Life Cycle Assessment study of Polylactic Acid food packaging including Food Waste

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Resumo

A necessidade urgente de reduzir a emissão de gases de efeito estufa na atmosfera assim como os resíduos alimentares destinados a aterros, levaram ao desenvolvimento de plásticos produzidos a partir de fontes renováveis. No entanto, o bio-plástico líder de mercado usado para fabricar embalagens de alimentos, é o ácido (poli)láctico (PLA) produzido pela Total-Corbion.

A análise apresentada nesta dissertação é um estudo sobre o ciclo de vida de embalagens fortemente contaminadas com resíduos alimentares húmidos. Este trabalho tem dois objetivos: primeiro, analisar qual será a melhor opção de fim-de-vida da embalagem de alimentos e, em segundo lugar, determinar qual a etapa do ciclo de vida que tem o maior impacto ambiental. Assim, recorrendo à metodologia de Avaliação de Ciclo de Vida (ACV), foi realizado um estudo desde o nascimento até a morte de todos os sistemas, tendo como cenários finais: a compostagem, incineração, digestão anaeróbica e aterro sanitário.

O presente estudo mostra que a incineração é mais favorável para embalagens destinadas a alimentos com baixo teor de humidade (<70%) como: copo de café, copo de iogurte e cápsula de café. A compostagem é mais favorável para embalagens com alto teor de humidade, como saco de chá e pepino. A digestão anaeróbica é a melhor opção para todos os sistemas analisados, mas tecnicamente não é um processo desenvolvido. O aterro sanitário é a pior opção, de uma perspetiva do ciclo de vida porque, embora o PLA permaneça inerte em aterros sanitários, o desperdício de alimentos decompõe-se em emissões nocivas.

Palavras-Chave

Bio-plásticos · ACV · PLA · Fim-de-vida

Abstract

The pressing need, in recent decades, to reduce the emission of greenhouse gases into the atmosphere, and the amount of food waste destined for landfills, has led to the wide development of bio-based plastics produced from renewable sources. However, the most important bio-plastic on the market, used to manufacture food packaging, is the poly(lactic acid) (PLA) produced by Total-Corbion.

The analysis presented in this dissertation, is a Life Cycle Assessment (LCA) study of packaging heavily contaminated with wet food residues, to determine the impact of packaging and food waste. The aim of this work is twofold: first, to analyse what might be the best end-of-life (EOL) option for PLA food packaging with food content and second, to determine which life cycle stage has the biggest impact. Therefore, by using the LCA methodology, a LCA cradle-to-grave was conducted for all the different food packaging systems, taking into consideration as final scenarios composting, incineration, anaerobic digestion and landfill.

The present assessment shows that, incineration is more favorable for food packaging with low moisture content (<70%), such as: coffee cups, yogurt cups and coffee capsules. Industrial composting is more favorable for food packaging with high moisture content, such as tea bags and cucumber wrapping. Anaerobic digestion is the best option for all systems but it is unfortunately technically challenging. Lastly, landfill, is the worse option, from a LCA perspective, because even though PLA will remain inert in landfills, food waste decomposes into harmful gaseous emissions.

Keywords

Bioplastics · LCA · PLA · End-of-life

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Nomenclature

AD	Anaerobic Digestion
AP	Acidification Potential
C	Carbon (element)
$C_{0.5}H_{2.9}O_{1.4}N_{0.002}$	Tea leaves
$C_{0.8}H_{3.3}O_{1.3}N_{0.04}$	Yogurt
$C_{2.9}H_{5.8}O_{2.8}N_{0.14}$	Cucumber
$C_{4.4}H_{9.5}O_{3.6}N_{0.1}$	Coffee
$C_6H_8O_4$	Poly(lactic) acid
CaO	Burnt lime
CH_4	Methane
CHP	Combined Heat and power
CO	Carbon Monoxide
CO_2	Carbon Dioxide
EOL	End-of-life
EP	Eutrophication Potential
ESP	Electrostatic precipitator
EU	European Union
FU	Functional Unit
GHGs	Greenhouse gases
GWP	Global Warming Potential
H	Hydrogen (element)
H_2O	Water
HCl	Hydrogen Chloride
HF	Hydrogen Fluoride
HHV	High Heating Value
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
Kg CO_2**-eq**	Kilograms of carbon dioxide equivalent
Kg PO_4^{3-}**-eq**	Kilograms of phosphate equivalent
Kg SO_{2-}**-eq**	Kilograms of sulphur dioxide equivalent
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment

LHV	Low Heating Value
LHV_{dry}	Low Heating Value Dry
LHV_{wet}	Low Heating Value Wet
LU	Land Use
MSWI	Municipal Solid Waste Installations
N	Nitrogen (element)
NaOH	Sodium Hydroxide
NH_3	Ammonia
NH_x	Nitrogen hydroxide
NREU	Nonrenewable energy use
NO_2	Nitrogen Dioxide
NO_X	Nitrogen Oxides
N_2O	Dinitrogen Oxide
O	Oxygen (element)
O_2	Oxygen
PE	Polyethylene
PET	Polyethylene Terephthalate
PLA	Poly(lactic acid)
PP	Polypropylene
PS	Polystyrene
REU	Renewable energy use
SCR	Selective Catalytic Reduction
SO_2	Sulfur Dioxide
SO_x	Sulfur Oxides
TPS	Thermoplastic elastomers
WF	Water Footprint
WSI	Water Scarcity
WtE	Waste to energy

Glossary

Biodegradation	Biodegradation is a term used in ecology to indicate the biochemical processes in which organic substances produced directly or indirectly from photosynthesis are broken down, and transformed back into the inorganic state.
Biodegradability	Biodegradability refers to a potentiality (i.e. the ability to be degraded by biological agents).
Combined Heat and Power	Simultaneous production of electricity and heat, both of which are used. The central and most fundamental principle of cogeneration is that, in order to maximize the many benefits that arise from it, systems should be based on the heat demand of the application. This can be an individual building, an industrial factory or a town/city served by district heat/cooling. Through the utilization of the heat, the efficiency of a cogeneration plant can reach 90% or more.
Glass Transition Temperature	The glass transition temperature for short is the reversible transition in amorphous materials (or in amorphous regions within semicrystalline materials) from a hard and relatively brittle "glassy" state into a viscous or rubbery state as the temperature is increased.
Co-product	Any of two or more functional flows from a co-production process.
Cradle-to-grave	The term cradle to grave is used in reference to a firm's perspective on the environmental impact created by their products or activities from the beginning of its life cycle to its end or disposal.

Chapter 1

Introduction

The growth of the global population combined with the increasing need for food and the quick pace of modern life, has increased production of single-serve packaging systems. Unfortunately, this type of plastic packaging ends up in the waste bin relatively soon due to its single-use design. This inefficient concept has increased both the production of plastics waste and the presence of food packaging in waste streams (Plastic Zero, 2017).

In order to address this issue, the European Commission has passed Directive 2008/98/EC on waste (Waste Framework Directive). The Waste Framework Directive obligates European Union (EU) member states, when implementing EU waste legislation and policy, to apply the waste management hierarchy in priority order. The hierarchy consists of five levels: 1) Prevention; 2) Reuse; 3) Recycling; 4) Other recovery and 5) Disposal. The five criteria are maintained in broad terms in the revised directive and are listen in priority order (Council T. E., 2008).

There is clear scientific evidence that greenhouse gas emissions arising from fossil fuel combustion, and land-use change as a result of human activities, are increasing the volatility of the Earth's climate (Solomon S, 2007). To achieve an environmentally sustainable economy that reduces greenhouse gas emissions, companies in various industrial categories have tried to move from fossil based resources to more sustainable resources for their products and production processes. Biodegradable plastics, such as PLA, constitute an encouraging case since they can be handled in all end-of-life options outlined in the waste hierarchy, including industrial composting and anaerobic digestion. These biodegradable plastics can help move food packaging up the waste hierarchy and divert food waste from landfills.

In line with waste hierarchy, recycling is the second best option for waste management, but for post-consumer plastics this disposal treatment is much more complicated. This is because post-consumer plastic waste is highly contaminated with impurities and a great amount of sorting must be carried out. Although the mechanical recycling of bio-plastics is technically feasible, the cost of sorting and the small volume of bio-plastics currently on the market significantly rule out the development of a waste stream exclusively for them (Günter Müller, 2014).

As consumers shift to a more sustainable pattern of consumption and demand for sensitivity to these sustainability principles increases, the calculation of credible environmental profiles for food packaging becomes an important step towards a circular economy. LCA's a method defined by the International Organization for Standardization (ISO), is the leading tool to assess food packaging environmental performance. An LCA study evaluates the relative potential environmental and human health impacts of products and services throughout their life cycle. The assessment begins, with raw material extraction and includes all aspects of production, use, and end-of-life treatment. (Quantis c. , 2015). Many software products have been developed to assist and facilitate LCAs, utilizing extensive databases containing reliable and validated data on several processes. One of the most popular LCA software programs has been used in this project, SimaPro, and the Ecoinvent v3.3 database has been used to model the life cycles of the different systems.

Thus, the main aim of this project is to assess and compare the environmental impacts coming from the life cycle of PLA plastic food packaging with food content, focusing on the disposal options, as well as providing information about the impact of the other stages.

1.1 Motivation

Consumers are increasingly demanding fresh and processed foods all year round, often sourced globally, in a form that is safe and convenient. A combination of different materials is used in the primary and secondary packaging to contain, protect, preserve, distribute and sell each food item. PLA packaging is designed to effectively contain and protect food across the supply chain while minimizing both food and plastic waste. Thus, this biodegradable plastic will help divert food waste from landfills.

The biodegradability of bio-plastics is an interesting characteristic because it offers new recycling routes in waste management, such as organic recycling (through composting or anaerobic digestion). This is a positive feature because more recovery options mean more effective plastic recovery.

Therefore, this project is divided into one main research question and one sub research questions:

1. From the environmental perspective, which end-of-life treatment is most suitable to process PLA food packaging including the organic waste?
2. Which stage has the biggest environmental impact?

A discussion of bio-based vs fossil-based materials was carried out but it falls outside of the scope of this thesis.

1.2 Outline of the report

This document is structured as followed. The first chapter contains the introduction and motivation for the work. The literature review is presented in chapter 2, State-of-art, to explain the previous research that has been done throughout the years. In chapter 3, Scientific Background and Methodology, where the theoretical framework is described as well as the approach of the project.

Chapter 4 defines the goal and scope, followed by a life cycle inventory analysis, involving data collection and calculation procedures. The life cycle impact assessment subsection which explains the categories assessed and the life cycle Interpretation with the results and sensitivity analysis. To finalize, the last chapter comprises the conclusions and suggestions for future work.

Chapter 2

State-of-art

This chapter is divided in four subsections. Starting with a recent review of the literature on the biodegradable food packaging life-cycle assessment and waste management life-cycle assessment to give a brief over view of the currently situation of the alternative materials. The last two subsections, are European legislations regarding plastic packaging waste and bio-waste.

2.1 Biodegradable food packaging life cycle assessment

A number of LCA studies have been published comparing food plastic packaging with other types of packaging as well as comparing and assessing different types of plastic. Various bio-based packaging materials, more specifically PLA, have been investigated and reported on. Extensive research focused on measuring environmental sustainability and identifying environmental performance-improvement objectives regarding PLA has been conducted by Nature Works™.

A cradle-to-grave LCA about two polymers that can be used in food packaging applications: PLA and polypropylene (PP), was performed by a group of consultants and reported on (Bohlmann, 2004). The purpose of their study, was to validate the hypothesis of whether biodegradable polymers offer the potential of addressing a wide range of environmental concerns associated with conventional polymers such as greenhouse gas emissions and sustainability. The overall environmental burden of a product including the system used for manufacturing it and its end-of-life treatment was considered, but it was focused on the disposal phase, because this stage was extremely important for short-lived consumer products such as packaging.

Figure 1 represents the system boundaries of the study, and the waste management representation is acceptable because a combination of source reduction, recycling, incineration, and composting is being developed as an alternative to landfilling packaging waste.

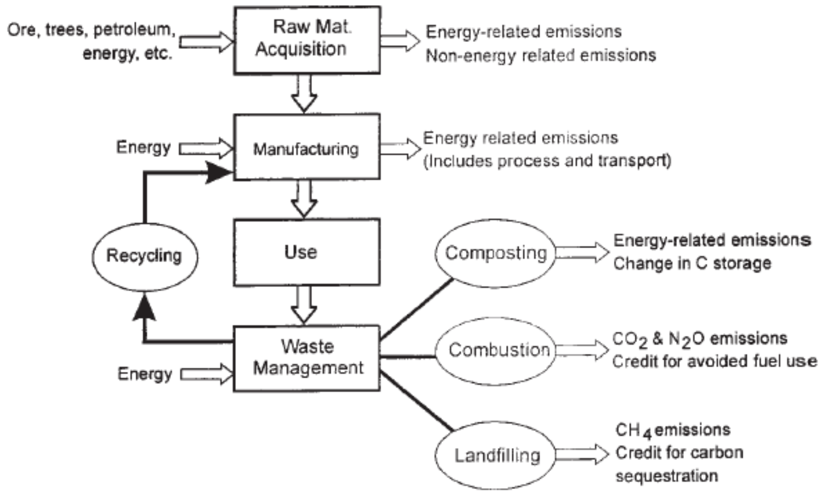

Figure 1 - Food packaging life cycle (Bohlmann, 2004).

The authors concluded that PLA is a more energy efficient polymer than PP for food packaging because PLA consumes almost no feedstock fossil energy. The two materials greenhouse emissions are equivalent if it is assumed that PLA is fully sequestered in a landfill.

Calculations on Nespresso coffee capsules were performed by (Quantis, 2011), to compare different coffee capsules made from different types of plastic, such as PLA, polystyrene (PS) and aluminum. Reaching the conclusion that recycling is the best disposal option for all plastic types but for the PLA coffee capsule, anaerobic digestion is a next best option. The same author, in 2015, (Quantis c. , 2015) compared single-served coffee capsules with bulk coffee, from the extraction and processing of all raw materials to the end-of-life management of the coffee and packaging systems, focusing on the North American market. The study shows, the single-served coffee system has the higher environmental footprint.

(Franklin Associates, 2011) prepared a LCA study for the Plastic Foodservice Packaging group assessing three different materials, polystyrene, paper and PLA. The primary intended use was to provide the environmental impacts from the life cycle of disposable foodservice products. The author reached the conclusions that PLA products have greenhouse gases (GHGs) net credits compared with the other two materials. Other authors, such as (Grzegorz Ganczewski, 2014) came to the same conclusion, highlighting the quality and advantages of PLA in food packaging in comparison with other polymers.

2.2 Waste management life cycle assessment

Numerous studies have also taken place trying to determine the optimal disposal method for plastic waste. They have compared different disposal scenarios of landfilling, incineration, recycling or a combination of the above by using the LCA tool.

(V. Rossi, 2015) compared the environmental impacts coming from the disposal of two different biodegradable plastics, PLA and thermoplastic elastomers (TPS). Among the possible treatment alternatives, six end-of-life options were selected and evaluated. The study concluded that mechanical recycling and incineration with energy recovery has the smallest environmental impact while industrial composting has the largest environmental impact. (Turconi, 2011) compared waste incineration with energy recovery of municipal solid waste in two European countries, Italy and Denmark. This study concluded that the Danish system was better than the Italian system, mainly because of higher heat recovery. (Piemonte, 2011) assessed the environmental impacts of the best final disposition of bioplastic wastes in order to maximize the energy savings. This study demonstrates how incineration, composting and anaerobic digestion processes are clearly under-performing, from an environmental point of view, with respect to the mechanical recycling process.

(Lasse Tobiasen, 2014), assessed incineration and anaerobic digestion, two thermal treatment options. Reaching the conclusion that for an energy system with district heating as an option, the energy recovery from incineration is much higher than anaerobic digestion. (Max J.Krause, 2016) performed a study based on PLA landfilling and reached the conclusion that PLA under certain temperatures becomes a carbon sink in landfills and doesn't biodegrade.

2.3 Directives of plastic packaging waste

Despite the high environmental impacts caused by the disposal of plastic waste, there is no actual legislation about the waste treatment of plastic in Europe. However, there are EU directives framing the policy that member countries must adopt (Biener, 2013).

The European Packaging and Packaging Waste Directive 94/62/EC was established to deal with packaging waste issues, obliging member states to meet targets for the recovery and recycling of packaging waste. Those targets are related to the use of recycled packaging materials in the manufacturing of packaging and other products, the reuse of products already purchased and also require for the manufacturing companies to design packaging that can be recovered or recycled (European Union, 1994). The European Bioplastics association wants to improve this directive, to clarify the definition of biodegradable and compostable plastics and to allow bio-based plastic to enter all waste collection and treatment systems, including mechanical recycling and energetic recovery (Bioplastics, European Bioplastics, 2017).

2.4 Directives of bio-waste management

The Waste Framework Directive (2008/98/EC) established a target for biological treatment, that in the future, must go hand-in-hand with enhanced separate collection to ensure good quality of compost and digestate. To achieve that target, on 2 July of 2014, the European Commission came up with a proposal relating to bio-waste, which included: 1) Recycling and preparing for re-use of municipal waste (including bio-waste) to be increased to 70 % by 2030; 2) Phasing out landfilling by 2025 for recyclable items (including plastics, paper, and bio-waste); 3) Measures aimed at reducing food waste generation by 30 % by 2025 and 4) Introduction of separate collection of bio-waste (EU Comission, 2016).

Chapter 3

Scientific background and methodology

This section gives a brief overview of the concept Biogenic Carbon Cycle and outlines the theoretical framework of the LCA study.

3.1 Biogenic carbon cycle

Carbon is ubiquitous in Earth's system and is in continuous and rapid circulation among carbon reservoirs on land, in the ocean, and in the atmosphere. Carbon resides in the atmosphere mostly as carbon dioxide (CO_2), but also as methane (CH_4), carbon monoxide (CO), and a variety of minor compounds. Through photosynthesis, plants take up carbon from the atmosphere to produce wood, sugars, carbohydrates, and other plant products that are, in turn, consumed by animals for food, shelter, and energy (IPCC, 2007c; King et al., 2007).

Figure 2 shows the biogenic carbon cycle, in which plants constantly remove carbon from the atmosphere through photosynthesis and emit carbon into the atmosphere through natural processes, including respiration and decay. On contrast, fossil fuels, such as coal, oil and natural gas, take millions of years to form and cannot replenish themselves in this same way in short time periods.

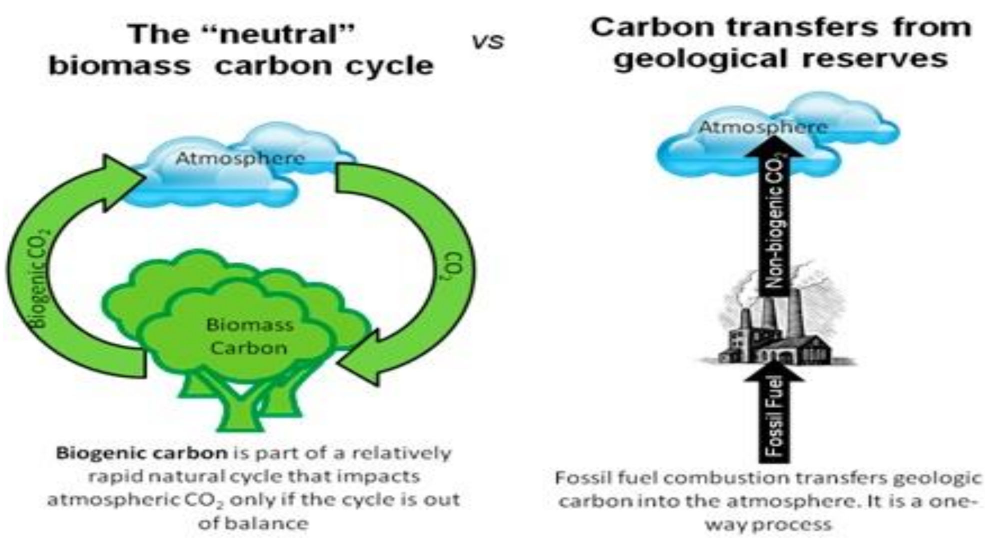

Figure 2 - Biogenic carbon cycle vs fossil carbon cycle (NCASI).

3.2 Theoretical framework

As environmental awareness increases, industries and businesses have started to assess how their activities affect the environment. The environmental performance of products and processes has become a key issue, which is why some companies are investigating ways to minimize their effects on the environment. Many companies have found it advantageous to explore ways of moving beyond compliance using pollution prevention strategies and environmental management systems to improve their environmental performance. An LCA, a concept that considers the entire life cycle of a product help companies to achieve this. A life cycle assessment is a cradle-to-grave approach for assessing industrial systems. Cradle-to-grave begins with the gathering of raw materials from the earth to create the product and ends at the point when all materials are returned to the earth. LCA evaluates all stages of a product's life from the perspective that they are interdependent, meaning that one operation leads to the next (United States Environmental Protection Agency, 2001).

The term "life cycle" refers to the major activities in the course of the product's life-span from its manufacture, use, maintenance, and final disposal; including the raw material acquisition required to manufacture the product. Figure 3 illustrates the possible life cycle stages that can be considered in an LCA and the typical inputs/outputs measured.

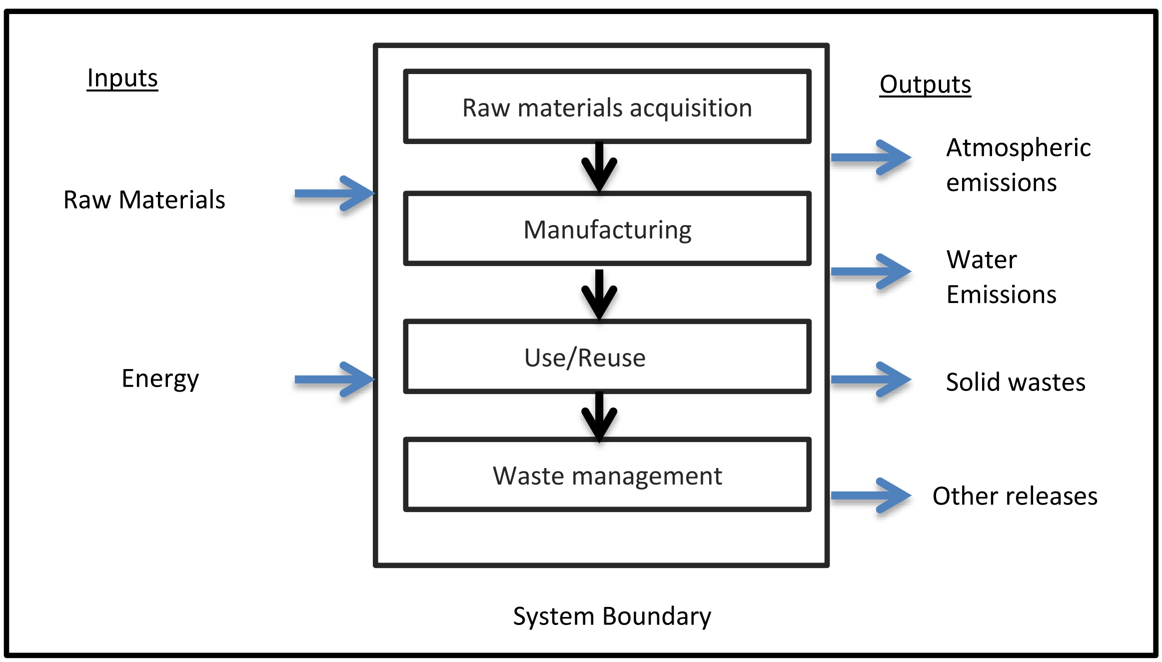

Figure 3 - Life cycle stages (Source: EPA, 1993).

The LCA process is a systematic, phased approach and consists of four components: goal definition and scoping, inventory analysis, impact assessment, and interpretation as illustrated I in Figure 4:

I. Goal definition and Scoping: The product to be studied and the purpose of the study are decided on. According to the ISO standard (ISO 14040 1997) the goal definition includes stating the intended application of the study and the reason for carrying it;

II. Inventory Analysis: To build a system model according to the requirements of the goal and scope definition. The system model is a flow model with certain types of system boundaries. The result is an "*incomplete"* mass and energy balance for the system;

III. Impact Assessment: Assess the human and ecological effects of energy, water and material usage and the environmental releases identified in the inventory analysis;

IV. Interpretation: Evaluate the results of the inventory analysis and impact assessment to select the preferred product, process or service with a clear understanding of the uncertainty and the assumptions used to generate results (Henrikke Baumann, 2012).

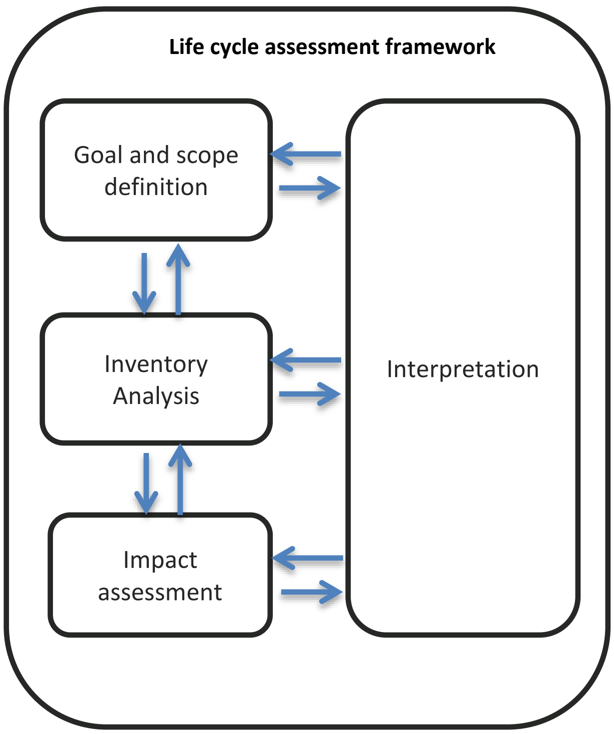

Figure 4 - LCA framework (Source: ISO, 1997).

