Life Cycle Assessment study of Polylactic Acid Packaging including Food Waste

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ARTICLE INFO

Date:

November 2017

Keywords

Bioplastics

Life Cycle Assessment (LCA)

PLA

Cradle-to-grave

End-of-life

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, coffee capsules. Industrial composting is more favorable for food packaging with high moisture content, such as tea bag and cucumber. 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 air emissions.

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 [1].

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 [2].

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 [3]. 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 [4].

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 [5].

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.

*2.*Methodology

2.1 Goal and Scope

The goal of this LCA is to quantify the environmental footprint of different PLA food packaging products including the food waste through a cradle-to-grave LCA, focusing on the end-of-life options. It includes different disposal alternatives, such as incineration with energy recovery, industrial composting, anaerobic digestion and landfill. The reference flow, called functional unit, is considered as 1 kg of PLA packaging including food waste from households, as the comparison unit in order to promote equivalence between the systems. The SimaPro software was used as a tool to facilitate the LCA implementation. The database used for background processes was Ecoinvent v3.3. The PLA inventory data were developed and collected by Total-Corbion from the core data for sugar cane milling, lactic acid and polymer production from their factory in Thailand.

2.2 System Description

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 modelled 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. 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, composting, incineration and landfill.

2.3 Life Cycle Inventory

2.3.1 Food supply

The dataset used for the four models with food supply were taken from the Ecoinvent 3.3 database.

2.3.2 PLA Feedstock

PLA is a thermoplastic material with rigidity and clarity similar 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 [6]. 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.

2.3.3 Packaging 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 [7]. 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. Table 1 summarizes the conversion processes together with the respective products produced from the different processes.

Table 1- Different conversion processes per product.

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

2.3.4 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 2.

Table 2 - Assumptions for distribution (Quantis, 2011) [8].

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

2.3.5 Use Stage

The consumption phase represents activities conducted by the consumer after purchasing the products. For coffee capsules, the use stage includes the machine and coffee cup. Even though the coffee capsules are modelled 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 [8].

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 [9]. 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 10g of waster remain in the leaves. To boil the water with a kettle 49.5 MJ of electricity per kg tea is needed [10]. 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 in. No refrigeration is needed.

2.3.6 End-of-life treatment processes

i) Incineration

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.

a) Air emissions

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 carbon dioxide (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

$$C_6H_8O_4 + 6\,O_2 \rightarrow 6CO_2 + 4\,H_2O \tag{1}$$

Yogurt

$$C_{0.8}H_{3.3}O_{1.3}N_{0.04} + 1\,O_2 \rightarrow 0.8\,CO_2 + 1.65\,H_2O + 0.04\,NO_2 \tag{2}$$

Coffee

$$C_{4.4}H_{9.5}O_{3.6}N_{0.1} + 5\,O_2 \rightarrow 4.4\,CO_2 + 4.75\,H_2O + 0.1\,NO_2 \tag{3}$$

Tea

$$C_{2.9}H_{5.8}O_{2.8}N_{0.14} + 3.1\,O_2 \rightarrow 2.9\,CO_2 + 2.9\,H_2O + 0.14\,NO_2 \tag{4}$$

Cucumber

$$C_{0.5}H_{2.9}O_{1.4}N_{0.02} + 0.5\,O_2 \rightarrow 0.5\,CO_2 + 1.45\,H_2O + 0.02\,NO_2 \tag{5}$$

b) Energy Recovery

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 [11]. 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).

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 [12].

ii) Industrial Composting

The biodegradation model for average industrial conditions was built based on the literature review done by [13]. It 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 [14].

It 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. 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) [15]. A study performed by Cargill Dow LLC showed that the hydrolysis rate of PLA increased dramatically above the glass transition temperature.

a) Gaseous emissions

The main gaseous emissions from composting are CO_2 biogenic, methane (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 [16]. The efficiencies of bio filters depend on air flow, load, residence time, materials and design [17].

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. 95 wt.%, 4 wt.% and 1 wt.% of the degraded C emitted turns into three direct emissions, CO_2, CH_4 and CO, respectively.

All systems except the coffee cup meet C/N ratio 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 N will turn into nitrogen oxides (NO_x) and only 0.8 wt.% into N_2O. The main greenhouse gases (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% [16].

iii) Anaerobic Digestion (AD)

It is a waste management process for organic waste materials producing biogas and a stabilized residue, called digestate, that can be used on agricultural land [18]. 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 [19]. The biodegradation of PLA, requires thermophilic conditions and a lengthy time for complete mineralization to CO_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 [20].

