Integration of food shelf-life in life cycle assessment of polymers

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MASTER THESIS

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Abstract

Biopolymers are being considered as a promising alternative to fossil-based polymers and this inclination towards biopolymers is due to their lower environmental impact owing to their origin from renewable resources. The environmental impact assessment, however, often does not consider the impact of barrier properties of polymers and the resulting differences in food waste generated in the supply chain. The goal of this project is to develop a shelf-life estimation tool for estimating the shelf-life offered by PET, PLA, and PEF for liquid food. The estimated shelf-life is used to quantify the food waste in retail due to differences in the barrier properties of the polymers, which is then included in the LCA of these packaging materials. The data required to complete these steps were obtained from various scientific articles and reports. Based on the findings, the conclusion highlights the difference that including food waste can bring in the total environmental impact of packaging material. The project compares the LCA of PEF, PET and PLA. The results highlight that when fossil-based polymers, like PET, are recycled, their overall environmental impact, due to packaging, could be lower than some biopolymers like PLA. According to the findings and analyses of different studies, including food waste in packaging LCA would aid in the design and development of more sustainable packaging material. The project also concludes that, food waste can have an impact on the overall environmental performance of the packaging material and that using packaging materials that extend shelf life decreases the impact percentage. Thus, the relationship between increased shelf life and reduced food waste is demonstrated implicitly.

Keywords: Food shelf-life, life cycle assessment, biopolymers, food packaging, sustainability, shelf-life induced food waste

Executive summary

Introduction and Background

Packaging is one of the most important elements for ensuring that food reaches consumers with all of its quality attributes intact. Growing population, rising food consumption, and evolving consumer preferences have led producers to look for packaging materials that can preserve food quality while also being convenient for consumers. The increased waste generated by food packaging is a challenge that arises from this scenario. Waste management is a global concern, and the growing manufacturing of food packaging material is contributing to the problem. Polymers produced from fossil fuels are used in the majority of packaging materials today. The increased demand for these polymers is owing to several factors, including their lightweight, ability to be easily moulded into any form, and potential for food protection. However, these polymers contribute to Greenhouse gas (GHG) emissions as well as marine pollution. Plastic packaging contributes to GHG emissions at every stage of its life, as per environmental impact studies (FoodPrint, 2019).

Biopolymers are in high demand as they are produced from renewable resources and, in most cases, from materials derived from food, such as sugarcane. As a result, their GHG emissions during the manufacturing process are lower than those of fossil-based polymers. Some biopolymers are also biodegradable. However, many of commercially available biopolymers perform poorly in terms of food protection and shelf-life extension and are therefore used for short shelf-life products. As a result, experts in life cycle assessment (LCA) have emphasised the need to include food waste produced as a result of packaging barrier property in their LCA. Few studies have attempted to incorporate shelf-life expiration-related food waste into packaging material LCA. Some of these studies used experimental data to quantify food waste, while others assumed the amount of food waste due to shelf life. In either instance, studies show that when this type of food waste is taken into account, the indirect impact of food is higher than the direct impact of packaging.

Method

This project's goal can be divided into two parts. The first part is to evaluate and understand shelf-life prediction models, as well as how they incorporate packaging material barrier property. The second part is developing a simple shelf-life prediction tool and incorporating the results into the packaging material's LCA. Food waste generated as a result of shelf-life expiration is important for the LCA, hence estimating shelf-life is not enough. It is difficult to establish a relation between shelf-life and food waste caused as a result of shelf-life expiration. WRAP conducted studies in this area, and the relation in this study was used to calculate the amount of food waste caused due to shelf-life expiration. This calculated food waste was then included in the LCA of packaging materials. The approach used to achieve the project's goal are illustrated in the figure below.