3.2.1 Goal definition and scoping

LCA is a versatile tool for quantifying the overall, cradle-to-grave, environmental impacts. The first step involves the goal and scope definition, in which the initial choices which determine the working plan of the entire LCA are made. The goal of the study is formulated in terms of the exact question, target audience and intended application. The scope of the study is defined in terms of temporal, geographical and technological coverage, ant the level of sophistication of the study in relation to its goal. Finally, the products that are the object of the analysis are described in terms of function, functional unit and reference flows (Jeroen B.).

The studies boundaries are drawn to define where the analysis of the specific life cycle begins and where it ends, and identifies the activities included within the technical system. A flow diagram is often used to help guide this process.

Connected with the goal setting is the selection of a ‘functional’ unit, which sets it apart from other environmental assessment approaches. It describes appropriately the product or process being studied. For independent LCAs of single products, the definition of the functional unit may not be as critical. However, careful consideration of the functional unit becomes more important when the goal of the LCA is to compare two or more products, in which case the basis of comparison should be equivalent use, i.e., each system should be defined so that an equal amount of product or equivalent service is delivered to the consumer.

3.2.2 Life cycle inventory

The inventory analysis is the phase in which the product systems are defined. In this context, defining includes setting the system boundaries, designing the flow diagrams with the unit processes, collecting the data for each of these processes, performing allocation steps for multifunctional processes and completing the final calculations. Its main result is in an inventory table listing the quantified inputs from and outputs to the environment associated with the functional unit.

A life cycle inventory (LCI) is a process of quantifying energy and raw material requirements, atmospheric emissions, waterborne emissions, solid wastes, and other releases for the entire life cycle of a product, process, or activity (United States Environmental Protection Agency, 2001).

3.2.3 Life cycle impact assessment

The life cycle impact assessment (LCIA) phase of an LCA is the evaluation of environmental performance of the packaging systems examined. These indicators stand for environmental issues generally perceived be relevant and they are widely used in LCA practice across Europe. The most important categories for Corbion, Total-Corbion and relevant stakeholders are: 1) Global warming potential (GWP), 2) Renewable energy use (REU), 3) Non-renewable energy use (NREU), 4) Acidification potential (AP), 5) Eutrophication potential (EP), 6) Water Scarcity (WSI) and 7) Land use (LU).

i) Global warming potential

The choice of these categories of impact was related (in first instance) to the need to provide an evaluation of the impact of the examined production in relation to climate change that can be readily communicated to and understood by the consumer, by GWP. Global warming potential measures contribution to the “greenhouse effect”. The greenhouse effect refers to the ability of some atmospheric gases to retain heat that is radiating from the earth.

ii) Renewable and non-renewable energy consumption

The non-renewable energy source category was selected to provide a view of the impacts of the consumption, which is considered one of the most critical issues in the primary sector, because reveals how much energy is required to produce a product or service throughout its life cycle.

iii) Acidification potential

Acidification potential is regarded as a regional effect, and it’s caused by releases of protons in the terrestrial or aquatic ecosystems. Acidifying pollutants have a wide variety of impacts on soil, groundwater, surface waters, biological organisms, ecosystems and materials. The major acidifying pollutants are sulfur dioxide (SO_2), nitrogen oxides (NO_x) and nitrogen hydroxides (NH_x).

iv) Eutrophication potential

Eutrophication potential covers all potential impacts of excessively high environmental levels of macronutrients, the most important of which are nitrogen and phosphorus. Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems. In aquatic ecosystems increased biomass production may lead to a depressed oxygen levels, because of the additional consumption of oxygen in biomass decomposition. As emissions of degradable organic matter have a similar impact, such emissions are also treated under the impact category “eutrophication”.

v) Water scarcity

The water footprint (WF) has been developed within the water resources research community as a volumetric measure of freshwater appropriation. With the purpose of integrating the WF in life cycle assessment of products, LCA scholars have proposed to weight the original volumetric WF by the water scarcity in the catchment where the WF is located, thus obtaining a water-scarcity weighted WF that reflects the potential local environmental impact of water consumption (Hoekstra, 2016).

vi) Land use

The impact category land use reflects the damage to ecosystems due to the effects of occupation and transformation of land. Examples of land use are agricultural production, mineral extraction and human settlement. Occupation of land can be defined as the maintenance of an area in a particular state over a particular time period. Transformation is the conversion of land from one state to another state, e.g. from its original state to an altered state or from an altered state to another altered state. Often transformation is followed by occupation, or occupation takes place in an area that has previously been transformed.

Table 1**,** sums up the impact categories and the characterization models and each impact category indicator.

Table 1 - Impact category, characterization models and impact category indicator.

Impact Category	Characterization models	Impact category indicator
Cumulative energy demand (CED)	Cumulative energy demand v1.09	MJ
Renewable energy consumption (REU)	Cumulative energy demand v1.09	MJ
Non-renewable energy consumption (NREU)	Cumulative energy demand v1.09	MJ
Global Warming Potential (GWP)	IPCC 2013 GWP 100a	kg CO_2 eq
Acidification potential (AP)	CML IA (version 4.2)	kg SO_2 eq
Eutrophication potential (EP)	CML IA (version 4.2)	kg PO_4 eq
Water Scarcity (WSI)	(Boulay, Buller, Bayard, Deschênes, & Margni, 2011)	WSI (Water Scarcity Indicator)
Land occupation (LU) urban + agricultural	ReCiPe midpoint v1.12 (Goedkoop, Heijungs, Huijbregts, Schryver, Struijs, & van Zelm, 2009	m^2a

3.2.4 Life cycle interpretation

Life cycle interpretation is a systematic technique to identify, quantify, check, and evaluate information from the results of the LCI and the LCIA, and communicate them effectively. Life cycle interpretation is the last phase of the LCA process. The International Organization for Standardization has defined the following two objectives of the life cycle interpretation:

1. Analyze results, reach conclusions, explain limitations and provide recommendations based on the findings of the preceding phases of the LCA and to report the results of the life cycle interpretation in a transparent manner;
2. Provide a readily understandable, complete and consistent presentation of the results of an LCA study, in accordance with the goal and scope of the study (ISO 1998b).

3.2.5 Implementation

The LCA analysis was performed by using the SimaPro 8.4 software that implements several LCA methodologies. In particular, the Intergovernmental Panel on Climate Change (IPCC) is used for the assessment of global warming, which is a "mid-point" method. (Levenmore, 2008). The "end-point" method used was LCA Lactide 2016 V1.01, which includes the most important impact categories of the mid-point level, such as GWP, non-renewable and renewable energy, eutrophication, acidification, water scarcity and land use. The development of the life cycle inventories has been carried out by using, petroleum-based plastics, bio-waste and agricultural data included in the Ecoinvent v3.3 database. This database includes information on the production of energy, extraction and processing of raw materials, transportation and production processes (Frischknocht R, 2007).

3.2.6 Identification of key concepts

i) Multifunctionality and allocation

A multifunctionality problem occurs in an LCA when a process fulfils one or more functions for the investigated product's life cycle, and a different function (or functions) for other products (Ekvall, 2001). To solve a multifunctionality problem, ISO 14044:2006 (International Standard ISO 14044, 2006) suggests a three-step procedure. The distribution of impacts between a product and coproduct based on a specific criterion (i.e. allocation) should be avoided "wherever possible", either by dividing multifunctional processes into sub-processes or by expanding the product system to include the additional functions related to the by-products.

Weidema and Schmidt (Weidema, 2010) state that system expansion always respects the mass and energy conservation laws, while allocation nearly always fails to do so. According to those authors, since allocation breaks the original system into two or more artificial systems according to the allocation criterion adopted, the only balance observed is given by that criterion, i.e. when mass regulates allocation, only mass conservation is respected.

Allocation is the partitioning of the input and output flows (emissions/resource use) to the products of a unit process. The system of waste incineration is a multi-input/multi-output problem because various waste fractions enter the system and various outputs (the service waste treatment, energy, and recycling products) leave it. Therefore, an allocation is necessary.

Chapter 4

Life cycle assessment of PLA food packaging

This chapter begins by defining the goal and scope of the project, followed by a life cycle inventory analysis and ends up with results and their discussion.

4.1 Goal and scope definition

This section describes the goal and scope of the LCA. It includes the objectives, a description of the product function and product system.

4.1.1 Goal

The general goal of the project is to quantify the environmental footprint of different PLA food packaging products including the organic waste through an LCA, focusing on the end-of-life options. The study analyses different alternatives, such as incineration with energy recovery, composting, anaerobic digestion and landfill.

4.1.2 Objectives

This project compares packaging systems with specific designs, such as coffee cups, coffee capsules, tea bags, yogurt cups and cucumber wraps.

The specific objectives of this study are to:

I. Establish credible and transparent profiles of the potential life cycle environmental impacts of different systems;
II. Evaluate and compare environmental impacts of food packaging (including food waste) waste management systems including incineration, industrial composting, landfilling and anaerobic digestion;
III. Identify the contribution of the different life cycle stages to the overall impact.

4.1.3 Scope

i) Functional unit

A life cycle assessment relies on a functional unit as a reference to evaluate the components within a single system and or among multiple systems on a common basis. It is therefore critical that this parameter be clearly defined and measurable.

The functional unit (FU) – the quantitative reference used for all inventory calculations and impact evaluations – is:

" 1 kg of PLA food packaging including food waste from households"

ii) General description of the studied product systems

The use of PLA in packaging has largely increased over the last few years. Research is being performed by both academia and industry with collaborative works between the two to strengthen the green-packaging market to meet consumer demands for packaging derived from renewable resources (S.Obuchi, 2010).

This project assessed five types of food packaging products that are detailed on Table 2, having in common the PLA packaging, but each one has a specific moisture and food content.

Table 2 -Study systems.

System 1 **Coffee Cups**	**System 2** **Yogurt Cups**	**System 3** **Coffee Capsules**	**System 4** **Tea bags**	**System 5** **Cucumber Wrapping**
Materials				
Packaging: PLA				
Food Supply: No food supply	Food Supply: Yogurt	Food Supply: Coffee	Food Supply: Tea	Food Supply: Cucumber
End-of-life options: -Landfill -Incineration -Composting -Anaerobic Digestion				

iii) Reference flows

To fulfill the functional unit, different quantities and types of material are required for each system and these are known as reference flows. The inputs for the disposal stage are shown in Table 3. In the next sub-section, these reference flows will be explained.

Table 3 - Reference flows after consumer's use.

Material per FU	Coffee Cups	Yogurt Cups	Coffee Capsules	Tea bags	Cucumber Wrapping
PLA Packaging (kg/FU)	1	1	1	1	1
Dry organic matter (kg/FU)	0	0.1	3.4	5.7	1.4
Moisture content (kg/FU)	0	0.6	7.4	30.3	36.2
Total (kg/FU)	1	1.7	11.8	37	38.6

iv) Description of the system

This study assesses the life cycle of food packaging using single-serve products, from the extraction and processing of all raw materials to the end-of-life of the food matter and its packaging system. The five different systems were chosen on account of the fact that this project seeks to address a wide range of products with different moisture and organic contents. In the case of the coffee cup, it was modeled to represent the dry biodegradable packaging without food contamination.

The system boundaries identify the life cycle stages, processes, and flows considered in the LCA and should include all activities relevant to attaining the above-mentioned study objectives.

Figure 5, describes the total amount of waste and the contribution of the packaging, food waste and water to each system. The tea bag, for example, has a light pouch, which means that for 1 kg of PLA, there will be almost 6 kg of food matter. That is why there is a higher peak on the green line for the tea bag.

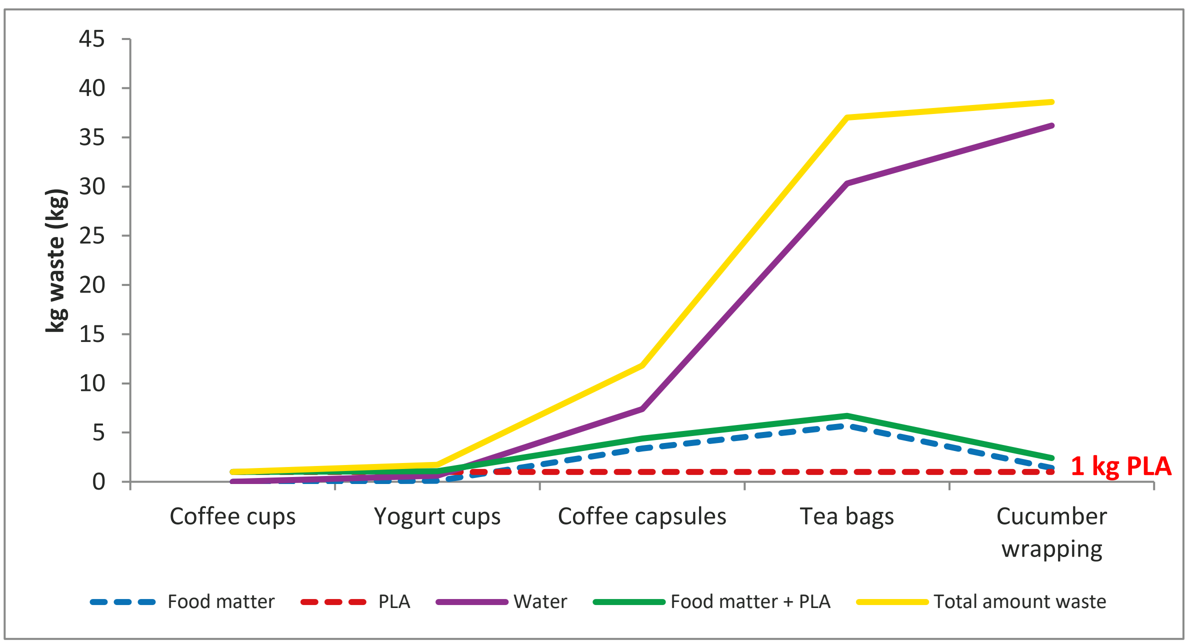

Figure 5 - Description of five different food packaging systems.

All the systems covered the full packaging life cycle, including primary material production, transformation into polymer resin, packaging manufacturing as well as end-of-life treatment. The waste management alternatives assessed in the systems are anaerobic digestion, industrial composting, incineration and landfill.

As illustrated in the next figures, the flow diagrams provide an outline of all the major unit processes to be modeled, including the following inter-relationships: 1) Food supply; 2) Materials and production; 3) Distribution; 4) Use and 5) End-of-life.

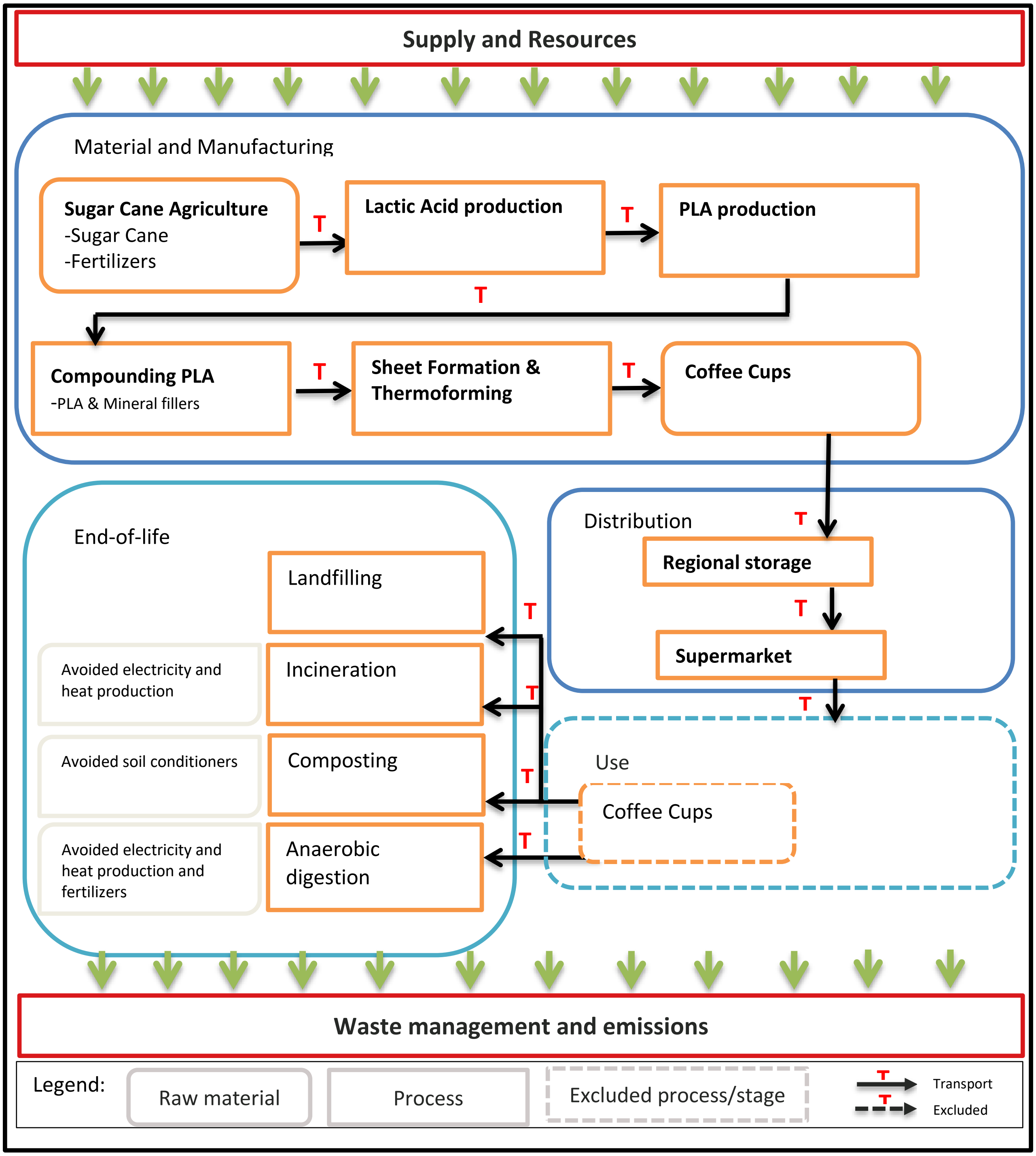

Figure 6 - Life cycle of coffee cups.

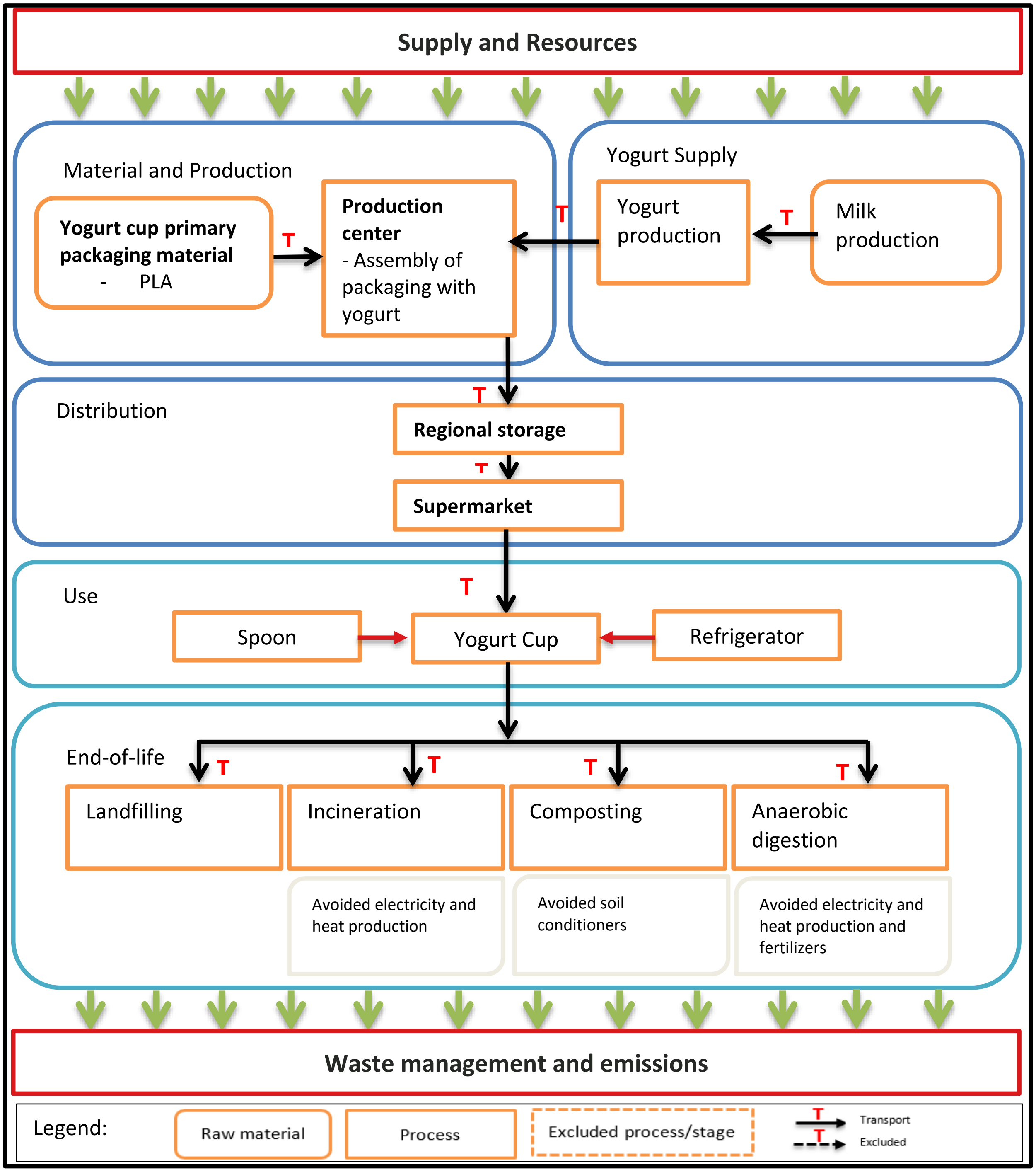

Figure 7 - Life cycle of yogurt cups.

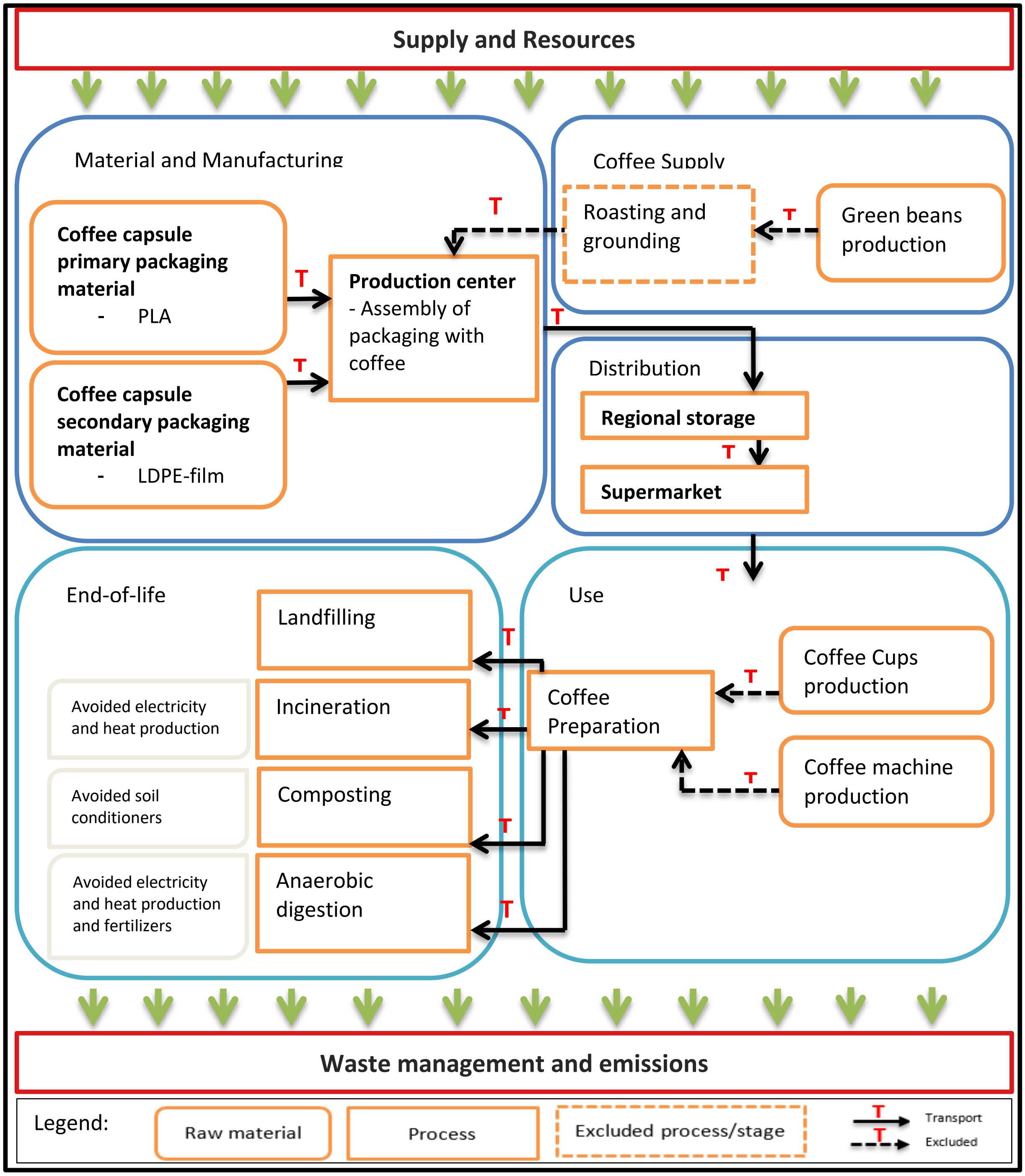

Figure 8 - Life cycle of coffee capsules.