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.

a) Biogas

Biogas production from organic substrates involves an internal redox reaction that converts organic molecules to methane and carbon dioxide, 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) and nitrogen (N). Applying this equation to each system, it allows the calculation of the value of biogas produced, which is displayed on Table3:

PLA

$$C_6H_8O_4 + water \rightarrow 3CO_2 + 3CH_4 \quad (6)$$

Yogurt

$$C_{0.8}H_{3.3}O_{1.3}N_{0.04} + water \rightarrow 0.32\ CO_2 + 0.45\ CH_4 + 0.04\ NH_3 \quad (7)$$

Coffee

$$C_{4.4}H_{9.5}O_{3.6}N_{0.1} + water \rightarrow 1.96\ CO_2 + 2.44\ CH_4 + 0.13\ NH_3 \quad (8)$$

Tea

$$C_{2.9}H_{5.8}O_{2.8}N_{0.14} + water \rightarrow 1.5\ CO_2 + 1.4\ CH_4 + 0.14\ NH_3 \quad (9)$$

Cucumber

$$C_{0.5}H_{2.9}O_{1.4}N_{0.02} + water \rightarrow 0.27CO_2 + 0.27\ CH_4 + 0.02\ NH_3 \quad (10)$$

Table 3- 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 3, the organic wastes produced biogas in a range that is expected and reported in (Burke, 2001) [19]. 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 co-generation of heat and power (CHP) plant was used for electricity and heat production, in incineration, and will be used in AD as well.

iv) Landfill

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 database, there is no information about PLA landfilling, so the PET landfill model is used as a basis for the PLA model.

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 CO_2, CH_4 and ammonia (NH_3) emissions and leachate. Landfilling works under anaerobic conditions, so the equation used in AD to calculate the values of the gaseous emissions is the same. Food waste can produce methane, carbon dioxide, ammonia and a liquid called leachate when it breaks down in landfills, which can contaminate water supplies. Leachate is collected and processed in a water treatment plant.

3. Results and Discussion

3.1 End-of-life options

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. Figure 1 shows the global warming potential (GWP) of landfilling for every system. As mention before, PLA will hardly degraded in landfills over the 100-year time scale considered, 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.

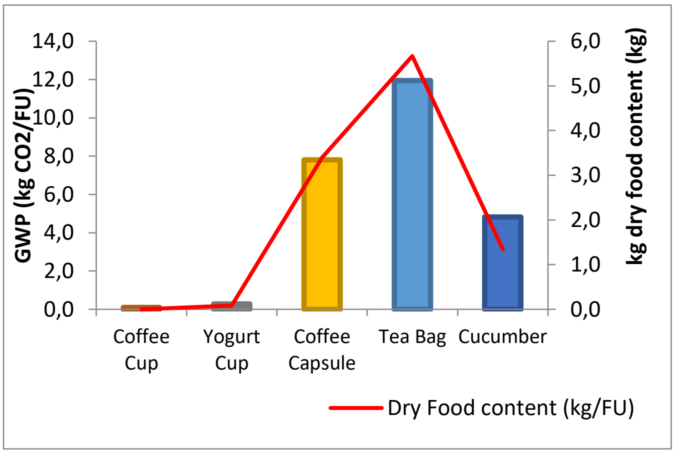

Figure 1 - Global Warming Potential of Landfill.

Figure 2 shows the GWP of composting and incineration. One of the most striking results to emerge from Figure 2 is that Incineration is favourable for packaging with low moisture content (<70%) like coffee cup, yogurt cup, coffee capsule. 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) [21], that show incineration of dry PLA has a small environmental impact. Remarkably, industrial composting is favourable for all the systems, even for food packaging with a high moisture content. For the coffee cup, 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.

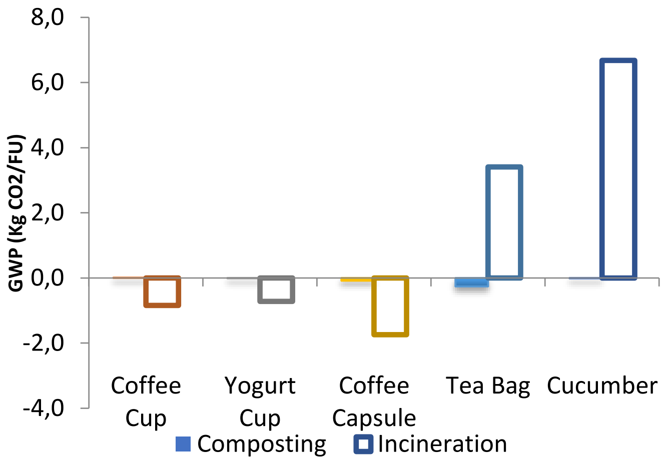

Figure 2 – Global Warming Impact of Composting and Incineration.