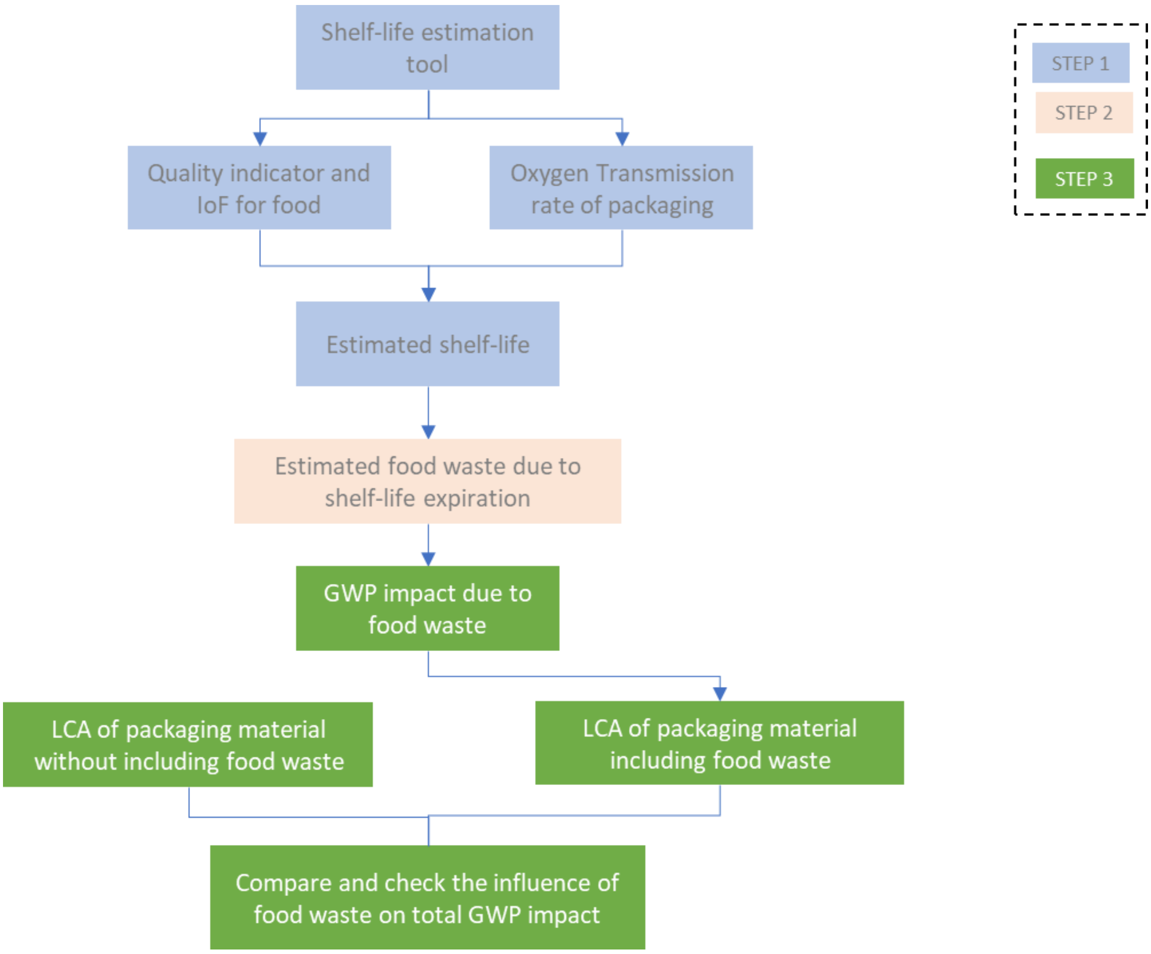

Figure I Approach used in the project

The dimensions and volume of the package were calculated using information from the literature. Scientific articles provided the permeability values needed to calculate the oxygen transmission rate (OTR) of different packaging materials. The estimated shelf-life generated by the tool was then used to calculate the food waste caused due to shelf-life expiration. The

WRAP report's relation was used for this, and the food waste generated in the supply chain was assigned for Polyethylene terephthalate (PET). This value was used as a baseline in the relation mentioned before and used to calculate the waste generated by Polyethylene 2,5-furandicarboxylate (PEF) and Polylactide (PLA). Finally, the food waste generated as a result of the packing material's barrier property was included in the LCA, and the results were compared and reviewed. Incineration of PET, PLA, and PEF, and an additional recycling scenario for PET, are included in the LCA end-of-life (EOL) scenario.

Result and Conclusion

The developed tool estimated that the biopolymer PEF offers the longest shelf life, followed by PET and PLA. This is in direct relation to each of these materials' oxygen barrier property. PEF has the lowest oxygen permeability of the three packaging materials, whereas PLA has the highest, which is reflected in their shelf-life results. The shelf-life results also imply that some newly developed biopolymers, such as PEF, provide better protection than fossil-based polymers, such as PET, and maybe a better alternative to fossil-based polymers. All calculations were carried out for two different packing sizes, i.e. 1000 ml and 500 ml.