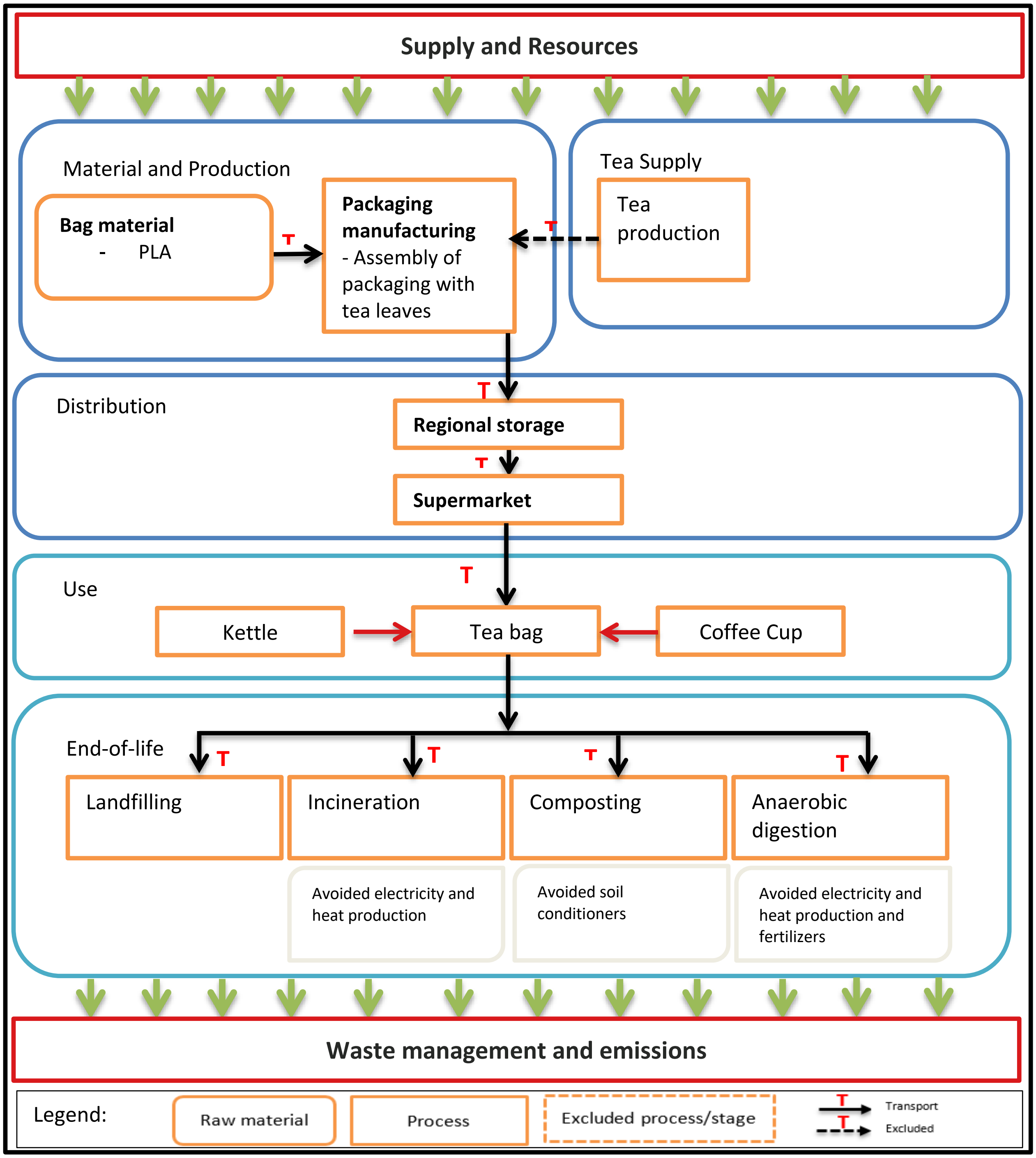

Figure 9 - Life cycle of tea bags.

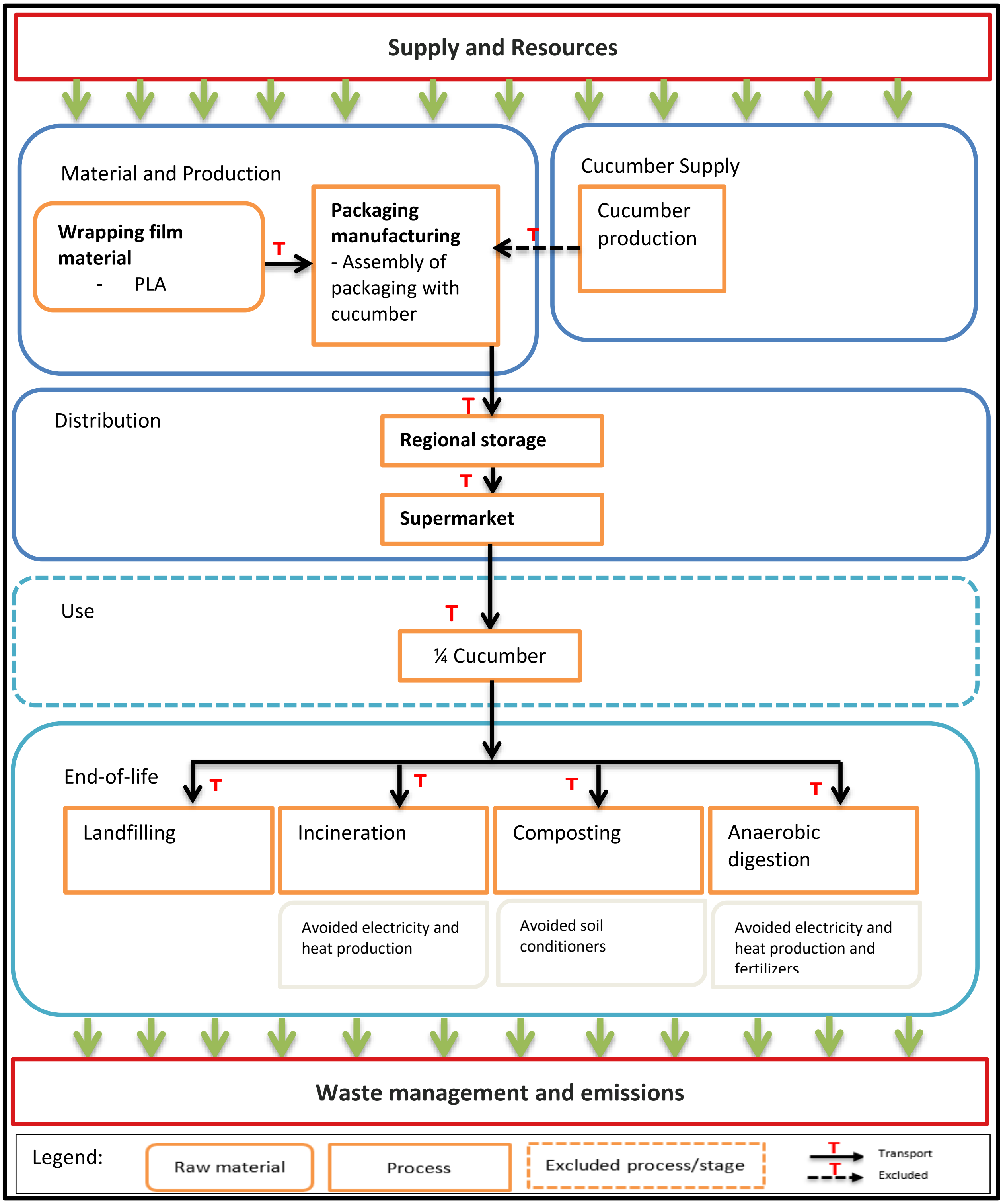

Figure 10 - Life cycle of cucumber wrapping.

v) Temporal and geographic boundaries

This LCA is representative of the waste treatment industry in Europe at the time the study is conducted (2017). It should be noted, however, that certain processes within the system boundaries may take place anywhere. Europe has been chosen as the region of disposal. These are "average" scenarios which could be representative for Europe but that could vary from country to country.

4.2 Life cycle inventory analysis

The quality of the LCA results depends on the quality of the data used in the evaluation. Every effort was made to rely on the most credible and representative information available in this study. An inventory analysis produces a list containing the quantities of pollutants released to the environment and the amount of energy and material consumed. The results can be segregated by life cycle stage, by media (air, water, land), by specific processes, or any combination thereof. Primary data was collected directly from Corbion on PLA production and from direct measurements and calculations from the primary materials and material weights.

Additional information describing the remaining aspects of life cycle was collected from a variety of scientific articles published by different journals and from Quantis LCA publications and from the Ecoinvent database, which is the main source for secondary LCA data.

4.2.1 Food supply

As mention before, there are five different systems with different specifications, but only four have food content. The dataset used for the four models were taken from the Ecoinvent database and its described in Table 4.

Table 4 - Food supply.

Type of food	Ecoinvent v3.3 model	Country
Yogurt	Yogurt, from cow milk {RoW}|production	Canada
Coffee	Coffee, green bean {IN}| coffee green bean production, robusta	India
Tea Leaves	Tea, dried {KE}| tea production, dried	Kenya
Cucumber	Cucumber {GLO}|production	Switzerland

4.2.2 Material and manufacturing

i) PLA feedstock

PLA is a thermoplastic material with rigidity and clarity similar to PS or poly(ethylene terephthalate) (PET). End uses of PLA are in rigid packaging, flexible film packaging, hot drink cups, apparel and staple fiber, injection moulded products and so on (Wim Groot, 2010). PLA can be produced by open ring polymerization directly from its basic building block lactic acid, which is derived by fermentation of sugars from carbohydrate sources such as corn, sugarcane or tapioca.

The PLA inventory data were developed and collected by Corbion from the core data for sugar cane milling, lactic acid and polymer production from their factory in Thailand, and was modeled according with the diagram in Figure 11.

Figure 11 - Process of PLA manufacture.

ii) Manufacturing

PLA package performance has been improved significantly by tailoring polymer processing, blending with other polymers, and adding compounds, such as nucleating agents, impact modifiers, and plasticizers, to meet the end needs (S.Obuchi, 2010). The manufacturing phase is different for each product and only includes the fabrication of the primary packaging, such as thermoforming of cups, injection moulding of capsules, etc. The energy demand is mainly met by electricity and it was given by the company in location X that converts polymer pellets into clam shells.

Processing of PLA has been extensively reviewed, and on 7.2 Appendix A2 – PLA Processing and LCA dataset, there is a more detailed explanation about each process and the life cycle inventory data for all the processes modeled. In this section, the main objectives are to explain which process is used for each container and to show the model inputs for this stage.

a. Coffee cups

PLA resin unfortunately has a limited heat resistance, and applications may be restricted. In order to increase the heat resistance blending PLA with polymers (additives) allows the manufacturing of drinking cups for hot drinks.

Thermoforming is a principal fabrication technique for rapidly creating large quantities of plastic products and it's used by Corbion to produce coffee cups, following the steps described in Figure 12. A sheet of extruded plastic is fed, usually on a roll or form and extruder, into a heated chamber where the plastic is softened. The sheet is then clamped over a negative mold while in a softened state and then cooled. A punch loosens the plastic forms and eliminates sheet webbing that is recycled back into the process. The yield of the thermoforming step is 55 %, and 44,9 % is recycled back into the process. The final coffee cup weights 3.23 g and has 200 ml of capacity.

Figure 12 - Coffee cup manufacturing process.

b. Yogurt cups

The yogurt cups are defined as the product that appears on retailer shelves. The primary packaging, consists of a PLA cup and lid. The containers are sold in a four-pack configuration, encased by a paperboard wrap. Figure 13, shows that thermoforming is used as well to manufacture the yogurt cups, but instead of using a high heat compounded PLA, a mix between a masterbatch and PLA is used as input material. A yogurt cup weights 5 g and has capacity for 125 g of yogurt. The production of the masterbatch is explained in 7.2 Appendix A2 – PLA Processing and LCA dataset, subsection 7.2.1 Compounding.

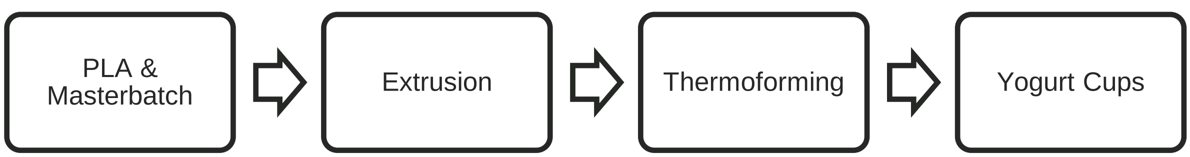

Figure 13 – Yogurt cup manufacturing process.

c. Coffee capsules

Coffee capsules were defined as a Nestle Dolce Gusto capsules as appears on retailer shelves. The primary packaging consists of a PLA capsule and the secondary packaging consists of a paper box, that contains 10 capsules. Injection molding in one of the primary fabrication techniques for rapidly creating large quantities of plastic articles such as disposable food containers. This plastic fabrication method is distinguished from others by using injection and a hollow mold form to shape the final container. In this case, as seen in Figure 14, before the injection moulding process, PLA is blended with mineral fillers to achieve certain properties. The compounding step is the same as the compounding step for the coffee cup.

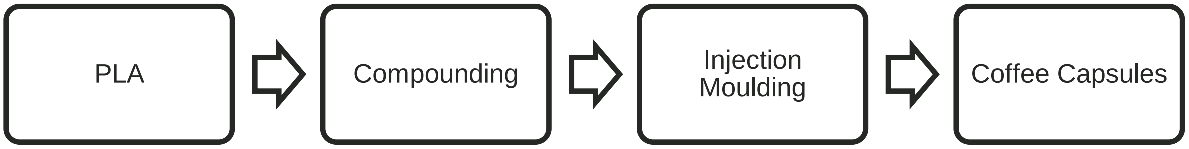

Figure 14 - Coffee capsule manufacturing process.

d. Tea bags

The tea bags are a non-woven manufacturing system that combines the spinning process with the sheet formation process by placing the bonding device in the same continuous line. This is called a Spund Bond Process (Figure 15) (Hosun Lim, 2010). Due to a lack of data, the model for sheet extrusion was used since the process is very similar. For this product, there is no need for a compounding step, since the fiber production gives tea bags a resistance to hot temperatures.

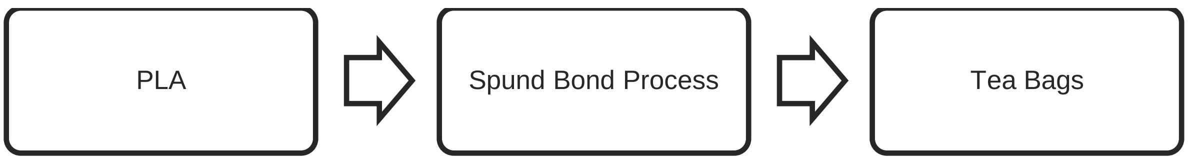

Figure 15 - Tea bags manufacturing process.

e. Cucumber wrapping

Blown film extrusion is a well-known production technology (Figure 16) to make thin films. The low melt strength of PLA requires the use of additives, like melt strength enhancers to be able to process neat PLA. Often PLA is part of a compound to make biodegradable film for use in objects such as shopping bags or mulch film (Corbion). For example, for food wrapping films, it is recommended an organic additive, lubricant, impact modifier or anti-static incorporated.

Figure 16 - Cucumber wrapping film manufacturing process.

iii) Packaging distribution

Packaging distribution includes the transportation of the PLA packaging input materials (e.g. PLA resin) between material producers and the respective container component manufacturers. The burdens of fuel production and fuel use for truck and ship transport were modelled and the assumptions for packaging distribution are displayed in Table 5.

Table 5 - Assumptions for packaging distribution.

Specific packaging distribution	Route	Transportation and kilometrage
PLA transportation from Corbion in Thailand to location X	From Corbion in Thailand to Thailand port	60 km by truck
	From Thailand port to X port	3412 km by ship
	From X port to a company in location X	60 km by truck
PLA scrap transportation to Incineration plant	From Corbion to Incineration plant in Thailand	30 km by truck
Transportation to Extrusion facilities	From one company to another company in location X	20 km by truck
PLA scrap transportation to Incineration plant	From certain company to incineration plant in location X	30 by truck
Transportation of PLA container to Europe	From location X company to X port	80 km by truck
	From X port to Rotterdam port	18781 km by ship
Transportation of PLA container to assembly center	From Rotterdam port to Obe	800 km by truck

iv) Production center

The production center where coffee capsules, yogurt cups and tea bags are filled is considered to be the same where the cucumber is wrapped. The production center is located in Obe, Switzerland. Even though, the transportation for the production center is considered, it's not considered in the assembly process itself.

4.2.3 Distribution

The distribution for all the food packaging systems is the same, except for yogurt cups, because they need refrigerate transportation. Environmental burdens associated with activities in the distributor/retailer phase were included in the system model, and the assumptions are exhibited in Table 6. All food packaging products are assumed to be distributed by supermarkets.

Table 6 - Assumptions for distribution. All assumptions are based on (Quantis, 2011).

Specific transportation	Route	Transportation and kilometrage

From Obe storage to consumer's house	From Obe storage to regional storage	500 km by truck
	From regional storage to supermarket	20 km by truck
	From supermarket to consumer's house	10 km by car

4.2.4 Use stage

The consumption phase represents activities conducted by the consumer after purchasing the products. For coffee cups and the cucumber wrapping, the environmental burdens of this stage were excluded.

For coffee capsules, the use stage includes the machine and coffee cup. Even though the coffee capsules are modeled as Dolce Gusto capsules only the data concerning the Nespresso machine (composition and consumptions) was available and therefore used in this study. The Nespresso capsule production data was obtained through a Quantis LCA study (Quantis, 2011) as shown in Table 7.

Table 7- Use stage main data and assumptions. All data on the machine production, transport and use are based on (Quantis, 2011).

Coffee capsules		
Use stage		
Machine Production	The machine considered is the Essenza model. The production is based on the material composition of the machine	
	Material	g/machine
	Aluminum	278
	Copper	295
	Steel	394
	ABS	1550
	Rubber	22
	Zinc	194
Machine Transport	The transport from factory to consumer is: 800 km by truck, 7400 km by ship, 20 km by train and 20km by van	
Machine use	Electricity consumption per capsule	25.4 wh/capsule
	Water per capsule	60 g/capsule
Cup Production	It is assumed that the PLA coffee cups are used to drink the coffee	
Espresso	Water per used capsule	20 g/used capsule
	Water per espresso	40 g/espresso

For yogurt cups, two activities are included: household refrigeration of the yogurt and the use of spoons by the consumer to eat the yogurt. Washing the spoons is not included in the model. The amount of energy used to keep yogurt chilled will vary depending on the size of the yogurt container, the length of time it is refrigerated and the energy efficiency of the refrigerator. A survey of currently available refrigerators showed that the most efficient, widely available models use only 0.054 $kWh/ft^3/day$ (Gregory A. Keoleian, 2004). After collecting all the data needed and assuming 4 days of refrigeration, which is based on the consumer eating one yogurt per day and purchasing a four-pack once per week, the energy burdens are calculated.

For tea bags, the use stage includes the kettle used to warm up the water and the production of coffee cups, to drink the hot beverage. In order to prepare a cup of tea, 250 ml of water is needed. After 4 minutes of infusion, the tea bag is removed from the cup, and approximately 10 g of waster remain in the leaves. To boil the water with a kettle 49.5 MJ of electricity per kg tea is needed (Jefferies, 2012).

For cucumber wrapping, its assumed that the wrapping film is peeled like a banana, and the consumer throws a quarter of the cucumber with the entire packaging into the waste bin. No refrigeration is needed.

4.2.5 End-of-life

End-of-life process modelling accounted for the environmental burdens that stemmed from waste management of used food packaging, including the transportation from the consumer to the disposal location. There is no separation of the food matter from the packaging, the entire product with food contamination is transported to waste management to be incinerated, landfilled, composted or anaerobically digested.

4.2.5.1 Incineration

The primary objective of municipal solid waste incineration (MSWI) is to treat waste by reducing the solid waste mass and allowing energy recovery. For this reason, the original designation of “incinerator” was dropped, and today it is known as energy from waste (or waste to energy, WtE) (Margallo M, 2014). Nevertheless, regarding operational conditions, the high combustion temperature makes necessary the employment of very specific materials, increasing the installation and maintenance costs. Likewise, additional fuel is required when waste does not reach the required low heating value (LHV), for example when it has high water content (Rodríguez JJ and Irabien, 2013).

Incineration is a direct combustion technology in which the feedstock is directly transformed into energy, which can be used for district heating and district electricity production. Biogenic carbon dioxide and water vapor are the major compounds emitted through the incineration of bio-waste. Additionally, the incombustible ash usually constitutes a concentrated inorganic waste that must be disposed properly. On chapter 7.3 Appendix A3 – Waste treatment options, subsection 7.3.1 Incineration, is displayed a more extensive explanation about incineration process.

i) Process model of waste incineration

The incineration model is based on Ecoinvent v3.3 process of MSWI for PET in Switzerland. The model includes combustion with a grate incinerator, an electrostatic precipitator, a wet flue gas scrubber system, electricity and heat production from waste heat recovery and landfilling of residues as shown in Figure 17.

Some changes were made to the model, in terms of:

1) Air emissions
    a. Oxygen input;
2) Energy replacing;
3) Ashes disposal.

These changes are described in the next sections.

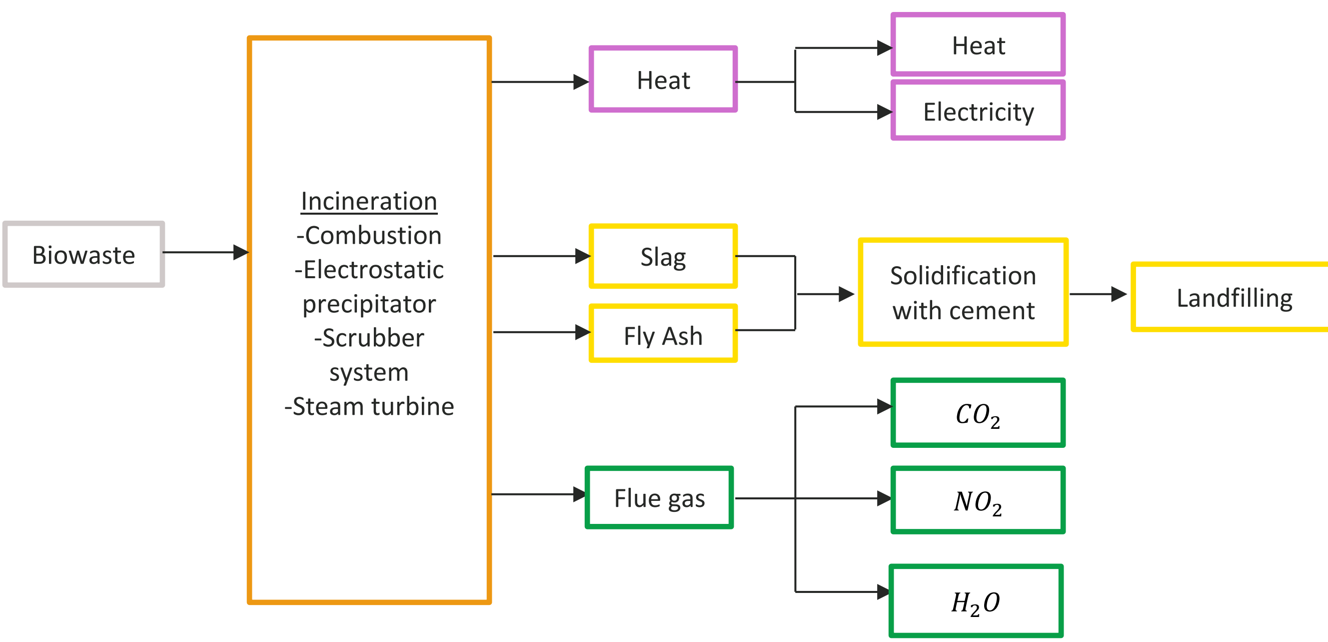

Figure 17- Process model of waste incineration and technologies.

ii) Ancillary materials

Several ancillary materials are used in the model for the flue gas scrubber system and the waste water treatment, as shown in Table 8. No changes were made to the PET model (Ecoinvent v3.3) regarding the input of these materials.

Table 8 - Ancillary materials and respective functions (Doka G., 2003).