Finally, the last disposal treatment is Anaerobic digestion, shown in Figure 3. 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.

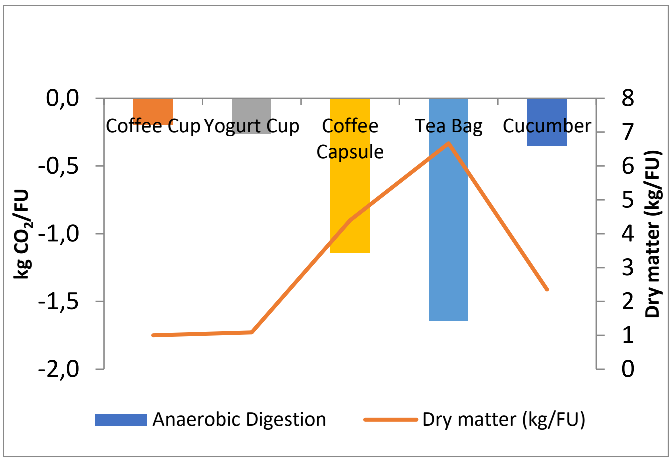

Figure 3 – Global Warming Impact of Anaerobic Digestion.

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) [21] and further support the conclusions that (V. Rossi, 2015) [22] achieved.

3.1.2 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 wet low heating value (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 4, 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.

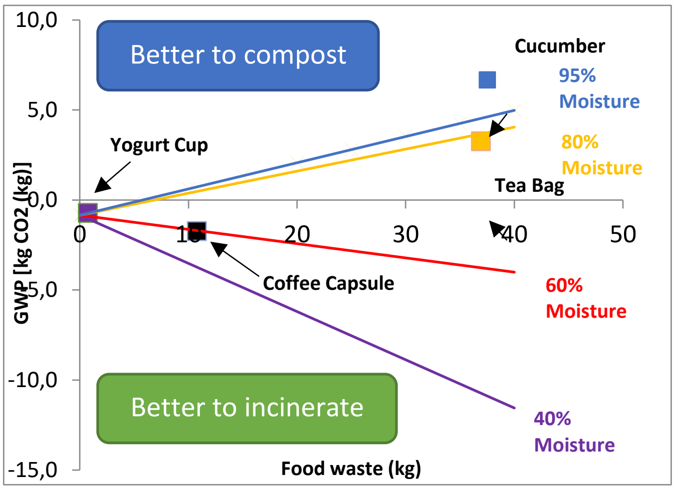

Figure 4 – Theoretical graph about a correlation between GWP, food waste and moisture matter of each system.

3.1.2 Non-renewable 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 5 and Figure 6 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.

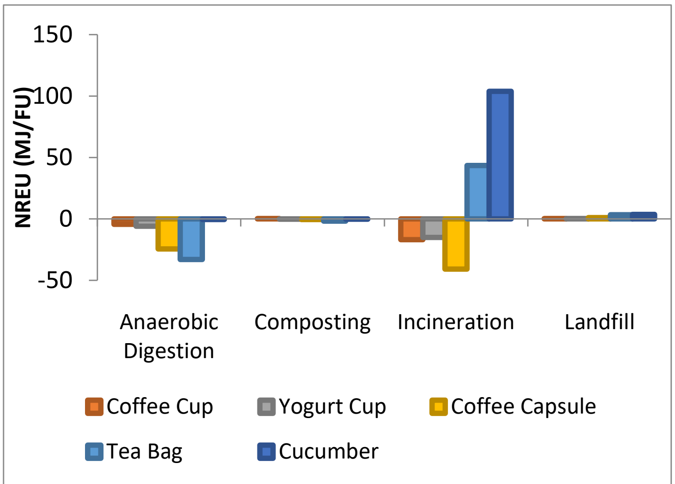

Figure 5 - Non-renewable energy of end-of-life options.

