in the anaerobic digestor and the fate of N and P when the composted digestate is spread on land.

The PHA production process does not seems to affect the overall in the tested scenarios but it has to be clear that the substitution of the virgin polymers with these new bio-polymers is not well defined as for the quality and the amount of plastic substituted by the produced PHA. The future objectives of the RES URBIS project have to clarify these assumptions.

So in the current modelling, conservative values for PHA substitution were adopted, as average EU data for the production of a generic polyester resin (Boldrin & Bassi Andreasi, 2017).

Furthermore, the material flow analysis showed that the real production in tonnes per year is significant for developing an industrial scaling-up of the technology in order to make these poly-esters affordable for the plastic market.

5 Conclusions

This study focused on the viability of the PHA production from bio-wastes in chosen clusters and compared it to their current managements in an optic of integration into already existing waste schemes. The three scenarios investigated were: the pilot plant of Treviso, the Province of Trento and Copenhagen metropolitan area.

The results show that the implementation of the production of PHA in a novel concept of bio-refinery is a real important step for the up-coming productions of bio-polymers instead of the fossil-based plastic.

Thanks to the life cycle assessment, we were able to identify the most important environmental impacts of the processes before the full-scale adaptation of this new technology.

Based on the uncertainties and the results obtained from the mass balances, the material flow analysis and the life cycle assessment suggestions on improvements and future research can be found.

The PHA production from the bio-wastes and the chemical characteristics of these bio-polymers should be further investigated to obtain an optimal composition for the future applications in an ideal fossil-free plastic world. The bio-refinery concept is the best option for the future up-grading of the wastewater treatment plants in an optic of circular economy. However, there is the necessity of the comparison of this model with the existing technologies, like landfill and incineration, for better understanding the possibility of integration in different realities and to hit the legal barriers and the social prejudices.

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