Ancillary materials	Function
Sodium Hydroxide (NaOH)	An aqueous solution of NaOH is used in the alkaline stage of the wet scrubber to transfer SO_2 to the scrubber liquid.
Quicklime	The scrubber liquids are transferred to a waste water treatment facility. Acids present in the scrubber liquids must be neutralized. An 95% aqueous solution of burnt lime (CaO) and water.
Hydrochloric acid	Small amounts of hydrochloric acid are used in the wastewater treatment for pH control.
Iron Chloride	Used to precipitate heavy metals during wastewater treatment. Only small amounts are used.
Polyelectrolyte solution	Aqueous solution of inorganic salts is used for flocculation in the wastewater treatment.
Ammonia	Used for reduction of NOx.
Cement	The boiler ash and precipitator ash are solidified with cement before being landfilled in a residual material landfill.
Selective Catalytic reduction (SCR) catalyst material	Reduce NOx levels in the flue gas.

iii) Air emissions

Emissions were calculated based on waste composition. To estimate the output flows from the incinerator it is necessary to assign chemical substances to each air emission. And these are shown in Table A- 9 present on chapter 7.4 Appendix A4 – Incineration dataset.

a) Main assumptions

A fair assumption is that the hydrogen in the waste stream is converted to water (H_2O), nitrogen to nitrogen dioxide (NO_2) and carbon to CO_2. This assumption primarily assumes that combustion is complete, which is reasonable given the fact that the furnace operates with an excess of oxygen supply, and the amount of CO produced is very small. Even though, the amount of CO was not calculated, its burden was included because for PET model included an input for this air emission, and it wasn't removed. This gives the following combustion reactions for each product:

PLA	$C_6H_8O_4 + 6\,O_2 \rightarrow\ 6CO_2 + 4\,H_2O$	(1)
Yogurt	$C_{0.8}H_{3.3}O_{1.3}N_{0.04}\ + 1\,O_2\ \rightarrow\ 0.8\,CO_2 + 1.65\,H_2O + 0.04\,NO_2$	(2)
Coffee	$C_{4.4}H_{9.5}O_{3.6}N_{0.1}\ + 5\,O_2 \rightarrow\ 4.4\,CO_2 + 4.75\,H_2O +\ 0.1\,NO_2$	(3)
Tea	$C_{2.9}H_{5.8}O_{2.8}N_{0.14}\ + 3.1\,O_2\ \rightarrow\ 2.9\,CO_2 + 2.9\,H_2O + 0.14\,NO_2$	(4)
Cucumber	$C_{0.5}H_{2.9}O_{1.4}N_{0.02} + 0.5\,O_2\ \rightarrow 0.5\,CO_2 + 1.45\,H_2O +\ 0.02\,NO_2$	(5)

iv) Energy recovery

Besides the disposal of waste, modern MSWIs provide the function of energy recovery. The average waste incinerated in Swiss MSWI plants contains approximately 12 GJ energy per tonne of municipal waste (Doka G., 2003).

The energy released as heat through flue gases in the incineration process can be used for electricity and heat generation. Conventional energy recovery involves passing these hot flue gases through a boiler. Water circulating through these tubes is turned to steam, which can be heated further, to increase its temperature and pressure to make electricity generation more efficient (McDougall F., 2001). The principal use of the energy is the production and supply to district-heating/electricity network. In this study, we consider that the energy produced from waste substitutes: 1) Heat from natural gas and 2) Electricity from European electricity mix (medium voltage).

Energy recovery is a key issue that strongly depends on geographical context. The colder climate together with highly developed district heating networks in northern European countries lead to a greater demand for heat from waste incinerations. In southern Europe, the main focus is on electricity production, due to the presence of smaller district heating networks and lower heat requirements. The impact of these efficiencies will be addressed in the sensitivity analysis.

As mention, the incineration process uses the energy contained in the waste to produce useful heat and electricity. On average, the gross efficiencies for Combined Heat and Power (CHP) plants are 65 % and 25 % for heat and electricity recovery. For internal consumption of electricity and heat, the average is 0.13 kwh/kg and 0.49 MJ/kg respectively (Ecoinvent 3.3, 2016).

As a general rule, incineration should only be considered if the incoming waste stream has an average calorific value of at least 7 MJ/kg. If the feedstock has a lower calorific value, a supplementary fuel input needs to be used for the combustion to occur (Council W. E., 2016). On the next section, the energy requirements of each system were accessed to confirm if the waste streams are suitable or not for combustion.

a. Thermal energy in the systems considered

The composition of the food waste was calculated using data from the database of The National Food Institute in Denmark (Institute, 2017). Using atomic weights of the respective elements and the equations on 7.1 Appendix A1 – Heat of Combustion Calculations, the calorific value of food matter and PLA were calculated. Table 9 shows the chemical composition, moisture content and energy content of food matter from the four food types and Table 10 shows those parameters for PLA.

Table 9 – Composition and calorific values of food.

	Yogurt	Coffee	Tea	Cucumber
C (wt.% dry)	26.8	43.7	39.7	19.2
H (wt.% dry)	9.7	7.8	6.7	8.8
O (wt. % dry)	61.8	47.3	51.9	68.1
N (wt. % dry)	1.6	1.5	2.2	1.0
Moisture (wt.%)	87.8	5.5	9.3	96.4
HHV (MJ/kg food)	14.48	19.38	15.98	10.02
LHV_{dry} (MJ/kg food)	12.36	17.69	14.52	8.10
LHV_{wet} (MJ/kg food)	-0.64	16.58	12.94	-2.06

Table 10 - Composition and calorific values of PLA.

	PLA
C (wt.% dry)	50
H (wt.% dry)	5.6
O (wt. % dry)	44.4
Moisture (wt.%)	0
HHV (MJ/kg food)	19.19
LHV_{dry} (MJ/kg food)	17.97
LHV_{wet} (MJ/kg food)	17.76

Combining the wet LHV of PLA, 17.76 MJ/kg value with the heating values of the organic matter presented on Table 9, the calorific values of the packaging systems after use can be calculated, and are presented on Table 11. On 7.1 Appendix A1 – Heat of Combustion Calculations those calculations are displayed. For coffee capsules and tea bags, the additional water introduced in the system during the use phase was, and has a Vaporization Heat of -2.26 MJ/kg (Wikimedia Foundation Inc., 2017). For the remaining systems, the water content was included in the composition of the food matter, as explained on Table 9.

Table 11 - Calorific values of PLA food packaging including food waste, as disposed (i.e. Including changes in composition due to the use phase).

	Coffee Cups	Yogurt Cups	Coffee Capsules	Tea Bags	Cucumber Wrapping
Moisture (wt.%)	0%	37%	63%	80%	94%
LHV_{wet} (MJ/kg waste)	17.76	10.06	5.2	0.86	-1.55
LHV_{wet} (MJ/FU)	17.76	17.31	61.2	31.64	-59.68

The calculations on Table 11 for the calorific values per kg of waste, showed that the coffee capsule, the tea bag and the cucumber wrapping, have a lower value compared with the requirements of the process (which is 7 MJ/kg). And the cucumber has a negative value which means that an additional energy input has to be included. The extra energy input used in the cucumber model was natural gas.

b. Energy balance

The energy balance of a system is done in accordance with the internal electricity and natural gas consumptions, and the energy and heat recovery by the combustion. And for two systems, an extra energy input, also contributes to the overall energy balance. The incinerator has a consumption of electricity and natural gas, to burn the bio-waste. That combustion leads to a heat release that is converted into electricity and heat, with an overall efficiency of 90 %. The products with higher moisture contents don't have energy recovery only energy burdens, because of the extra input of energy. Subtracting the energy consumption and the extra inputs (when needed) and adding the energy recovery, the energy balance is complete. There are energy losses, but without specific data given by incineration companies, it is difficult to include in the energy balance.

v) Disposal of solid combustion residues

It is assumed that the solid process residues (slag and fly ash) are landfilled. The amount of material landfilled depends on the waste composition of the packaging systems. It is assumed that food waste itself is completely burned because it is mainly composed of organic matter or water. The packaging waste has some inorganic compounds in its matrix, that cannot be combusted and will end up in slag and fly ashes. Only coffee cups and coffee capsules have mineral fillers blended with PLA, that cannot be burned and will become solid residues. Before these residues are sent to landfills, they are mixed with cement and solidified, using the same amount that was used in the original model.

4.2.5.2 Industrial Composting

Industrial composting is a natural process by which organic material is decomposed into a soil-like substance, called compost which is used as soil conditioner. Decomposition is mainly performed by microorganisms (mesophilic and thermophilic), including bacteria, fungi, and actinomycetes. These microorganisms use organic matter as their food source, generate CO_2, and produce compost (organic matter) as an end product. This natural process requires availability of carbon, nitrogen, water, and oxygen (Gaurav Kale, 2007).

Industrial composting has two mainly factors affecting the rate of biodegradation: 1) Temperature and 2) Moisture content. A moisture content of 50-60 % is generally considered optimum for composting. Microbially induced decomposition occurs most rapidly in the thin liquid films found on the surfaces of the organic particles. Whereas too little moisture (<30 %) inhibits bacterial activity, too much moisture (>65 %) results in slow decomposition, odor production in anaerobic pockets, and nutrient leaching. PLA is biodegradable under industrial composting conditions, in which ultimate PLA degradation results from the action of naturally occurring microorganisms under thermophilic conditions, which means at a high temperature (58ºC) (T. Kijchavengkul, 2008). A study performed by *Cargill Dow LLC* showed that the hydrolysis rate of PLA increased dramatically above the glass transition temperature.

i) Process model of industrial composting

The composition and characteristics of the feedstock are very important for both designing and operating the composting plant and for the final quality of the compost (Haug, 1993). When the feedstock contains food waste and packaging waste, and the most widely used technology for food waste is an Enclosed Technology according to (Boldrin A., 2009). In enclosed systems, the composting process takes place in an enclosed building, which allows the possibility of controlling the exhaust gases and a common treatment is filtration of the air in bio filters. The diagram in Figure 18 explains how the model was built.

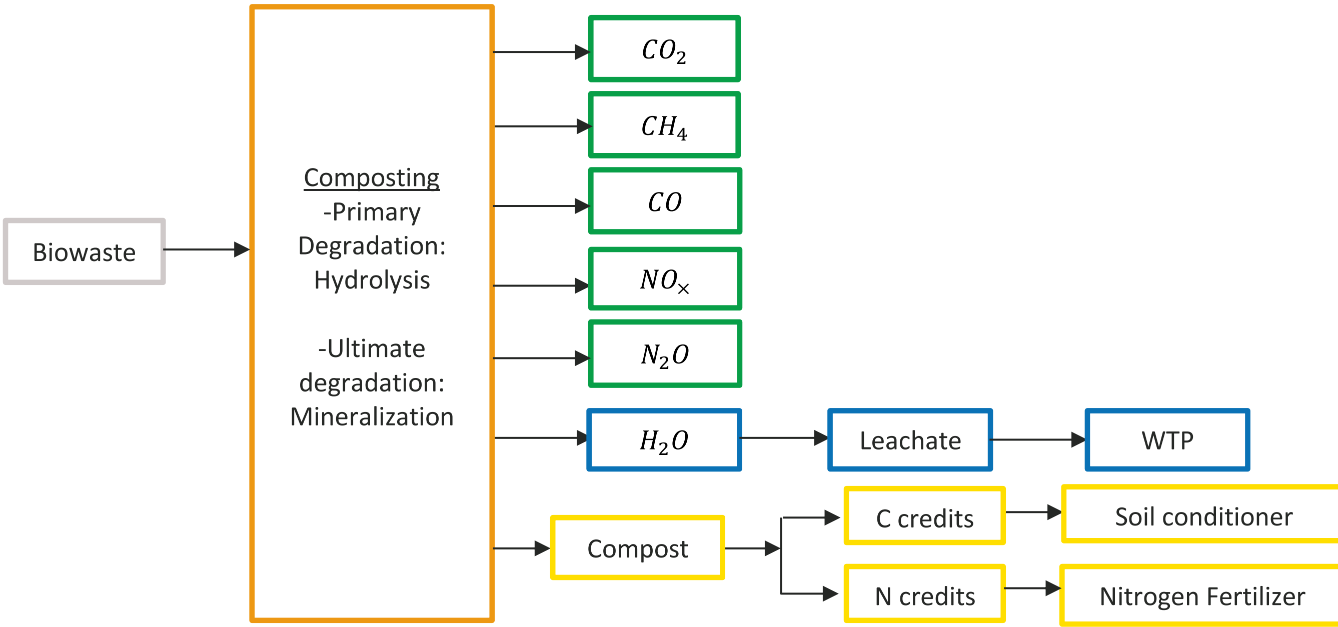

Figure 18 - Process model of composting.

ii) Gaseous emissions

The main gaseous emissions from composting are CO_2 biogenic, CH_4 and dinitrogen oxide N_2O. The release of these gases depends on the technology, the waste input and above all the management of the process. Enclosed technologies are equipped with odor removal devices. A common and inexpensive treatment is filtration of exhausts in bio filters (Boldrin A., 2009). The efficiencies of bio filters depend on air flow, load, residence time, materials and design (Powelson, 2006) (Chung, 2007).

The level of biodegradation achieved during composting is also very much determined by the particle size of the product. The thicker a material, the smaller the level of biodegradation reached. After conducting a literature survey on bio-based materials, it was selected an average value for biodegradation of PLA, of 95 wt.% carbon degradation. According with Table A- 10, on 7.5 Appendix A5 – Composting dataset, 95 wt.%, 4 wt.% and 1 wt.% of the degraded carbon emitted, turns into three direct emissions, CO_2, CH_4 and CO, respectively.

All systems except the coffee cup meet C/N ratio (Table 12) due to nitrogen in food waste. For simplification, the coffee cup model does not include the required nitrogen input and the respective N_2O emission. The nitrogen degradation, of food matter is 70 wt.%, in which, 99.2 wt.% of the degraded nitrogen will turn into NO_x and only 0.8 wt.% into N_2O. The main GHGs that contribute to global warming are CH_4 and N_2O, and the release of these compounds needs to be controlled. In order to control those emissions, biofilters are installed with different efficiencies, for each gas. For methane, the efficiency can be between 47-100% and for N_2O, 90% (Boldrin A., 2009).

Table 12 - C/N mass ratio of feedstock.

Systems	C/N mass ratio
Yogurt Cups	20
Coffee Capsules	44
Tea bags	21
Cucumber wrapping	25

iii) Carbon and nitrogen credits of compost

According to Table A- 10, in section 7.5 Appendix A5 – Composting dataset, part of the carbon remains stored in the form of compost. Two specific benefits are considered in this analysis: I) carbon contained in compost is used as soil conditioner replacement and II) nitrogen contained in compost is used as an organic fertilizer replacement. (B.G Hermann, 2011) used a factor of 79 % to replace a synthetic fertilizer, which means that 1 kg of compost can replace 0.79 kg of peat.

This compost degrades further over time, on the field, but at a smaller rate than during the biological treatment. In order to correctly quantify the credits assigned to compost, those air emissions are considered and 40 wt.% of organic carbon present in the compost becomes biogenic carbon dioxide.

iv) Leachate

After, the primary degradation of the polymer, the short polymer chains suffer the ultimate degradation called mineralization, in which the feedstock breaks down into water. A moisture content of 50-60 % is generally considered optimum for composting. Whereas too little moisture (<30 %) inhibits bacterial activity, too much moisture (>65 %) results in slow decomposition, odour production in anaerobic pockets, and nutrient leaching.

4.2.5.3 Anaerobic Digestion

Anaerobic digestion (AD) is a waste management process for organic waste materials producing biogas and a stabilized residue, called digestate, that can be used on agricultural land (MØller, 2009). AD contributes to greenhouse emissions, mainly from fugitive emissions released from bioreactors, the combustion of biogas, and emissions from the digestate when applied to soil. This process has a large potential for global warming savings through substitution of fossil fuel by biogas and from carbon storage in soil and nitrogen fertilizer. Anaerobic digester systems have been used for decades at municipal wastewater facilities, and more recently, have been used to process industrial and agricultural wastes. These systems are designed to optimize the growth of the methane-forming (methanogenic) bacteria that generate CH_4. Typically, using organic wastes as the major input, the systems produce biogas that contains 55 % to 70 % CH_4 and 30 % to 45 % CO_2 (Burke, 2001).

The biodegradation of PLA, requires a lengthy time for complete mineralization toCO_2 or CH_4 because the microorganisms need to adapt and induce metabolic activity for polymer degradation. This process is particularly suited for PLA food packaging waste, because usually it has a high energy potential due to its high amount of kitchen waste or food scraps with high moisture contents and compostable plastics. (Bioplastics, European Bioplastics, 2017).

So far, little information on anaerobic biodegradation of bioplastics is known, and further research is welcome to assess the potential biogas (energy) production due to bioplastics.

i) Process model of anaerobic digestion

The AD of bio-waste was modelled by assuming that PLA is biologically degraded under thermophilic conditions in an anaerobic manner with a biodegradation degree equal to 60 wt.% (Jae Choon Lee, 2016) and food is biologically degraded in an anaerobic manner with a biodegradation degree equal to 70 wt.%. The biogenic gas produced is recovered with an efficiency of 95 %.

The C/N ratio is an important factor for production of biogas from food waste. The presence of nitrogen is important to build up bacterial communities which are essential for fermentation. A C/N mass ratio of 20-30 is optimum, if this ratio is high it will affect microorganisms. As shown in Table 12 food packaging waste has an optima C/N ratio.

The diagram of Figure 19 explains how the model was built, specially the gaseous emissions, the energy recovery and the carbon and nitrogen credits of compost. The presence of water inside the digester is crucial to hydrolyze the bio-waste, but a significant amount of leachate is produced and a small part needs to be removed and treated in a water treatment plant. Compost credits were modelled in AD as they were modelled in industrial composting.

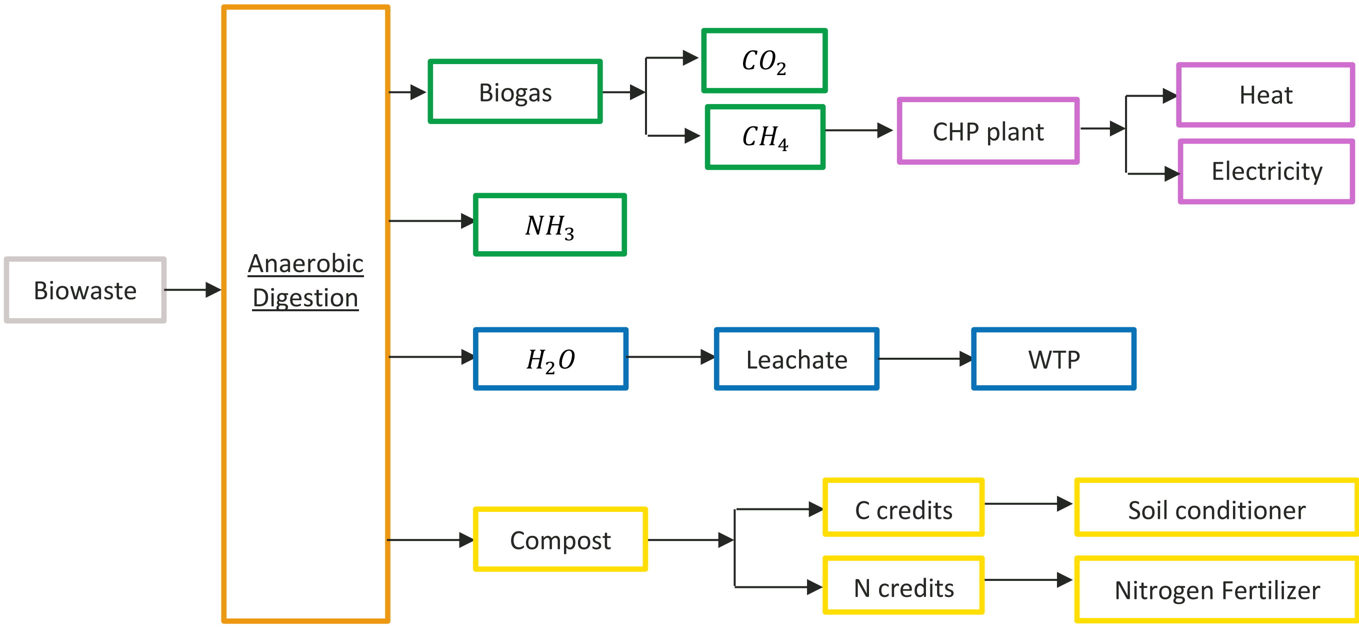

Figure 19 - Process model of anaerobic digestion.

ii) Biogas production and ammonia emissions

Biogas production from organic substrates involves an internal redox reaction that converts organic molecules to methane, carbon dioxide and ammonia (NH_3), the proportion of these gases being dictated by the composition and biodegradability of the substrates.

The production of biogas can be predicted using Buswell's equation, which is a stoichiometric equation based on the atomic composition of the feedstock, taking into account the elements, carbon (C), hydrogen (H), oxygen (O) an nitrogen (N). The equation is:

$$C_cH_hO_oN_n + \frac{1}{4}(4c - h - 2o + 3n)H_2O \rightarrow \frac{1}{8}(4c - h + 2o + 3n)CO_2 + \frac{1}{8}(4c + h - 2o - 3n)CH_4 + nNH_3 \quad (5)$$

Applying this equation to each system, it allows the calculation of the value of biogas produced, which is displayed on Table 13:

PLA	$C_6H_8O_4 + water \rightarrow 3CO_2 + 3CH_4$	(6)
Yogurt	$C_{0.8}H_{3.3}O_{1.3}N_{0.04} + water \rightarrow 0.32\,CO_2 + 0.45\,CH_4 + 0.04\,NH_3$	(7)
Coffee	$C_{4.4}H_{9.5}O_{3.6}N_{0.1} + water \rightarrow 1.96\,CO_2 + 2.44\,CH_4 + 0.13\,NH_3$	(8)
Tea	$C_{2.9}H_{5.8}O_{2.8}N_{0.14} + water \rightarrow 1.5\,CO_2 + 1.4\,CH_4 + 0.14\,NH_3$	(9)
Cucumber	$C_{0.5}H_{2.9}O_{1.4}N_{0.02} + water \rightarrow 0.27CO_2 + 0.27\,CH_4 + 0.02\,NH_3$	(10)

Table 13- Biogas composition.

Biogas Composition	$\%mol(CO_2)$	$\%mol\ (CH_4)$
PLA	50%	50%
Yogurt	41%	59%
Coffee	45%	55%
Tea	51%	49%
Cucumber	50%	50%

According to Table 13, the organic wastes produced biogas in a range that is expected and reported in (Burke, 2001). Biogas formed in the anaerobic digester bubbles to the surface and may accumulate in a collection system, typically plastic piping, which directs the biogas to gas handling subsystems. Prior to this, biogas will be processed to remove moisture and CO_2, the main contaminants in dairy biogas, because only methane has energy value. Recovered biogas is combusted in an engine to generate electricity or flared.

In most cases, biogas is used as fuel for combustion engines, which convert it to mechanical energy, powering an electric generator to produce electricity. Appropriate combustion engine need to be chosen according with final purpose of the energy. On this project, a CHP plant was used for electricity and heat production, in incineration, and will be used in AD as well.

4.2.5.4 Landfill

Studies have proven that there is little risk posed by biodegradation of biodegradable bio-plastics in landfills (Kim & Townsend, 2012). Most bio-plastics remain inert in landfills, where they potentially sequester carbon. Unfortunately, landfilling remains a widely-applied method of waste treatment in Europe, with large variations between member states. About 38 percent of all post-consumer plastics waste in Europe is buried in landfills and neither the material value nor the energy content of the plastic material is utilized. (ASTM, 2012)

i) Process model for landfill

As mentioned above, PLA remains as a carbon sink in landfills, which means, it does not degrade and generates zero methane. Likewise, PET has the same behaviour in landfills as PLA, and also remains a carbon sink. The landfill model is based on the Ecoinvent v3.3 process of PET landfill. In the Ecoinvent v3.3 database, there is no information about PLA landfilling, so the PET landfill model is used as a basis for the PLA model, but some changes were made, shown in Figure 20.

The packaging waste contains food waste, that produces methane, in landfills. The extra input introduced in the model was the food contribution, in the form of methane, carbon dioxide, ammonia and a liquid called. Landfilling works under anaerobic conditions, so the equation used in AD to calculate the values of the gaseous emissions is the same. Leachate is collected and processed in a water treatment plant.

Emissions from carbon through leachate are rarely addressed in LCA, and in this case, is also not included. The N_2O emissions in landfills are also left unconsidered. However, emissions from landfills will in reality occur over very long-time periods, so in this LCA, was used a restricted timeframe of 100 years was used.