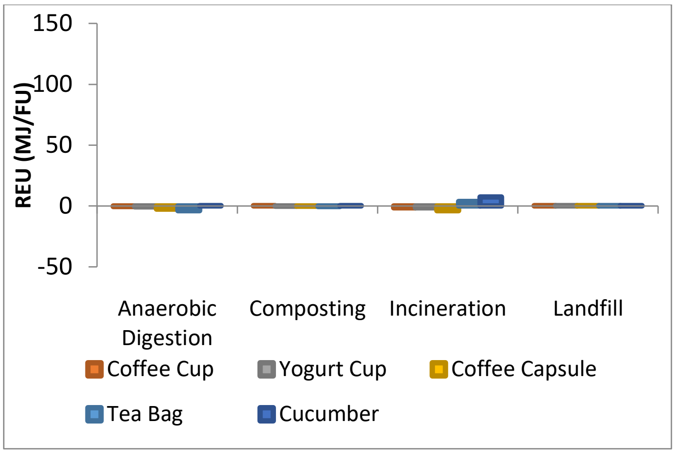

Figure 6 - Renewable energy of end-of-life options.

3.2 LCA stages

The complete life cycle results for the five food packaging systems are presented in Figure 7 for the global warming potential indicator.

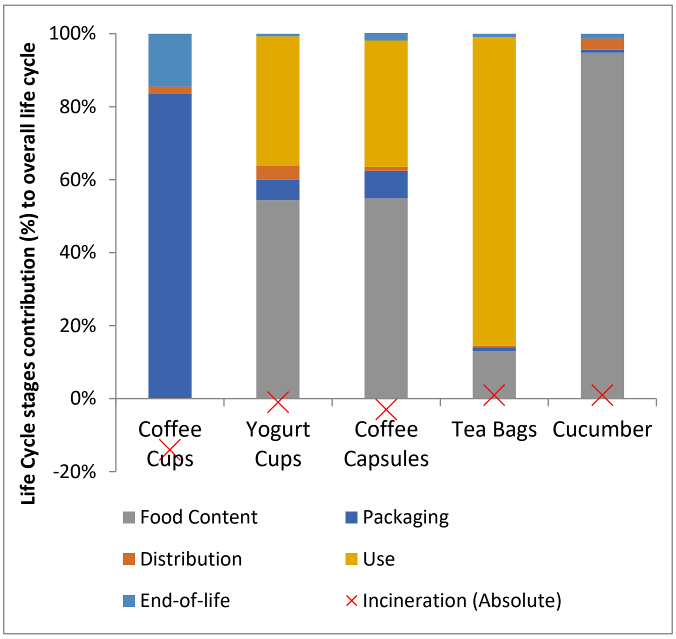

Figure 7 – Overall comparative results for GWP.

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.

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

As an extra analysis, the GWP of incineration of fossil-based polymers was quantified, as comparison with PLA. The only way to analyse 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 8, 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.

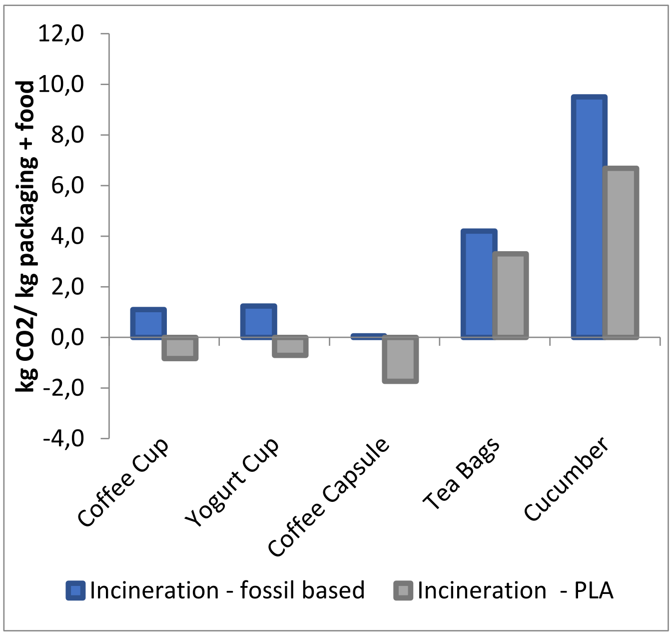

Figure 8 - Global warming potential of fossil-based plastics vs bioplastics.

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.

A sensitivity analysis on incineration with energy recovery has been performed by changing the efficiency of the CHP plant. The results showed that electricity and heat efficiencies are a critical parameter, and the better they are, the smallest the environmental footprint will be.

Other two analyses were made on AD and industrial composting, showing that percentage of biodegradability of PLA and the amount of methane retained by biofilters are critical parameters, that can modify the environmental footprint.

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 favourable 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 favourable 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.

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