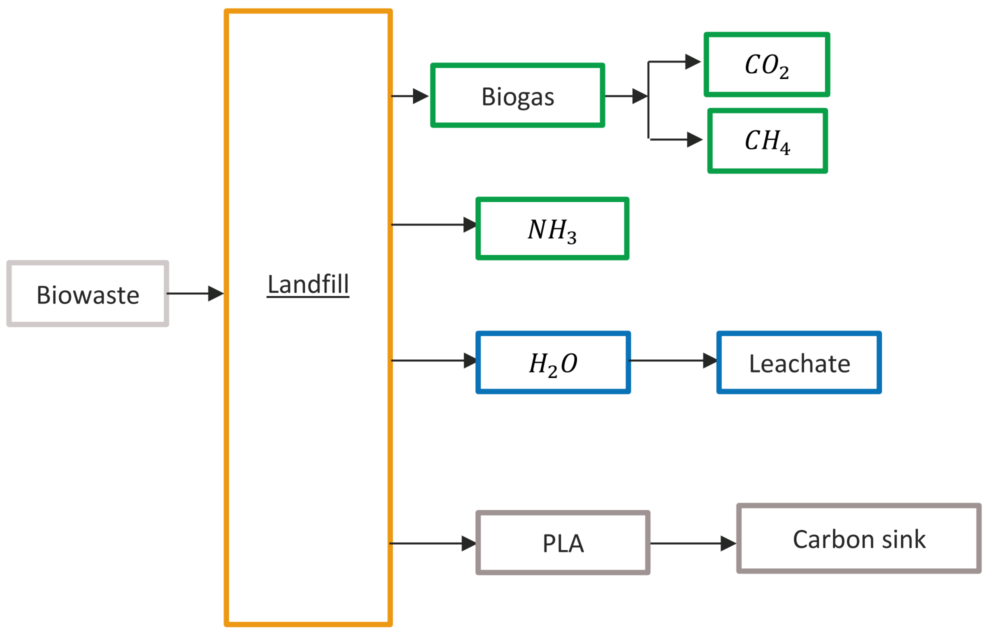

Figure 20 - Process diagram of landfill.

4.3 Results and Discussion

The results are presented in three sections. Production impacts of the final product (cradle-to-gate) are presented separately from the end-of-life impacts for two reasons. First, to facilitate comparison among end-of-life options. Secondly, to identify the relative contribution of the end-of-life stage to the total life cycle impacts. The first section is divided by impact categories, the second section is only about global warming potential and the final section, it's out of scope, is only about the global warming potential of bio-based and fossil-based materials.

4.3.1 Comparison of end-of-life options for each system

4.3.1.1 Global warming potential

This section presents the end-of-life scores for global warming, which includes all emissions occurred in the first 100 years, for the different end-of-life options: landfill, industrial composting, incineration and AD.

Figure 21 shows the GWP of landfilling for every system. As mention before, PLA will hardly degraded in landfills over the 100-year time scale considered, which is equivalent to a biogenic carbon sink, for this reason coffee cups have the lowest environmental impact among the systems. The other packaging systems have food contamination, which is why, they have higher environmental impacts. The red line, in the graph represents the amount of dry food matter presented in each system, to help understand the impact that it has on the system. The higher the amount of organic matter the bigger the impacts are. Due to decay of organic waste, biogas is released into the atmosphere, and that biogas is composed mainly of methane. Methane has 25 times more impact than Carbon Dioxide.

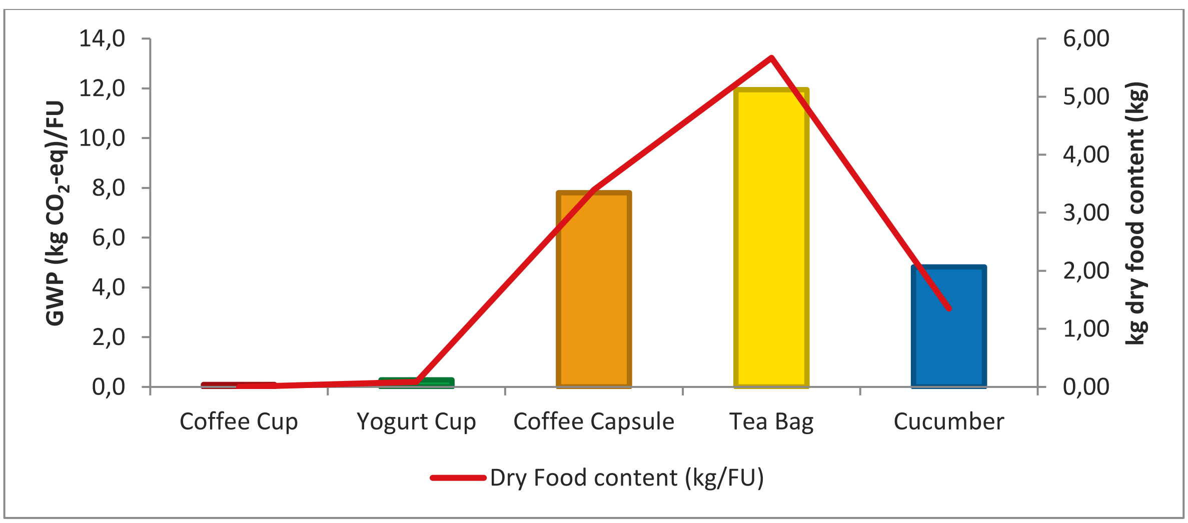

Figure 21 - Global warming potential of landfill.

Figure 22 shows the GWP of industrial composting and incineration. One of the most striking results to emerge from Figure 22 is that incineration is favorable for packaging with low moisture content (<70%) like coffee cups, yogurt cups, coffee capsules. The feedstock has an overall calorific value quite high, so per FU, there's a big amount of energy produced which makes this process viable. The other products, have a high moisture content, and in the case of cucumber wrapping, there is a need for an extra energy source, so the process is no feasible. These results are in line with previous findings in (Piemonte, 2011), that show incineration of dry PLA has a small environmental impact.

Remarkably, industrial composting is favorable for all the systems, even for food packaging with a high moisture content. For the coffee cups, the impact is positive, which means that this system has a small environmental impact. But for the other products there are benefits (negative impact credits), due to high amounts of food matter. The bottom part of Figure 22, helps to visualize the impacts of water and food matter in the scenarios.

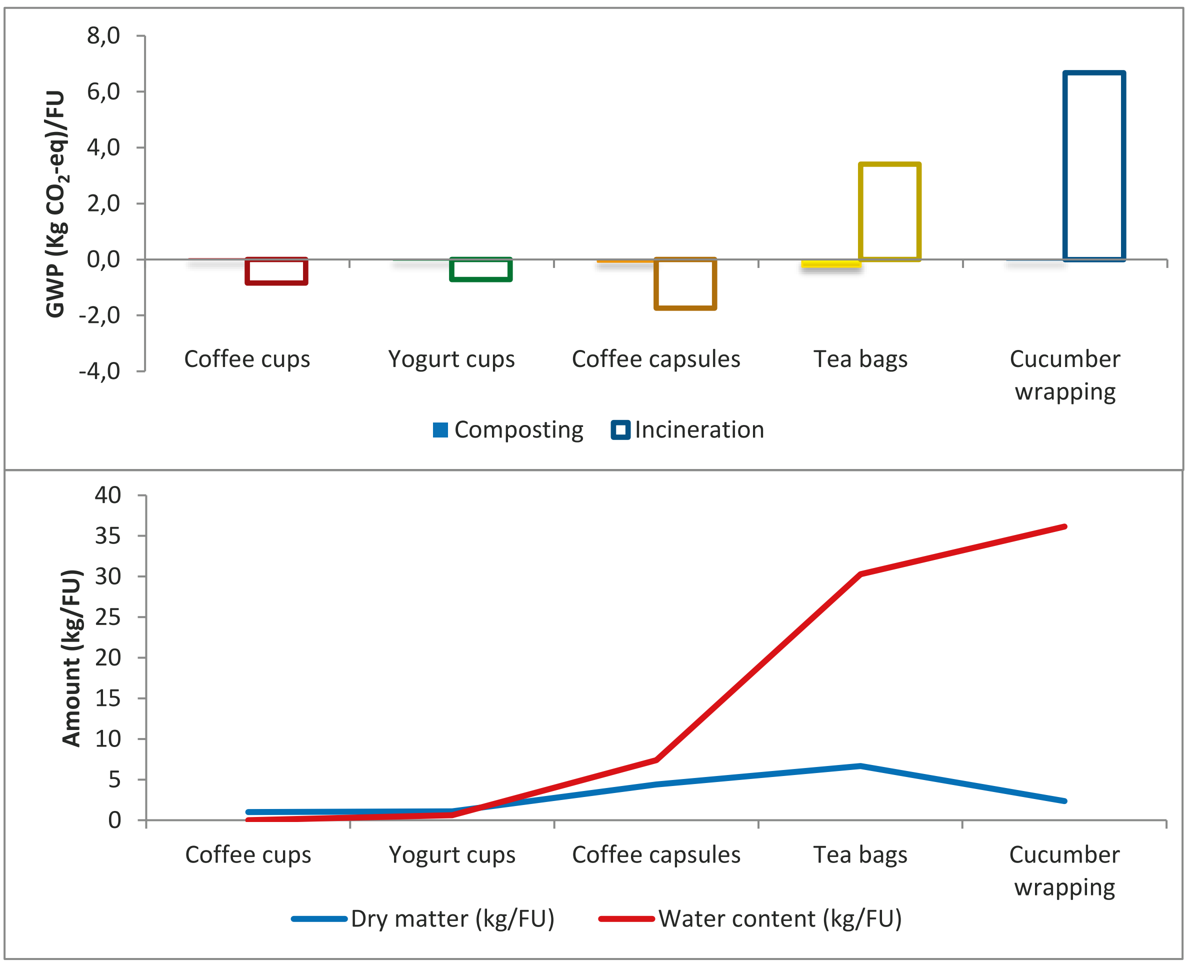

Figure 22 - Global warming impact of the waste treatments: composting and incineration and reference flows of the packaging systems.

Finally, the last disposal treatment is Anaerobic digestion, shown in Figure 23. Biogenic gas recovery for energy production purpose, appears to be interesting, mainly in comparison with the incineration process. AD and Incineration present similar overall impacts because both recover energy with a limited yield.

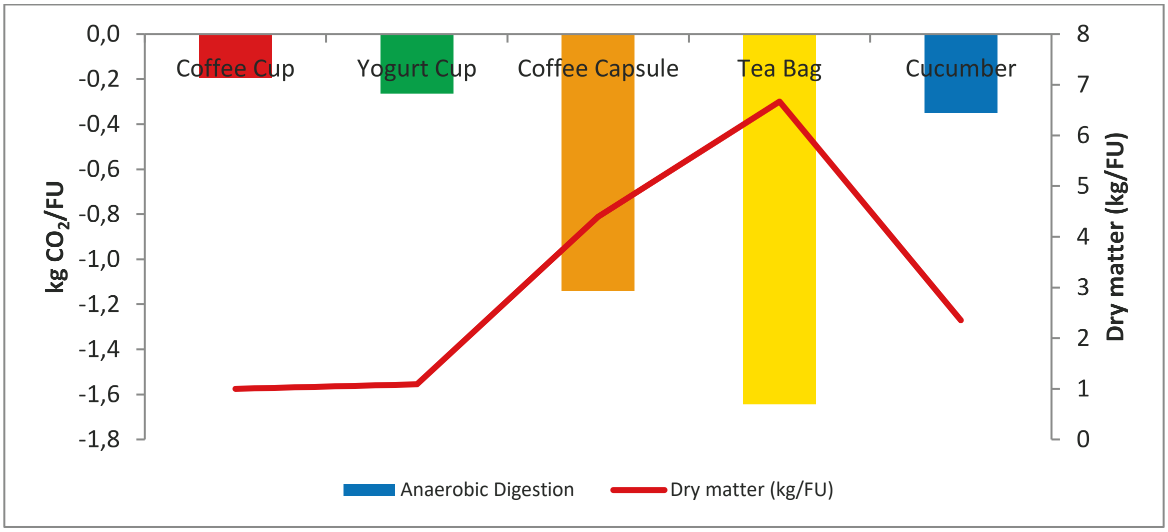

Figure 23 - Anaerobic digestion of five food packaging systems.

In many of the assessed impact categories, either AD or Incineration have the lowest environmental impacts. This is related to substantial benefits (negative impacts counting as credits) associated with the recovery of a large amount of thermal energy and recovery of material.

These results correlate satisfactory with (Piemonte, 2011) and further support the conclusions that (V. Rossi, 2015) achieved.

4.3.1.2 Non-renewable energy and renewable energy

All waste to energy technologies, AD and incineration produce energy and therefore reduce the environmental impact by relieving an energy burden, and for that, they have a beneficial contribution to the environmental. Negative results in Figure 24 and Figure 25 signify a beneficial environmental contribution. Landfill has positive results for non-renewable and renewable, which means is consuming resources. In Incineration, for the tea bags and cucumber, there is no beneficial contribution to the environment, due to the amount of moisture content. Supporting the conclusion taken before, that this process is not suitable to treat tea bags and cucumbers.

An energy credit rather than a burden due to electricity production from incineration and AD and due to material recovery from composting and AD. Each means, on those models it can be avoided burdens from generating electricity by burning fossil fuels, except for tea bags and cucumber. For that reason, they have burdens in Incineration. Comparing non-renewable and renewable energy, demonstrates that renewable energy on EOL has a smaller impact comparing with non-renewable.

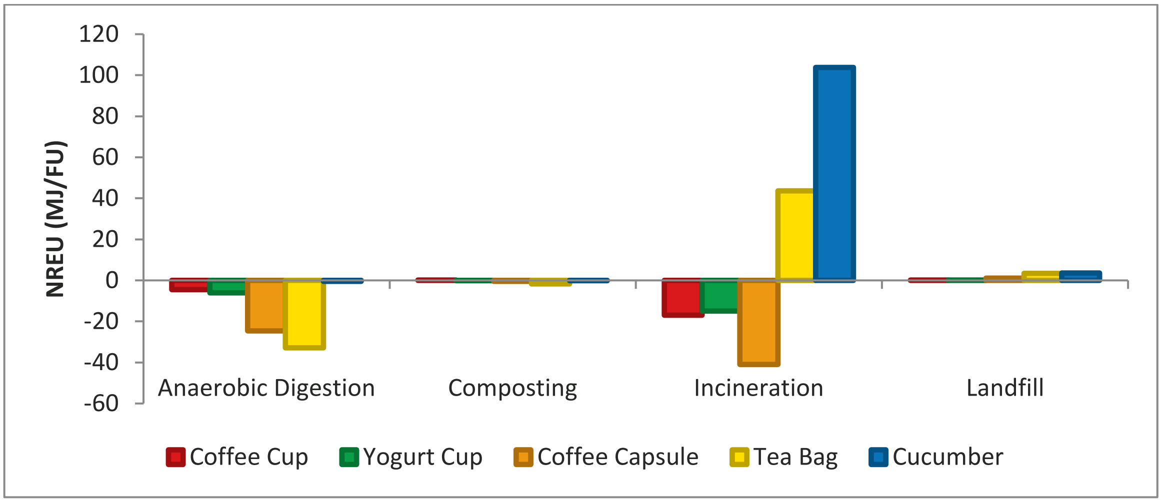

Figure 24 - Non-renewable energy of end-of-life options.

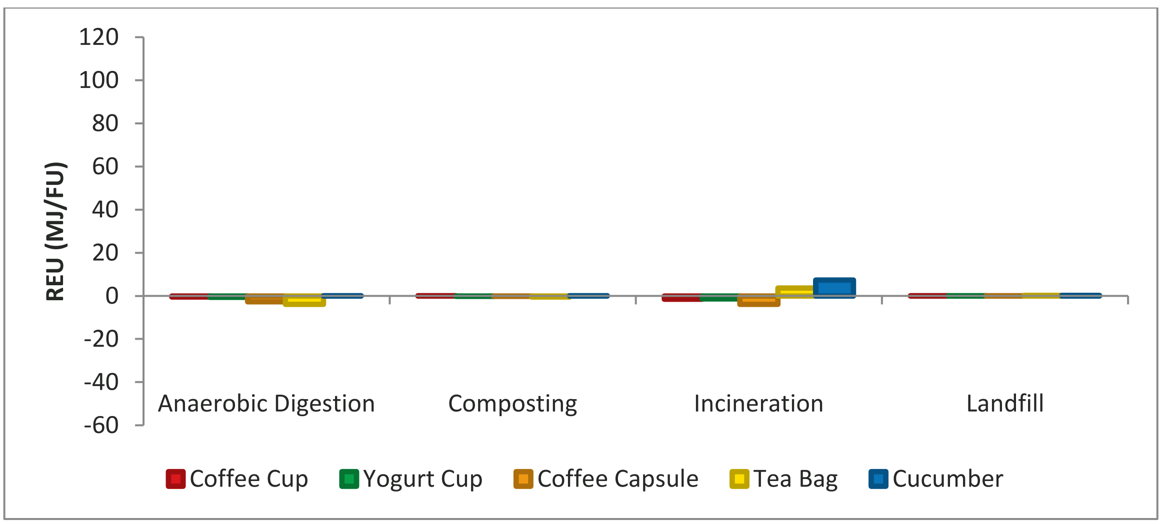

Figure 25 - Renewable energy of end-of-life options.

4.3.1.3 Eutrophication

Figure 26 presents the Eutrophication potential as kg PO_4^{3-} per functional unit for all the waste treatments. Nitrogen and phosphorus are two nutrients most implicated in eutrophication. Maximum eutrophication assumes that all nutrients eventually end up in aquatic systems. On landfill, the system with the higher water content will have the higher impact, as shown in Figure 26.

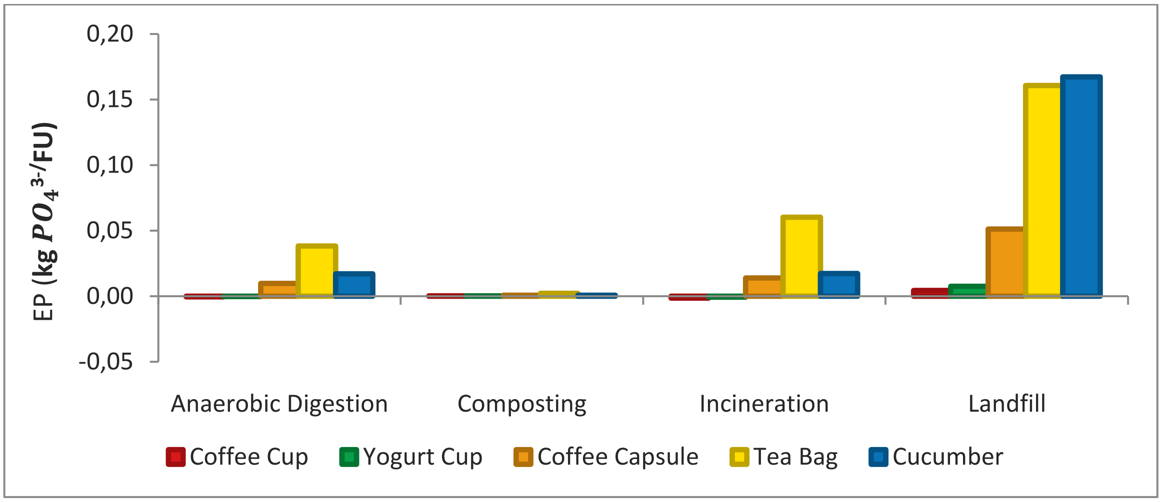

Figure 26 - Eutrophication potential of end-of-life options.

4.3.1.4 Acidification

Figure 27 presents the acidification potential as kg SO_2-eq per functional unit for the four waste treatments. The major acidifying pollutants are ammonia and nitrogen dioxide. On AD besides biogas, there is an amount of ammonia release, which depends on the amount of organic waste. On Incineration, one of the gas emissions is NO_2, that also depends on the amount of food waste. As seen before, tea bags have the higher amount of organic waste of all the systems, and consequently have the higher acidification impact.

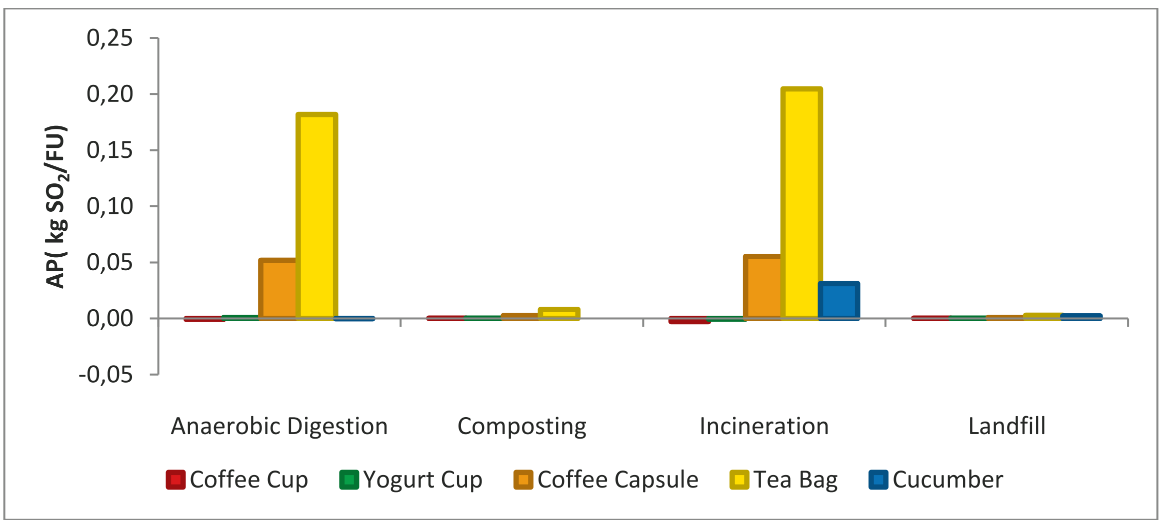

Figure 27 - Acidification potential of End-of-life options.

4.3.1.5 Water scarcity and land use

Weighting of water consumption with water scarcity index, shows that Incineration of tea bags and cucumber wrappings has a negative impact on the environment.

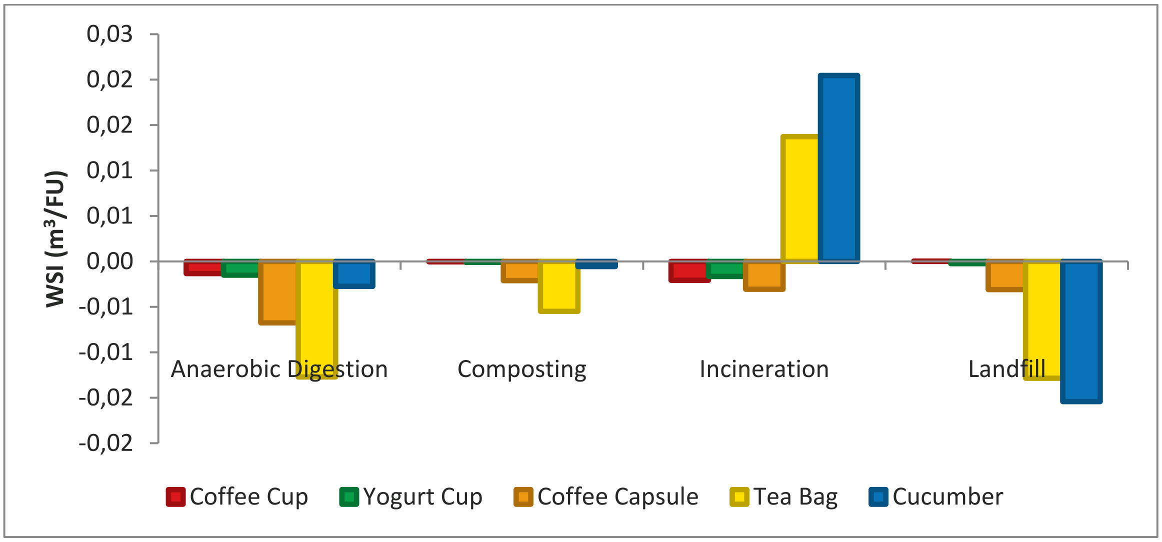

Figure 28 - Water scarcity of end-of-life options.

Landfill has higher burdens compared with the other waste treatment, except for incineration of tea bags and cucumber wrappings.

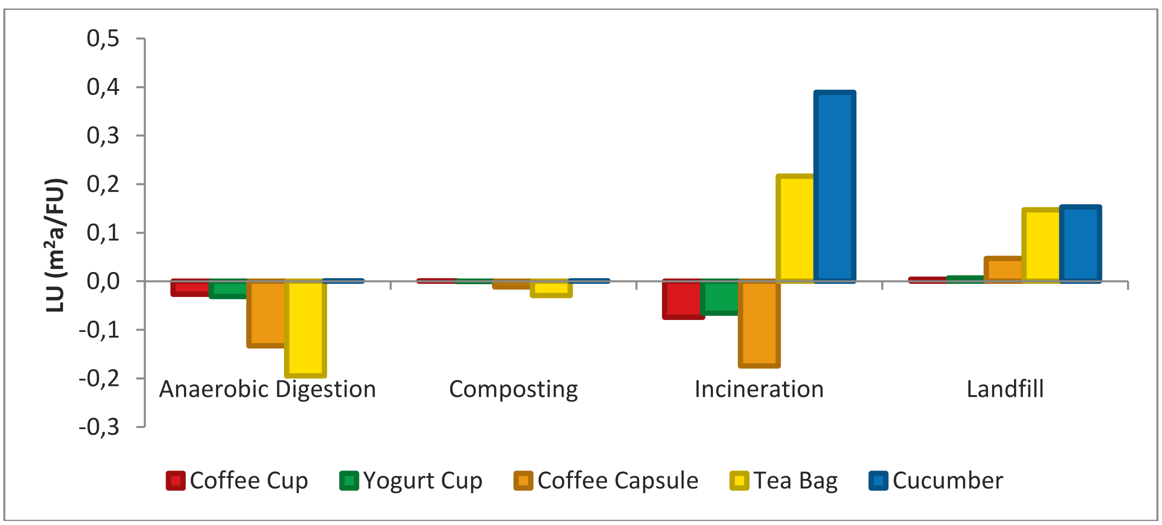

Figure 29 - Land use of end-of-life options.

The analysis did not reveal clear results for these two impact categories.

4.3.1.6 Theoretical GWP results

The graph displayed above was developed to show the relationship between Global Warming Potential, the amount of food waste sent to disposal treatments and moisture content.

The origin (0, -0.84), sets the frame of reference which is the impact of the packaging without food contamination (0 kg of food) and it is the value obtained by coffee cup model, because is the only one with zero food contamination.

Starting from there, using a correlation between the LHV_{wet} for each system, the GWP obtained with the simulations and the kg of food waste, it was possible to build a theoretical graph that sums up the results. Figure 30, shows that for food waste with higher water contents is better to compost and on the other hand for systems with lower moisture values is better to incinerate.

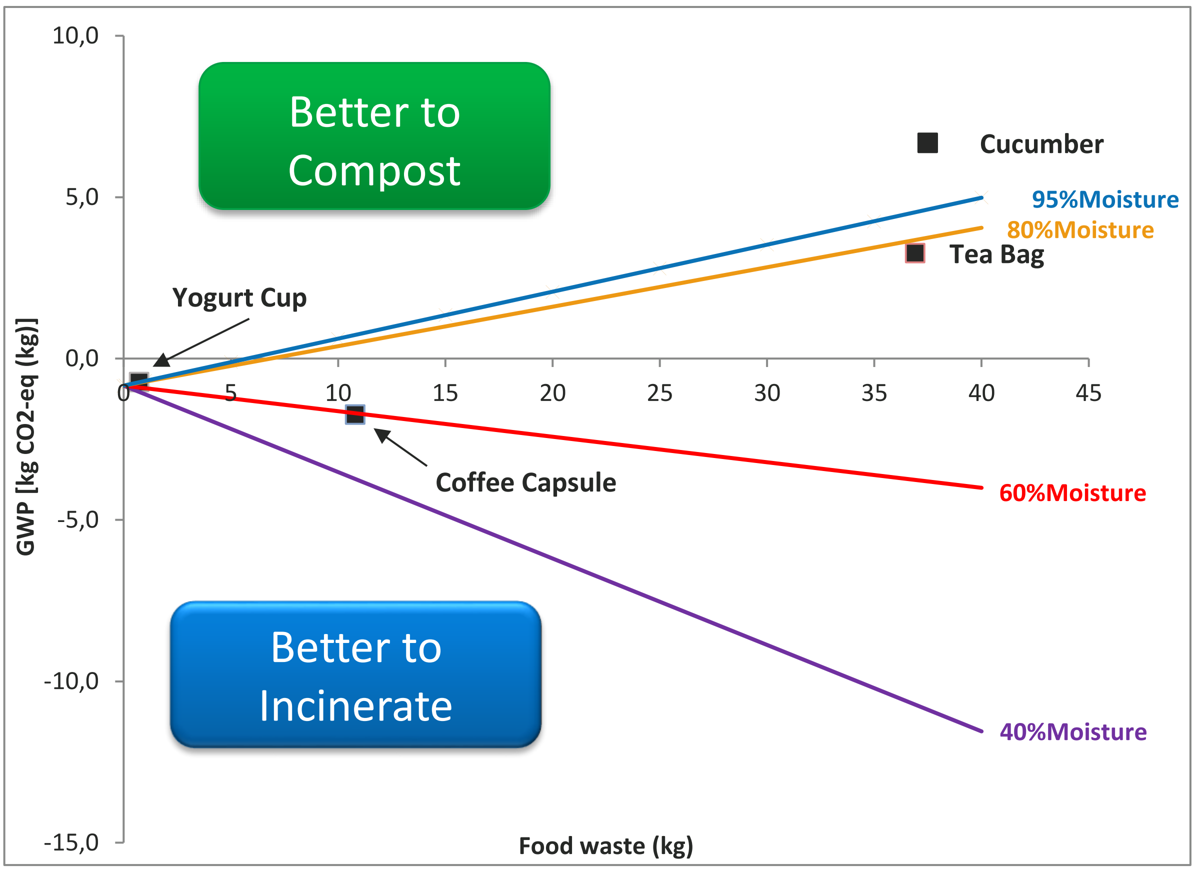

Figure 30 - Theoretical graph about a correlation between GWP, food waste and the moisture matter of each system.

4.3.2 Overall life cycle results

The complete life cycle results for the five food packaging systems are presented in Figure 31 for the global warming potential indicator.

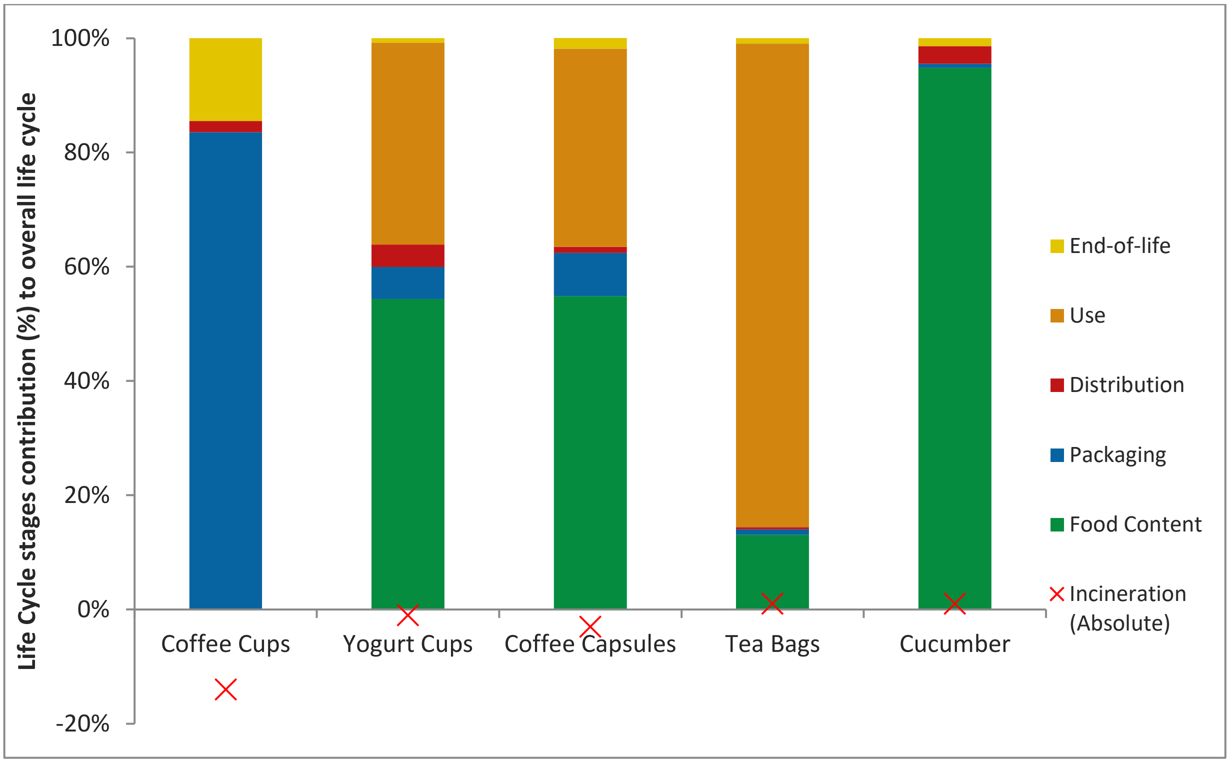

Figure 31 - Overall comparative results for global warming potential.

The profile of total air emissions demonstrated a similar trend for each packaging system. The two phases with the heaviest contribution to GWP were food supply and use stages, followed by packaging manufacture and finally distribution. The disposal treatment used in this graph, was incineration, because it was not possible to include all of waste treatments because this graph is presented by percental contribution of each life stage. End-of-life stage for all the systems does not significantly contribute to the overall life cycle impact. The red crosses, represent the absolute value of incineration, that for some cases is negative.

For the yogurt cups, regarding the food supply stage, the impact is mostly driven by the use stage, which consists on the refrigeration of the yogurts in the fridge. For the coffee capsules, coffee supply has such a high value due to cultivation and irrigation impacts. Food production, preservation and distribution consume a considerable amount of energy, which contributes to total CO_2 emission.

The use stage, includes the manufacture of the coffee machine and the energy that it requires to brew a coffee and the production of the coffee cups to drink the coffee. For the tea bags, the use stage has such a high value, due to the energy requirements of a kettle to prepare a lot of tea drinks. The cucumber production, occurred in a greenhouse, and besides the impact of the cultivation and irrigation of the vegetable, the energy requirements of the greenhouse also have a big impact.

The study shows that the most relevant environmental aspects for coffee capsules are brewing (i.e. the heating of water on the coffee machine) and coffee production. Transport is of minor importance. Brewing and coffee production have an impact share of 89 percent, regarding the global warming potential. On 7.7 Appendix A7 – Results of all Life Cycle Stages there are displayed the remaining results per impact category.

4.3.3 GWP comparison of bio-based PLA and fossil-based polymers

In this section, as an extra analysis, the GWP of incineration of fossil-based polymers (PS, polyethylene (PE), PP and PET) was quantified, as comparison with PLA. The only way to analyze the origin of the carbon content of these polymers is to apply a cradle-to-grave analysis for incineration as a disposal phase.

The results reported in Figure 32, clearly show the GHGs savings achievable by displacing the fossil-based plastics with PLA and this is one of the main drivers today for producing biopolymers. The values for PLA are lower because CO_2 is sequestered from the atmosphere and fixated in the polymer. For the fossil polymers, the process-related emissions are not removed from the atmosphere, they are related with crude oil extraction.

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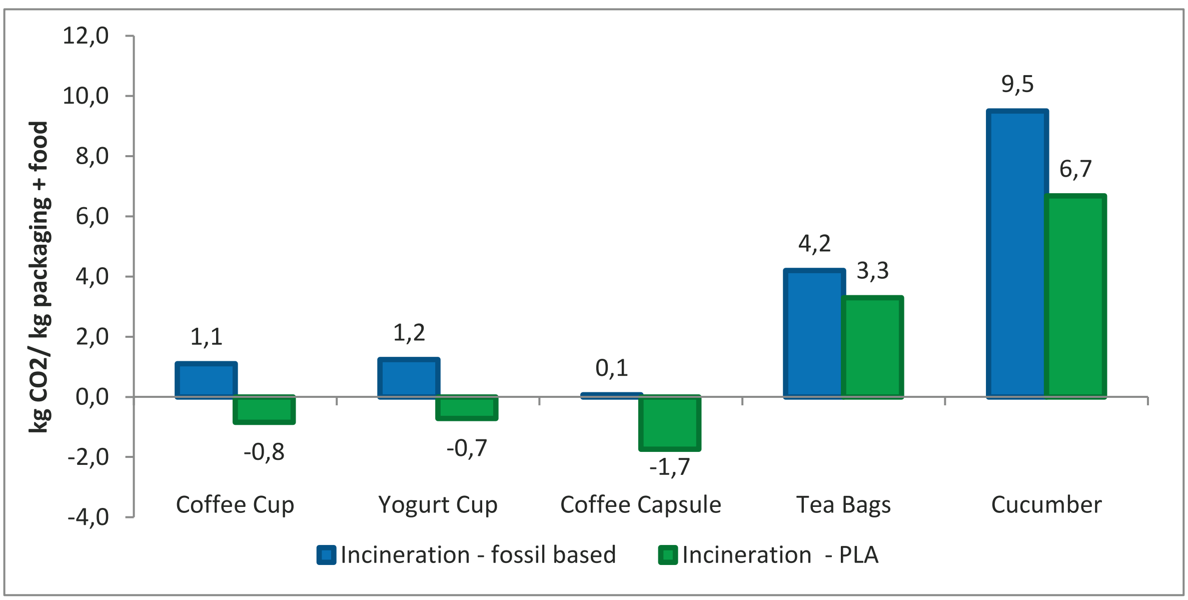

Figure 32 - Global warming potential of fossil-based plastics vs bioplastics.

4.4 Sensitivity Analysis

The sensitivity analysis is designed to assess the robustness of the conclusions, such as the efficiency of disposal waste treatments. The goal is to evaluate the sensitivity of the results in respect to the assumptions for several key input parameters and evaluate the probability that the conclusions regarding GWP are maintained, based on the uncertainty of all the input parameters.

4.4.1 Incineration

A sensitivity analysis on Incineration with energy recovery has been performed by changing the efficiency of the CHP plant. The Table 14 shown above, has the parameters that were changed and on Figure 33 the impacts on GWP of the disposal treatment.

Table 14 - Sensitivity analysis of incineration with energy recovery.

	Electricity efficiency (%)	Heat efficiency (%)
Inc-1	25	65
Inc-2	18	37
Inc-3	20.7	74
Inc-4	70.3	5.5

Figure 33 shows that electricity and heat efficiencies are a critical parameter. Inc-1 is the model with the higher carbon credits because the overall efficiency is 90% and is the highest among the four models.

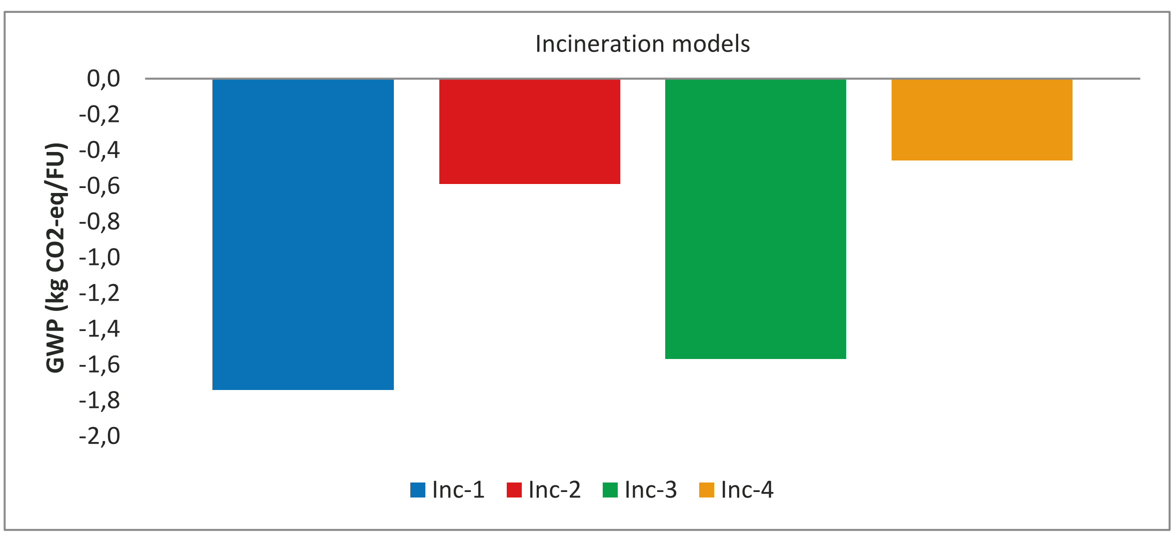

Figure 33 - Sensitivity analysis of the impact of CHP plant efficiency.

4.4.2 Anaerobic Digestion

A sensitivity analysis on anaerobic digestion has been performed by changing the percentage of biodegradability of PLA and food under anaerobic conditions. Table 15 shown above, has the parameters that were changed and on Figure 34 the impacts on GWP of the disposal treatment. AD-1 was used in the model to simulate the waste treatment, and AD-2 and AD-3 are the new scenarios.

Table 15 - Sensitivity Analysis on anaerobic digestion.

	PLA Biodegradability (wt.%)	Food Biodegradability (wt.%)
AD - 1	60	70
AD -2	95	95
AD-3	50	50

Figure 34 shows that biodegradability of the waste input is a critical parameter. AD-2, has higher impact compared with the others. Which means that as higher the biodegradability of the waste is, the production of biogas will be higher and consequently the amount of energy produced.

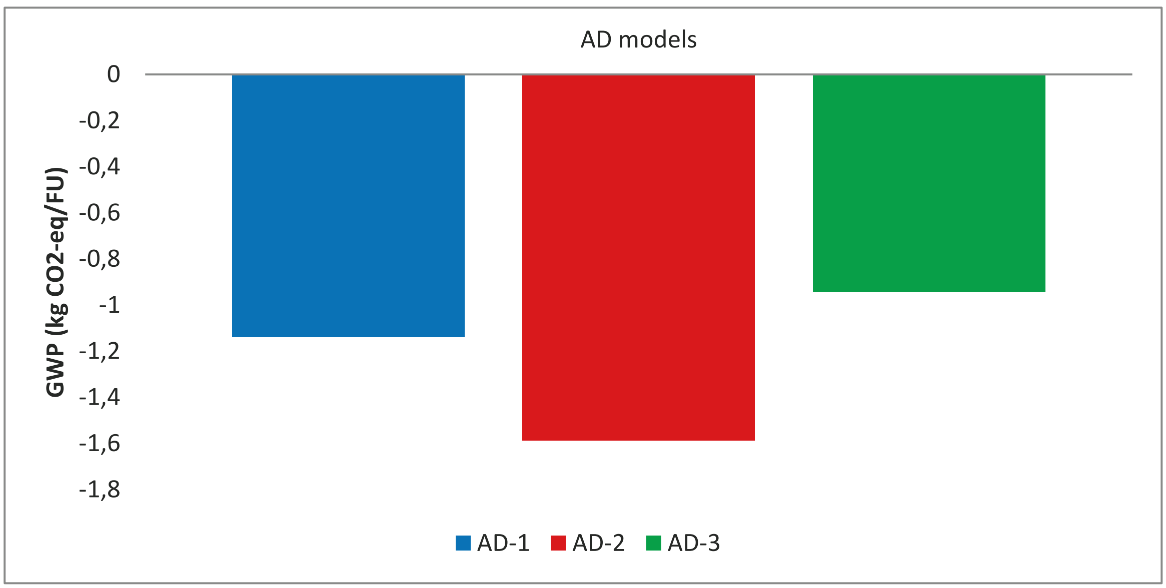

Figure 34 - Sensitivity analysis at PLA and food biodegradability under anaerobic conditions.

4.4.3 Industrial Composting

Two different parameters were studied on composting, such as the amount of methane retained by the biofilters and the biodegradability of the food content and PLA. The Table 16 shown above, has the parameters that were changed and the impacts on GWP of the disposal treatment are displayed in Figure 35 and Figure 36. Composting -1 was used in the model to simulate the waste treatment, and Composting-2,-3,-4, -5 are the new scenarios.

Table 16 - Sensitivity analysis on composting.

	PLA Biodegradability (wt.%)	Food Biodegradability (wt.%)	Methane captured (wt.%)
Comp-1	95	70	100
Comp-2	95	95	100
Comp-3	50	50	100
Comp-4	60	70	80
Comp-5	60	70	20

Starting with, Figure 35, Comp-2 has a higher carbon credit in comparison with Comp-1 e Comp-3 because is the model with the highest food biodegradability value. Comp-3 has a positive impact showing that PLA biodegradability has a big impact on GWP.

Figure 36, shows that the amount of methane retained by the biofilters has the highest impact on global warming potential, because CH_4 has 25 times more impact than CO_2.

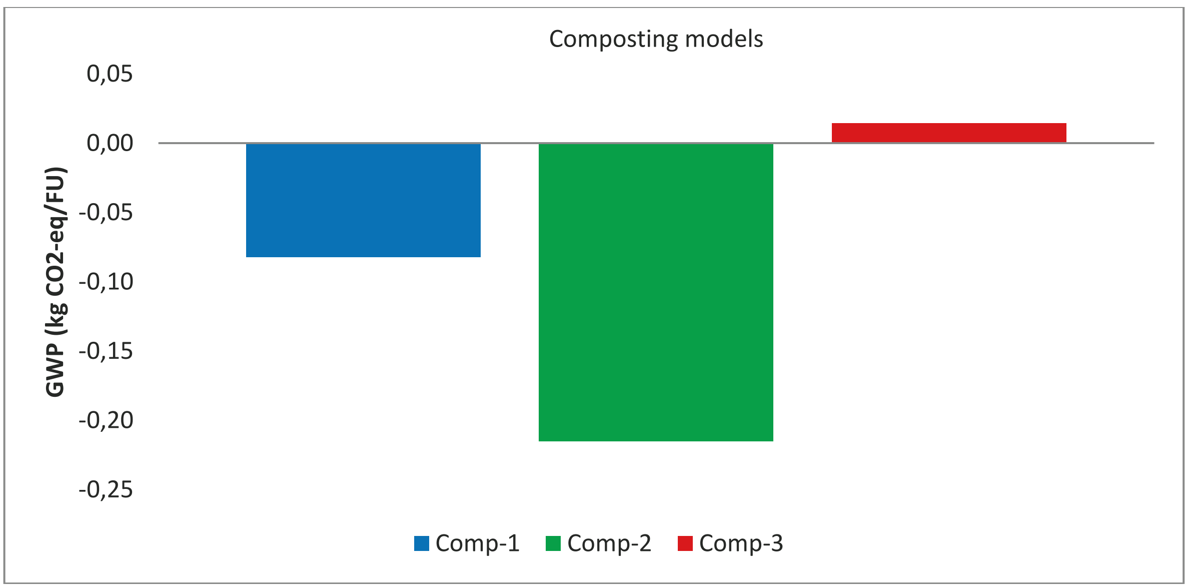

Figure 35 - Sensitivity analysis on the impact of food and PLA biodegradability under aerobic conditions.

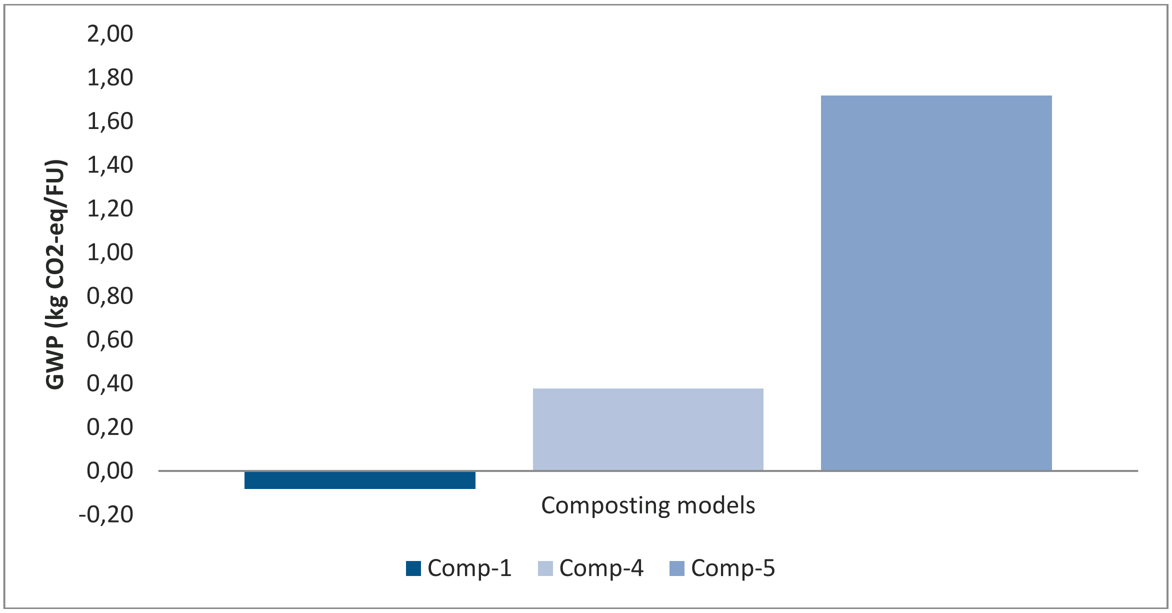

Figure 36- Sensitivity analysis of the impact of methane release on a composting plant.

Chapter 5

Conclusions

For all three systems, the ranking observed never matches the ranking suggested by an interpretation of the EU waste hierarchy. This is mostly because composting impacts are higher than energy recovery by incineration. Unquestionably, landfilling is the worst waste management option for bio-waste. However, for the management of biodegradable waste diverted from landfills, there seems to be several environmentally favorable options. Incineration with energy recovery appears to be the best solution for coffee cups, yogurts cups and coffee capsules. For tea bags and cucumbers, incineration is not suitable due to the high amount of moisture content, and because of that composting is the best solution.

Taking the entire production chain into account, the LCA results show that the most significant impacts are related to the use phase, especially if a heating device is used, such as a kettle, coffee machine or refrigerator. Finally, the influence of packaging disposal is very small in comparison with the rest of the life cycles.

Recovering the energy from bio-based packages is far more favorable than burning synthetic plastics because the carbon content of bio-based plastics does not stem from fossil sources. The bioplastics production for the replacement of a part of fossil-based plastics seems to be a real and effective strategy towards sustainable development. In fact, the displacing of conventional plastics with bioplastics can lead to considerable energy and GHGs emissions savings.

The AD of organic waste is clearly on the rise within the EU because its main advantages lies in converting organic waste into biogas, a renewable energy source. The next decade is likely to witness a considerable rise in research regarding anaerobic digestion of PLA.

Sensitivity analysis, show that some assumptions for several key input parameters are very important due to the uncertainty of all the input parameters.

5.1 Future work suggestions and study improvement

For future work, a mechanical and chemical recycling model should be done to make this analysis even more complete. A landfill model including methane capture is also something that should be addressed. Since the conclusions about land use and water scarcity were inconclusive, a new project focusing on them could be interesting. A cost analysis should be done, to complete the study.

Chapter 6

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Chapter 7

Appendixes

7.1 Appendix A1 – Heat of Combustion Calculations

The higher heating value (HHV) of a fuel represents the maximum amount of heat that can be obtained from combusting that fuel. It can be approximated by the following empirical relation (Phyllis2, 2012), with Y the mass fraction (%) of the corresponding element in the dry fuel:

$$HHV\ [MJ/kg] = 0.341 * C + 1.332 * H - 0.12 * O - 0.12 * N + 0.0686 * S - 0.0153 * ash \quad \text{(i)}$$

The lower heating value (LHV) can be calculated from the HHV by considering the heat of evaporation of the water formed from the hydrogen and moisture (H%, M%) in the fuel according to the following equations (Phyllis2, 2012):

$$LHV_{dry}\ [MJ/kg] = HHV - 2.442 * 8.936 * \frac{H}{100} \quad \text{(ii)}$$

$$LHV_{wet}\ [MJ/kg] = LHV_{dry} * \left(1 - \frac{M}{100}\right) - 2.442 * \frac{M}{100} \quad \text{(iii)}$$

After the use phase, the calorific values of PLA and food matter are combined to obtain the heating value of each system per kg of waste and per kg of functional unit. The purpose to calculate the calorific value per kg of waste, is to evaluate if these systems have a final heating value that can be accepted in an Incineration Plant.

To calculate this value, per kg of waste, the reference flows presented on Table 3 need to be converted to new ratios. Instead of having 1 kg of PLA food packaging including the kgs of associated household food waste, it has an overall value of 1 kg of waste. The "new" reference flow is described in Table A- 1 .

Table A- 1 - Reference flows per kg of waste after consumer's use.

Material per kg waste	Coffee Cups	Yogurt Cups	Coffee Capsules	Tea bags	Cucumber Wrapping
PLA Packaging (kg/kg waste)	1	0.60	0.1	0.03	0.03
Dry organic matter (kg/kg waste)	0	0.05	0.3	0.17	0.03
Moisture content (kg/kg waste)	0	0.35	0.6	0.80	0.94
Total (kg/kg waste)	1	1	1	1	1

Using the equations (i), (ii) and (iii), the wet low heating value of PLA was calculated and has a value of 17.76 MJ/kg PLA. The same equations are used to calculate the heating values of the organic matter, that are presented on Table 9. For the coffee capsules and the tea bags, the additional water introduced in the system during the use phase was included, and has a Vaporization Heat of -2.26 MJ/kg (Wikimedia Foundation Inc., 2017).

Combining the reference flows of Table A- 1 , with the heating values and with the water vaporization heat, the calorific values of the systems can be calculated. The coffee capsule has 0.09 kg of PLA, 0.30 kg of food matter and 0.61 kg of water, the heating value of the 1 kg of the coffee capsule waste can be calculated, as demonstrated above:

$$\text{PLA} \rightarrow 0.09 \times 17.76 = 1.6$$

$$\text{Coffee} \rightarrow 0.3 \times 16.58 = 5$$

$$\text{Water} \rightarrow 0.6 \times (-2.26) = -1.4$$

$$\text{Coffee Capsule} \rightarrow 1.6 + 5 - 1.4 = 5.2 \ \frac{MJ}{kg\ waste}$$

The other systems followed the same calculations.

To calculate this value, per functional unit, it's the exact same thing as the calculations per kg of waste, but instead of using the reference flows of Table A- 1 , it is used the values of Table 3 and the calculations are the same.

7.2 Appendix A2 – PLA Processing and LCA dataset

For plastics, a huge variety of different conversion processes are possible. Table A- 2 summarizes the conversion processes together with the respective products produced from the different processes.

Table A- 2- Different conversion processes per product.

Conversion process	**Products**
Extrusion	Films, Non-woven
Injection moulding	Coffee Capsules
Thermoforming	Coffee Cups and Yogurt Cups

7.2.1 Compounding

Compounding is a process of melt-mixing PLA with polymers, additives, fillers and/or reinforcing materials. Not all the products need this compounding step. Typically, this is done to improve certain properties of the PLA polymer (Purac). For the production of high-heat PLA, to be used in coffee cups and coffee capsules, a compounding step was needed, to blend mineral fillers with PLA resin. The inventory for high heat PLA compounding step is shown in Table A- 3.

Table A- 3- Life cycle inventory data for high-heat PLA compounding step.

Compounding			
Inputs	Amount	Unit	Source
Z	L	kg	Corbion Purac
W	M	kg	
X	N	kg	
Y	R		
Electricity	1.01	kWh	
Water	0.03	m^3	
Aluminum foil bag	0.008	kg	
Outputs	Amount	Unit	Source
A	V	kg	Corbion Purac
B	P	kg	
Water	0.00015	m^3	

For the production of yogurt cups, impact modifiers are needed. Impact modifiers, modify the mechanical properties of thermoplastics by increasing the tensile stress of said thermoplastics. They exist in the form of a masterbatch, wherein it is dispersed in a polymeric matrix, typically a thermoplastic matrix, a PLA matrix. The matrix does not qualify herein as an additive. Such masterbatches can comprise for example from 10 % to 60 % by weight of polymeric matrix. (International Publication Patent No. WO 2014/068348 A1, 2014)

Table A- 4- Life cycle inventory data for masterbatch production.

Compounding of Masterbatch			
Inputs	Amount	Unit	Source
PLA	X	kg	Corbion Purac
Impact modifier	Y	kg	
Electricity	1.00725	kwh	
Water	0.03	m^3	
Aluminum foil bag	0.008	kg	
Outputs	Amount	Unit	Source
Masterbatch	0.995	kg	Corbion Purac
PLA to waste	0.005	kg	
Water	0.00015	m^3	

7.2.2 Extrusion

Extrusion of PLA in a heated screw is the first step before any further processing of PLA, such as injection, thermoforming or spinning, takes place. The extruder provides the heat to melt the resins by heater bands wrapped around the barrel.

Table A- 5- Life cycle inventory data for sheet formation.

Sheet Formation			
Inputs	Amount	Unit	Source
PLA compounded pellets	1	kg	Corbion Purac
Additives	0.01	kg	
PLA scrap recycled	0.45	kg	
Electricity	0.83	kWh	
Water	0.006	m^3	
Outputs	Amount	Unit	Source
PLA sheet	1.41	kg	Corbion Purac
PLA to waste	0.04	kg	
Water	0.0003	m^3	

Table A- 6- Life cycle inventory data for sheet formation.

Sheet Formation			
Inputs	Amount	Unit	Source
PLA pellets	0.97	kg	Corbion Purac
Masterbatch	0.3	kg	
Additives	0.01	kg	
PLA scrap recycled	0.45	kg	

Electricity	0.83	kWh	
Water	0.006	m^3	
Outputs	Amount	Unit	Source
PLA sheet	1.41	kg	Corbion Purac
PLA to waste	0.04	kg	
Water	0.0003	m^3	

7.2.3 Thermoforming

Thermoforming is a standard method to produce PLA containers such as coffee cups and yogurt cups. It's a process in which a pliable plastic is pressed into a final shape by vacuum or air pressure.

To prevent thermoplastics from damaging, polymer modifiers are widely used to ensure impact modification and reduce brittleness. Conventional food packages, for example yogurt pods, are often thermoformed. These co-polymers, however, are complex and expensive compounds. There is a need to have a cheap and practical way to modify the commercially available biodegradable polyester preferably with a masterbatch that contains an additive providing the mandatory properties like transparency and snap ability modification. (International Publication Patent No. WO 2014/068348 A1, 2014)

Table A- 7- Life cycle inventory data for Thermoforming.

Thermoforming			
Inputs	Amount	Unit	Source
PLA sheet	1	kg	8 Corbion Purac
Silicone	0.0004	kg	
Electricity	0.22	kWh	
Outputs	Amount	Unit	Source
PLA container	0.55	kg	Corbion Purac
PLA recycled to sheet formation	0.45	kg	
PLA scrap to waste	0.004	kg	

7.2.4 Injection moulding

Injection moulding is the process of melting a PLA polymer or PLA compound, injecting it under high pressure into a mold and solidifying it until a stable part is achieved. Standard PLA compounds will result in an amorphous structure whereas high heat PLA compounds can result in a semi-crystalline structure. This process is described as being after extrusion, the most frequently employed processing method and an energy-intensive process. The most important process steps are melting, injection, cooling and shaping. (Hischier, 2007)

There are two main parts to an injection moulding machine: The injection unit and the molding unit: 1) In the injection unit, plastic is loaded into a hopper and pushed through a heated chamber by a screw to bring the resin to a semifluid state and 2) The molten plastic is then injected through a nozzle into the clamped molding unit. The mold is cooled to return the material to a solid state. Cooling is typically achieved by circulating water through chambers within the molding plate. The mold then unclamps and ejects the part for finishing. Finishing steps may include printing and packaging.

Table A- 8- Life cycle inventory data for Injection moulding.

Injection Moulding			
Inputs	Amount	Unit	Source
Compounded PLA	1	kg	(Hischier, 2007)
Lubricants	0.003	kg	
Electricity	1.48	kWh	
Heat (natural gas)	4.21	MJ	
Heat (other than natural gas)	0.23	MJ	
Water	0.01	m^3	
Outputs	Amount	Unit	Source
PLA coffee capsule	1	kg	(Hischier, 2007)
PLA to waste	0.003	kg	

7.2.5 Blown film extrusion

Blown film extrusion is a well-known production technology to make thin films. The low melt strength of PLA requires the use of additives, like melt strength enhancers to be able to process neat PLA. Often PLA is part of a compound to make biodegradable film for use in objects such as shopping bags or as mulch film (Corbion).

7.2.6 Spund Bond process – Spinning of PLA fibers

PLA fibers are gaining importance since they have lower water barrier properties. One process for fiber spinning is the spund bond process. Which is widely used to produce nonwoven fabrics. It's a nonwoven manufacturing system which combines the spinning process with the sheet formation process by placing the bonding device in the same continuous line (Hosun Lim, 2010). The spundbond process consists of several integrated steps; a polymer feed, an extruder, a filament attenuator, a drawing and deposition system, a collecting belt, a bonding zone, and a winding, as shown in Figure A- 1. Due to lack of data, the model for sheet extrusion was used since the process is very similar.

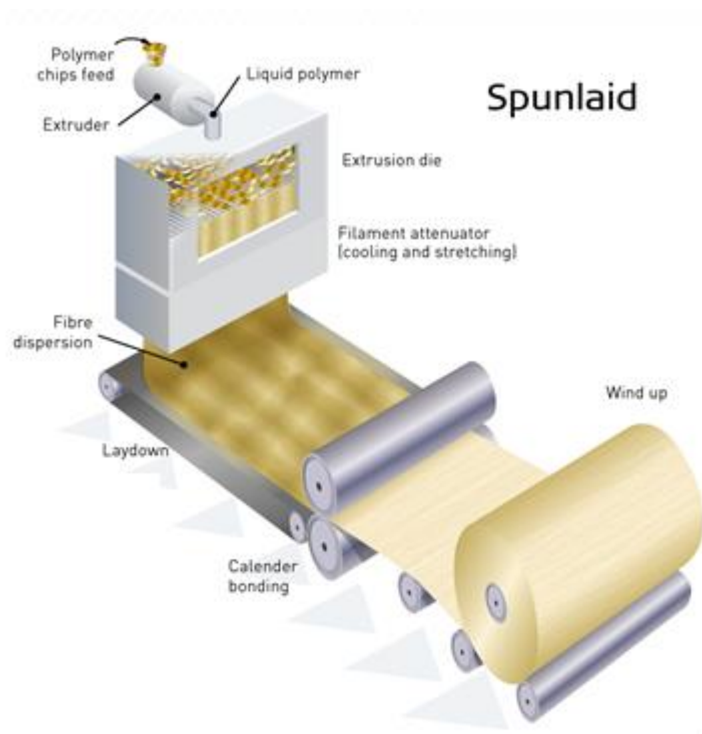


Figure A- 1 – Spundbond process.

7.3 Appendix A3 – Waste treatment options

7.3.1 Incineration

Europe has a lot of experience with waste incineration, having Denmark and Sweden has leaders in using energy generated from incineration for more than a century. In 2005, waste incineration produced 4.8 % of electricity consumption and 13.7 % of the total domestic heat consumption in Denmark. (Kleis, 2007).

The typical design for a MSWI plant consists of two or three incineration lines in parallel, as shown in Figure A- 2. Each incineration line is equipped with a grate-type furnace (8). At the end of the grate the unburnable remains are collected as slag (bottom ash) and quenched in water (9). The raw gas is led to an integrated steam boiler (10). The recovered heat is passed to a steam turbine (24) to generate electricity. The expanded steam is sometimes directed to a district heating network (25) or used as process steam for neighboring industries. After being cooled down in the steam boiler, the flue gas of the MSWI is then passed into an electrostatic precipitator for fly ash separation (12). Electrostatic precipitators (ESP) use the principle of electrostatic attraction to remove particles from the raw gas. They consist of rows of discharge electrodes (wires or thin metal rods), through which a high voltage is applied, and which run between an array of parallel rows of metal plates which collect the charged particles. After the ESP, a multistage wet scrubber (14) is used to eliminate harmful components of the flue gas like sulfur oxides ($SO_{\times}$), hydrogen chloride (HCl) by washing the raw gas in a reaction tower. Designed to provide a high gas-liquid contact, the gases are cooled by water sprays in the first stage, removing HCl, hydrogen fluoride (HF), some particulates and some heavy metals. In the second stage calcium hydroxide or another suitable alkali is used to remove SOx and any remaining HCl. The scrubbing liquid is neutralised (18), heavy metals are precipitated (19) and separated as a sludge (20) in a wastewater treatment facility. The treated water is usually discharged to a river. After the wet scrubber the purified flue gas enters a DeNOx installation3 (15). Usually SCR or SNCR-DeNOx technology is employed. The purified flue gas is led into a stack. Approximately 75% of the original waste mass is transferred to gaseous compounds like carbon dioxide, elemental Nitrogen and water and minor trace gases. (Doka G., 2003)

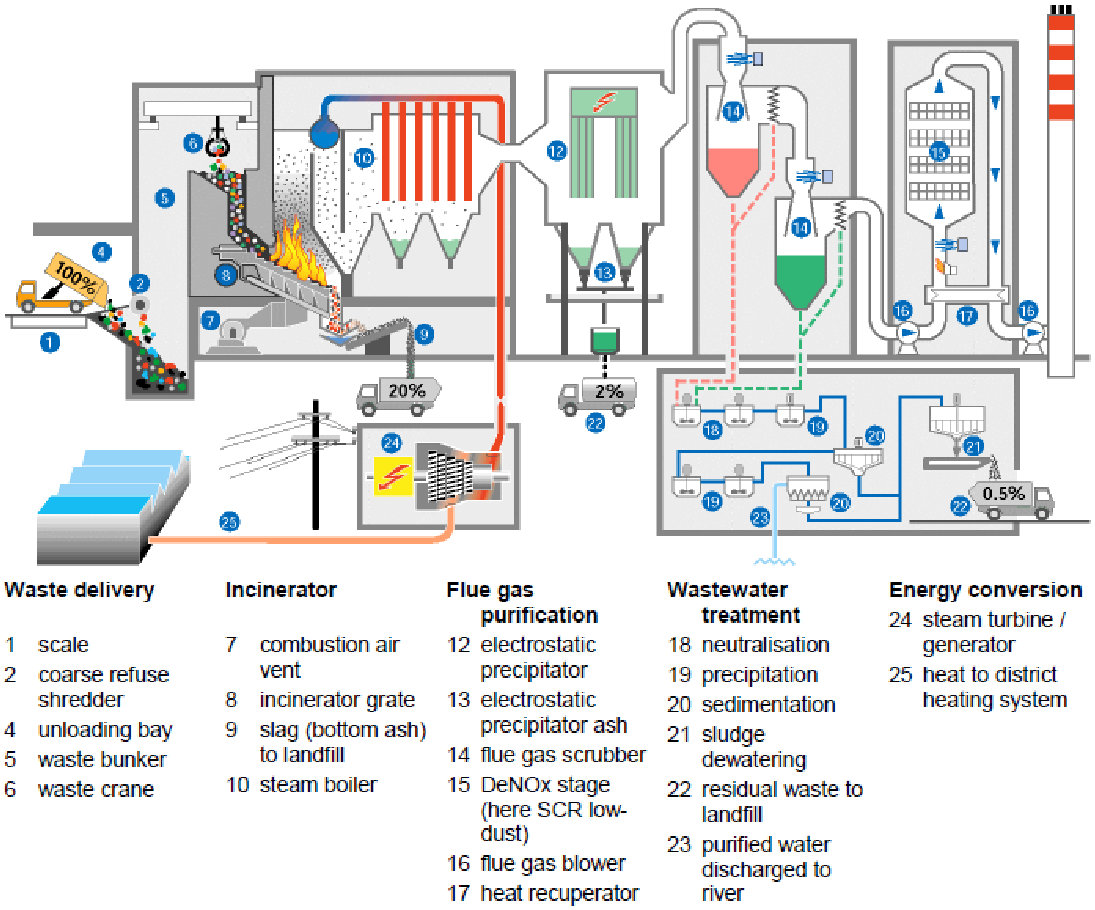


Figure A- 2- Scheme of a typical Swiss municipal solid waste incinerator (Doka G., 2003).

7.3.2 Industrial Composting

There are two main factors that make a material compostable: the material itself and the microorganisms in the compost. A compost pile is a great source of microbial activity, because it has a high moisture content and temperature. This makes it is a suitable environment for a variety of microbes, such as bacteria, to live and reproduce. Those microorganisms are able to attack and biodegrade the organic materials, by enzymatic mechanisms that can be divided into two categories: enzymatic oxidation or enzymatic hydrolysis, followed by mineralization, as shown in Figure A- 3.

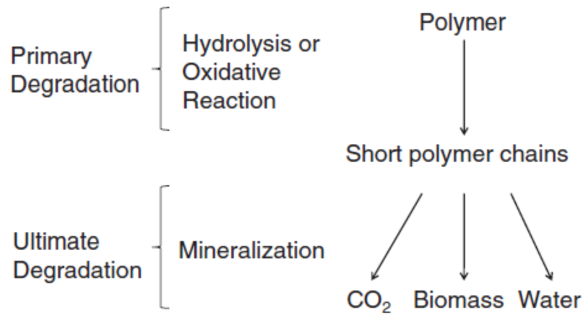


Figure A- 3- Schematic of polymer biodegradation mechanism.

Since biodegradation is an enzymatic reaction, it is very specific to chemical bonds and structures of particular functional groups. Microorganisms can attack only specific functional groups at specific sites, and the polymer chain also has to be conformationally flexible enough to fit into the active site of the enzyme. PLA and food waste are polymers that have atoms such as carbon, oxygen and nitrogen, in their backbones. Those atoms make the polymers susceptible to hydrolysis and therefore susceptible to biodegradation. Hydrolysis is controlled in part by the rate of diffusion of the water in the amorphous regions of the polymer. Some plastics like PLA, will not biodegrade without prior hydrolysis (Gopferich, 1997). Food waste has a high moisture content and little physical structure, and is very susceptible to odor production and tends to generate large quantities of leachate. (Hampton, 2017).

7.3.3 Anaerobic Digestion

Anaerobic digestion is used to treat organic waste with the ability to recover energy in the form of biogas (mainly methane). Anaerobic digestion is also a naturally occurring process of decomposition and decay, by which organic matter breaks down into simple chemical compounds, producing biogas and digestate (a relatively stable oil residue similar to compost). Biogas is a mixture of gases, mainly methane, which can be used to produce heat and electricity, and carbon dioxide. The digestate can be used as a soil amendment, much like humus, for application like farming or landscaping.

At the moment, more than 200 AD plants worldwide, are processing different types of organic waste, especially in Germany where many of them are situated. (IEA, 2017) Those plants can be characterized according to the following options: 1) dry/wet digestion and 2) thermophilic/ mesophilic digestion. If the process is dry or wet depends on the moisture content in the reactor (dry: less than 75%, wet: more than 90%). The systems have different moisture content which differ in a wide range, between 0% to 94%, which means that coffee cups, yogurt cups and coffee capsules will operate as dry process and the cucumber and tea bag as wet process. The temperature is externally controlled, and digesters are run either at mesophilic temperatures (35-40°C), or at thermophilic temperatures (50-55°C). In these two temperature zones, different types of anaerobic bacteria show maximum activity (mesophilic and thermophilic bacteria respectively). The rate of activity is higher at thermophilic temperature.

7.3.4 Landfill

A landfill is a site dedicated for the disposal of waste materials by burial. A sanitary landfill is isolated from the environment by measures to control the leachate and gas emissions. For this purpose, the landfill is equipped with a bottom liner and a surface seal. The bottom line consists of several layers. As leachate forms and passes through the waste, organic and inorganic compounds become dissolved and suspended in the leachate potentially contaminating groundwater and surface water. For this purpose, landfills are equipped with drainage systems and usually also with waste water treatment installations.

7.4 Appendix A4 – Incineration dataset

Table A- 9– Life cycle inventory data for the incinerator.

Incineration in Europe						
Technical configuration						Source
Furnace						
Furnace type	Grate					(Doka G., 2003)
Input Waste	Coffee Cup	Yogurt Cup	Coffee Capsule	Tea Bag	Cucumber	
Lower Heating value (MJ/FU)	17.76	17.31	61.2	31.64	-59.68[1]	Calculations – Appendix A
Energy Recovery – Co-Generation Heat and Power Efficiencies						
Electricity, net	25%					(Walter R. Niessen, 2010)
Heat, net	65%					(Walter R. Niessen, 2010)
Ancillary materials						
Sodium Hydroxide (NaOH) (kg/FU)	1.9×10^{-4}					(Doka G., 2003)
Quicklime (kg/FU)	3.3×10^{-4}					(Doka G., 2003)
Hydrochloric acid (kg/FU)	8.8×10^{-5}					(Doka G., 2003)
Iron Chloride (kg/FU)	1.0×10^{-4}					(Doka G., 2003)
Ammonia (kg/FU)	1.2×10^{-3}					(Doka G., 2003)
Cement (kg/FU)	1.3×10^{-3}					(Doka G., 2003)
DeNox catalyst	7.7×10^{-5}					(Doka G., 2003)
Gaseous emissions	Coffee Cup	Yogurt Cup	Coffee Capsule	Tea bag	Cucumber	
CO_2 (kg/FU)	1.83	1.12	0.61	0.27	0.08	Stoichiometric calculations
NO_2 (kg/FU)	0	0.002	0.01	0.01	0.001	Stoichiometric calculations

[1] Products like the cucumber, which LHV is negative, can't be disposed in a municipal waste incineration because they would take more energy to burn than would be given out by their combustion.

						and (Doka G., 2003)
H_2O (kg/FU)	0.5	0.7	0.87	0.92	0.98	Stoichiometric calculations
Solid Outputs	Coffee Cup	Yogurt Cup	Coffee Capsule	Tea bag	Cucumber	
Bottom and fly ashes (kg/FU)	0.15	0	0.15	0	0	Stoichiometric calculations

7.5 Appendix A5 – Composting dataset

Table A- 10- Life cycle inventory data for the composting.

Composting of bio-waste		
Apparatus		Source
Technology	Enclosed Technology	(Boldrin A., 2009)
Bio filters	Catch CH_4, $NO_\times$ and N_2O emissions	(Boldrin A., 2009)
Conditions		
Temperature (ºC)	Thermophilic conditions (58±2)°C	(B.G Hermann, 2011)
Water content (%wt.)	50-60%	(Trautmann, 2017)
Biodegradation of materials		
PLA packaging (%wt.)	95% C degradation	(B.G Hermann, 2011)
Food waste (%wt.)	70% C degradation	(Boldrin A., 2009)
Food waste (%wt.)	70% N degradation	(Boldrin A., 2009)
Gaseous emissions		
CO_2 production (%wt.)	95% of C-emitted	(Andersen, 2010)
CH_4 production (%wt.)	4% of C-emitted	(Andersen, 2010)
CO production (%wt.)	1 % of C-emitted	(Andersen, 2010)
$NO_\times$ production (%wt.)	99.2% of N-emitted	(Andersen, 2010)
N_2O production (%wt.)	0.8% of N-emitted	(Andersen, 2010)
Bio filters		
Removal efficiency of CH_4 (%)	47-100%	(Boldrin A., 2009)
Removal efficiency of N_2O (%)	90%	(Boldrin A., 2009)
Production of compost		
PLA packaging (%wt.)	5% C mineralization	(B.G Hermann, 2011)
Food waste (%wt.)	30% C mineralization	(Boldrin A., 2009)
Food waste (%wt.)	30% N mineralization	(Boldrin A., 2009)
Production of Leachates		
H_2O production	Depends on the waste composition	Stoichiometric calculations
Production of waste		
Waste	Inorganic waste	(B.G Hermann, 2011)

7.6 Appendix A6 - Anaerobic Digestion dataset

Table A- 11- Life cycle inventory of anaerobic digestion.

Anaerobic Digestion of bio-waste			
Apparatus			Source
Technology		Dry/Wet Digestion	(MØller, 2009)
Conditions			
Temperature (ºC)		Thermophilic conditions	(MØller, 2009)
Water content (%)		0-99%	(MØller, 2009)
Biodegradation of materials			
PLA packaging (%wt.)		60% C degradation	(Jae Choon Lee, 2016)
Food waste (%wt.)		70% C degradation	(Boldrin A., 2009)
Food waste (%wt.)		70% N degradation	(Boldrin A., 2009)
Gaseous emissions			
Biogas production	CO_2 production (%mol)	Table 13- Biogas composition	
	CH_4 production (%mol)	Table 13- Biogas composition	
NH_3 production (%wt.)		100% of N-emitted	Buswell's equation
Biogas			
Biogas collection (%)		95%	(Krueger M, 2006)
CH_4 flared (%)		4%	(MØller, 2009)
CH_4 emissions (%)		1%	(MØller, 2009)
Combined Heat and Power Plant			
Electricity, net		25%	(Walter R. Niessen, 2010)
Heat, net		65%	(Walter R. Niessen, 2010)
Production of Leachates			
H_2O production		Depends on the waste composition	Stoichiometric calculations
Production of waste			
Waste		Inorganic waste	(B.G Hermann, 2011)

7.7 Appendix A7 – Results of all Life Cycle Stages

This chapter has all the results of each life cycle stage per impact category.

7.7.1 Non-renewable and renewable energy impacts for all stages

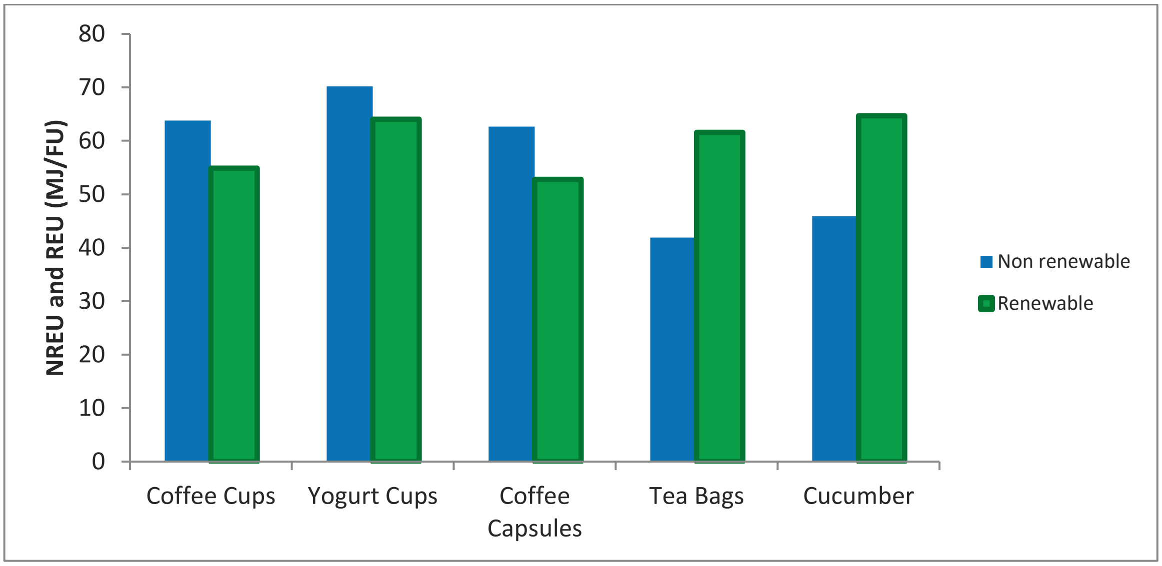
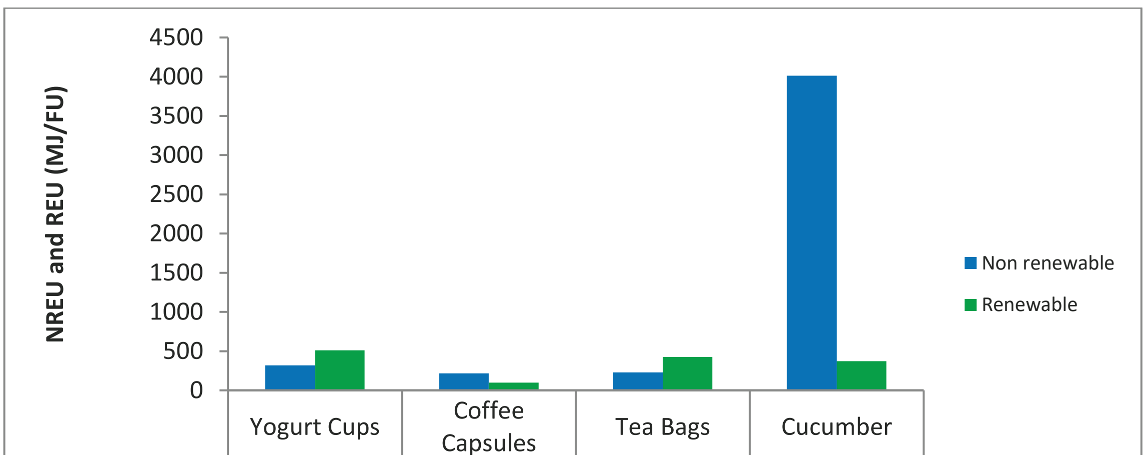
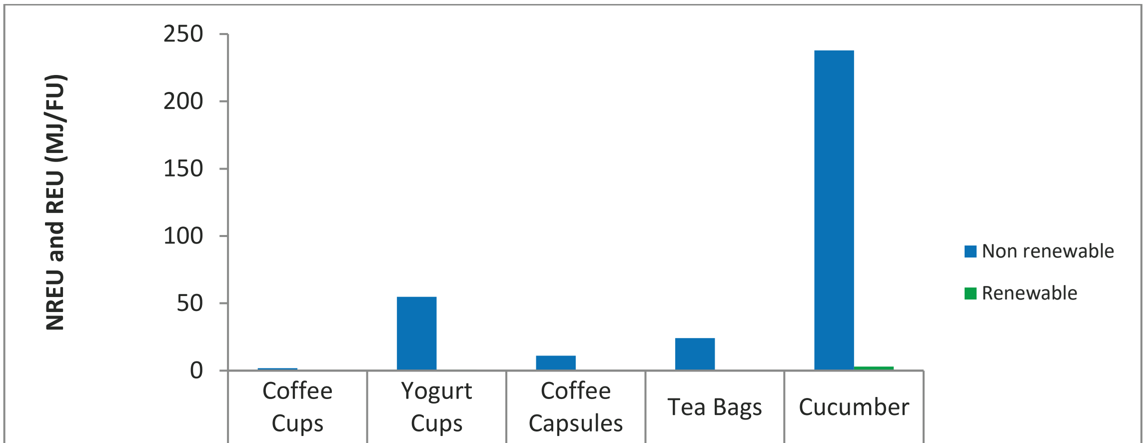


Figure A- 4- Non-renewable and renewable energy impacts of Packaging stage.



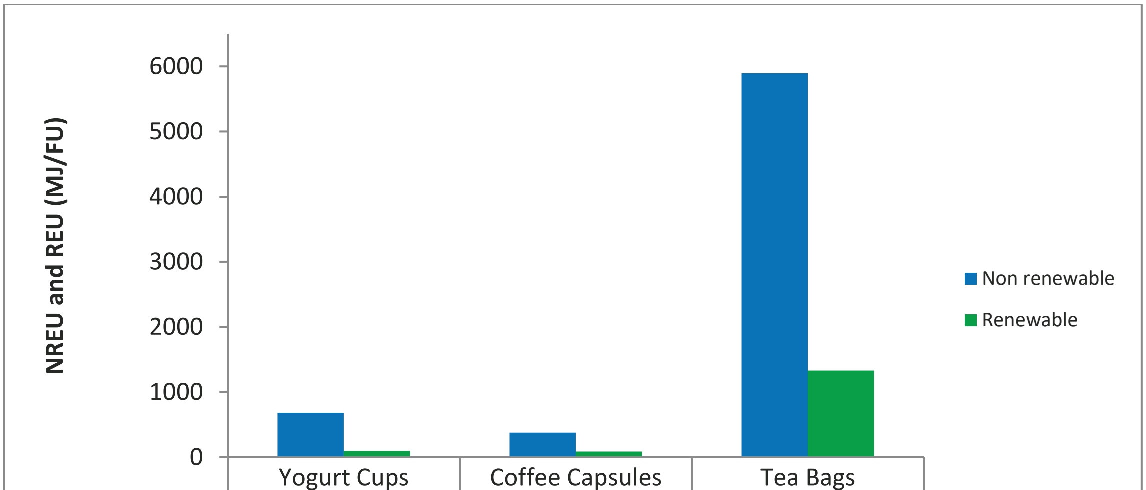
	Yogurt Cups	Coffee Capsules	Tea Bags	Cucumber
Non renewable	319,19	218,02	229,25	4013,64
Renewable	510,79	99,01	425,65	372,96

Figure A- 5- Non-renewable and renewable energy impacts of Food Supply stage.



	Coffee Cups	Yogurt Cups	Coffee Capsules	Tea Bags	Cucumber
Non renewable	1,84	54,87	11,05	24,15	237,81
Renewable	0,02	0,68	0,14	0,30	2,95

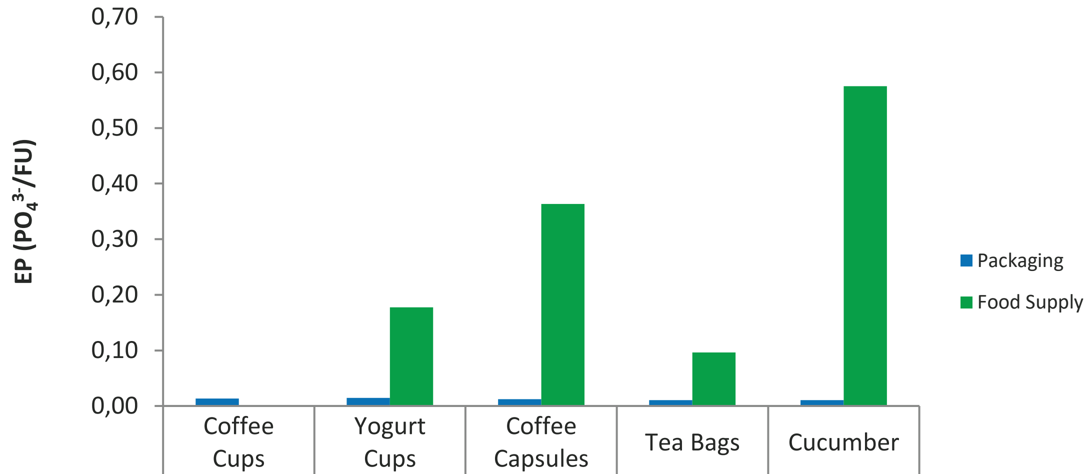
Figure A- 6- Non-renewable and renewable energy impacts of Distribution stage.



	Yogurt Cups	Coffee Capsules	Tea Bags
Non renewable	683,30	377,48	5895,61
Renewable	95,95	87,48	1332,56

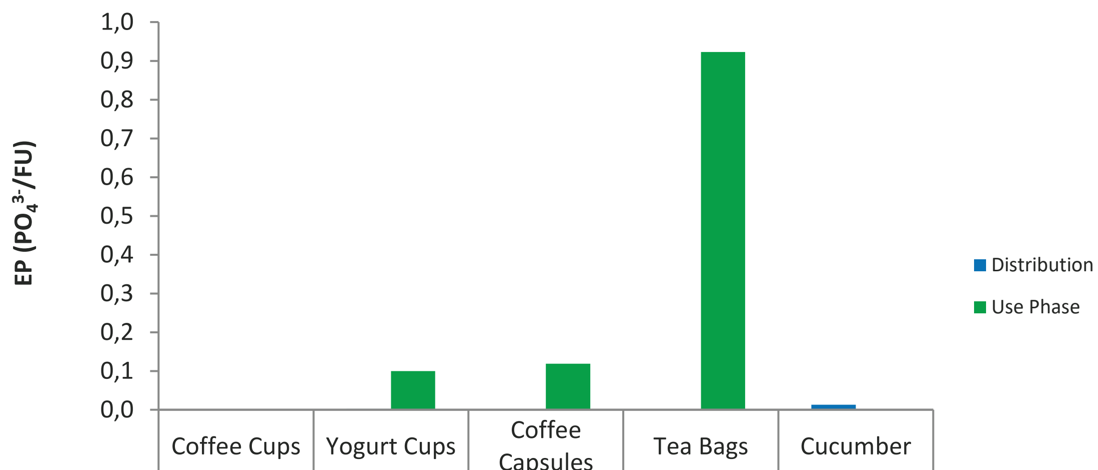
Figure A- 7- Non-renewable and renewable energy impacts of Use stage.

7.7.2 Eutrophication potential



	Coffee Cups	Yogurt Cups	Coffee Capsules	Tea Bags	Cucumber
Packaging	0,013	0,01	0,01	0,01	0,01
Food Supply	0	0,18	0,36	0,10	0,58

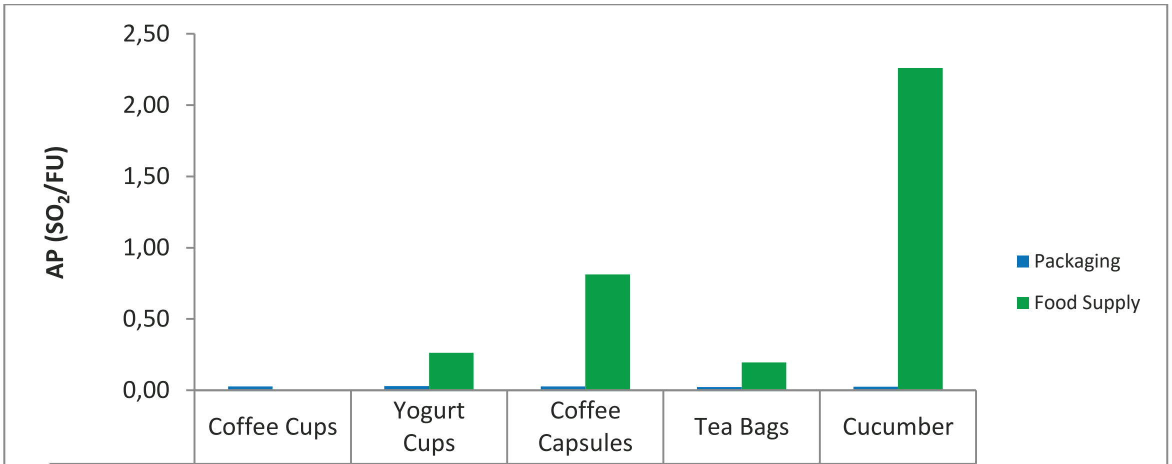
Figure A- 8- Eutrophication potential of Packaging and Food supply stages**.**



	Coffee Cups	Yogurt Cups	Coffee Capsules	Tea Bags	Cucumber
Distribution	0,0001	0,00	0,001	0,001	0,01
Use Phase	0	0,10	0,12	0,92	0

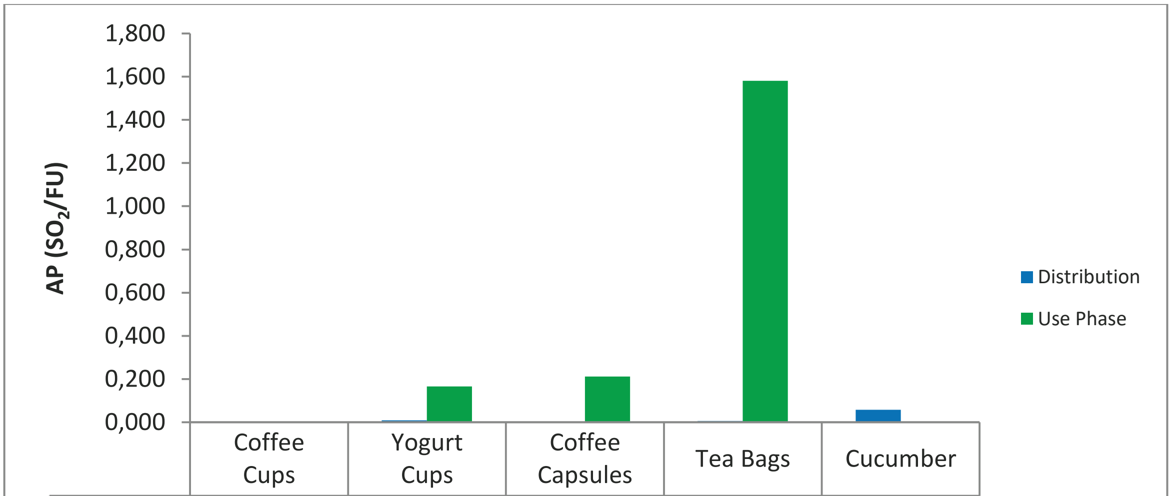
Figure A- 9- Eutrophication potential of Distribution and Use stages.

7.7.3 Acidification potential



	Coffee Cups	Yogurt Cups	Coffee Capsules	Tea Bags	Cucumber
Packaging	0,028	0,03	0,03	0,02	0,02
Food Supply	0	0,26	0,81	0,20	2,26

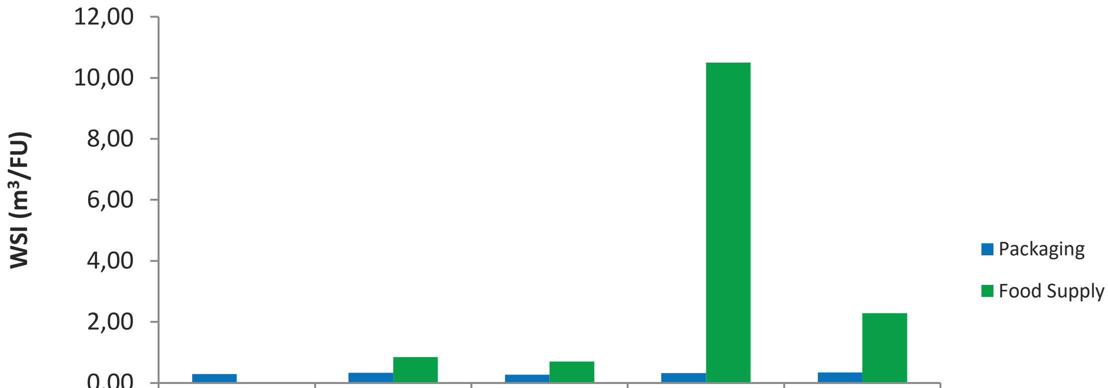
Figure A- 10- Acidification potential of Packaging and Food supply stages.



	Coffee Cups	Yogurt Cups	Coffee Capsules	Tea Bags	Cucumber
Distribution	0,00045	0,01	0,003	0,01	0,06
Use Phase	0	0,17	0,21	1,58	0

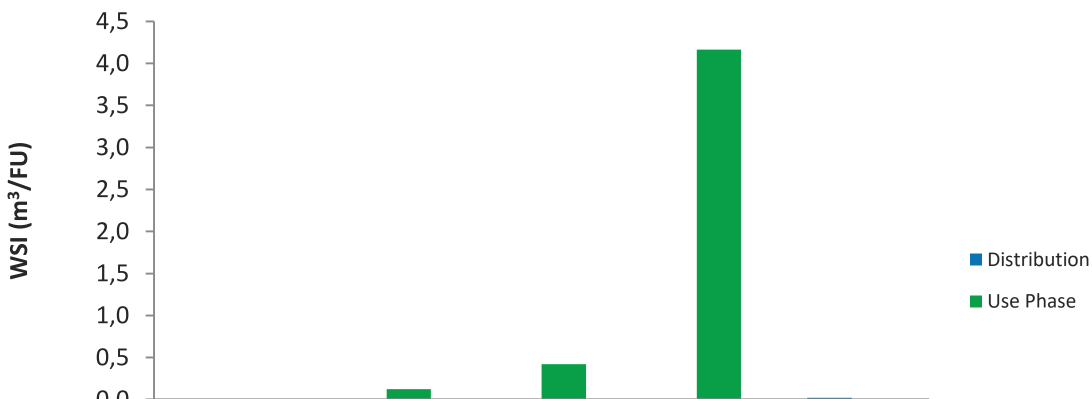
Figure A- 11- Acidification potential of Distribution and Use stages.

7.7.4 Water Scarcity



	Coffee Cups	Yogurt Cups	Coffee Capsules	Tea Bags	Cucumber
Packaging	0,29	0,33	0,27	0,32	0,34
Food Supply	0	0,85	0,70	10,50	2,29

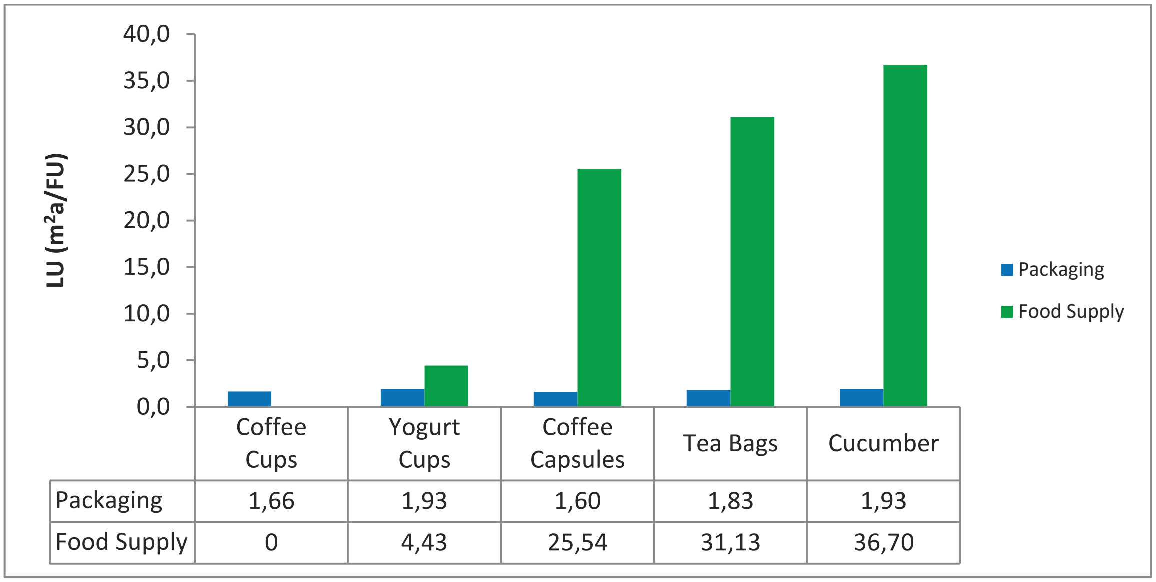
Figure A- 12- Water Scarcity potential of Packaging and Food supply stages.



	Coffee Cups	Yogurt Cups	Coffee Capsules	Tea Bags	Cucumber
Distribution	0,00017	0,01	0,001	0,002	0,02
Use Phase	0	0,12	0,42	4,17	0

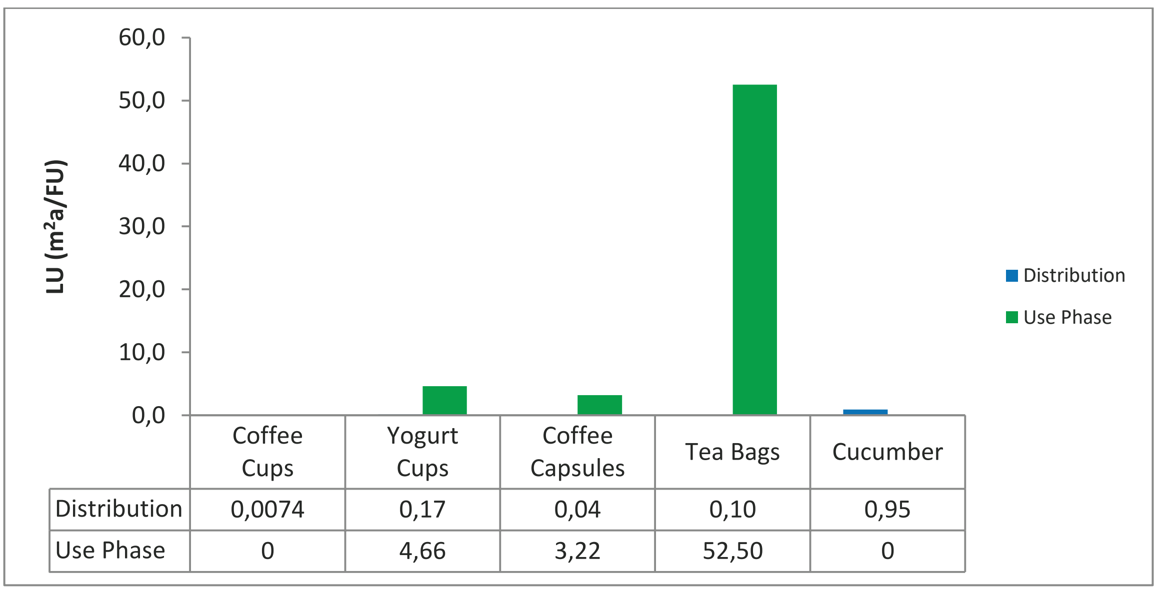
Figure A- 13- Water Scarcity potential of Distribution and Use stages.

7.7.5 Land use



	Coffee Cups	Yogurt Cups	Coffee Capsules	Tea Bags	Cucumber
Packaging	1,66	1,93	1,60	1,83	1,93
Food Supply	0	4,43	25,54	31,13	36,70

Figure A- 14- Land use potential of Packaging and Food supply stages.



	Coffee Cups	Yogurt Cups	Coffee Capsules	Tea Bags	Cucumber
Distribution	0,0074	0,17	0,04	0,10	0,95
Use Phase	0	4,66	3,22	52,50	0

Figure A- 15- Land use potential of Distribution and Use stages.