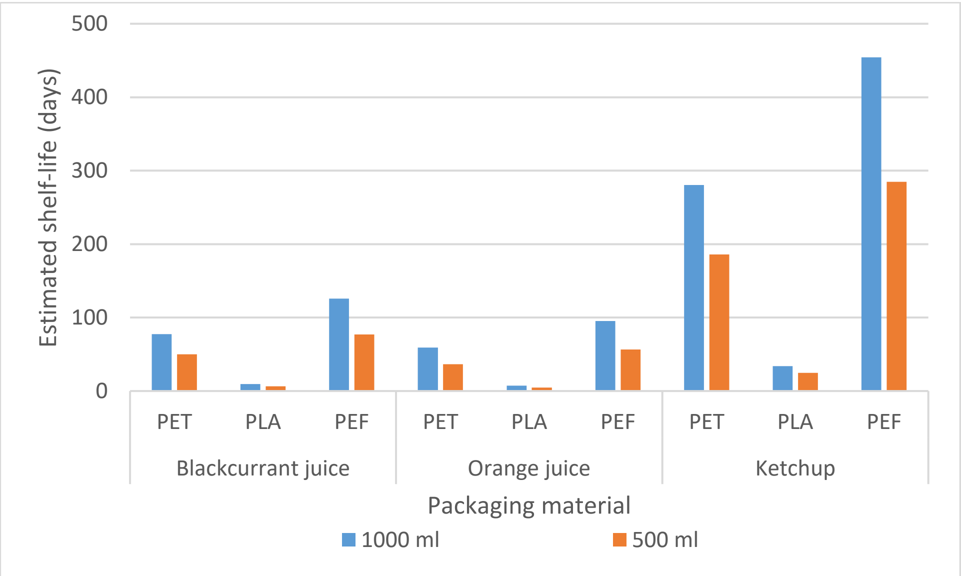

Figure II Shelf-life estimated by the developed tool

First, a comparative LCA was performed on all three packing materials without taking into account food waste. The PET recycling scenario was also considered in the analysis. According to the results, PEF has a 61 per cent lower environmental impact than PET (EOL incineration), while PLA has a 41 per cent lower environmental impact than PET (EOL incineration). When PET recycling is taken into account, PET (EOL recycling) has a 55 per cent lower environmental impact than PET (EOL incineration). The difference between PET (EOL recycling) and PEF reduces drastically with PEF having a 16 per cent lower impact than PET. The LCA results, which exclude food waste, indicate that packaging material production is the largest contributor to GHG emissions. Since biopolymers, PLA, and PEF are made from renewable materials, their total global warming potential (GWP) impact is lower than that of PET. As biopolymer, like PEF, is not manufactured on a large scale, its impact on production can decrease further as production is scaled up.

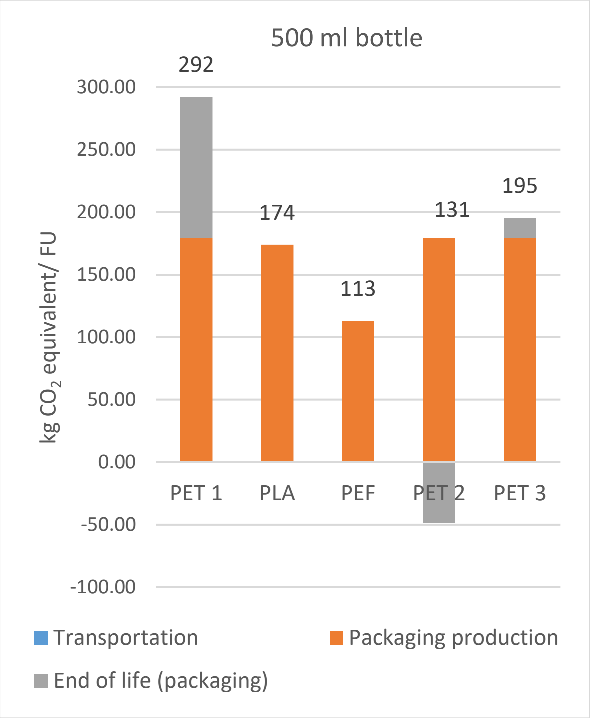

Figure III GWP impact of packaging without considering food waste for 500 ml bottle

The comparative LCA was then performed with food waste included, and the results show that introducing food waste alters the ratio between the GWP contributors and total GWP impact. Because the food product in this report has low GHG emission, the change in the ratio described before is not very evident. However, after including food waste, the GWP impact difference between PLA and PET was lowered by 2 per cent, and the difference between PEF and PET was reduced by 1 per cent. When only the food waste generated as a consequence of the oxygen barrier property of PET, PLA, and PEF were taken into account, PET had a GWP impact that was on average 6 per cent lower than PLA, the packaging with the lowest oxygen barrier property.

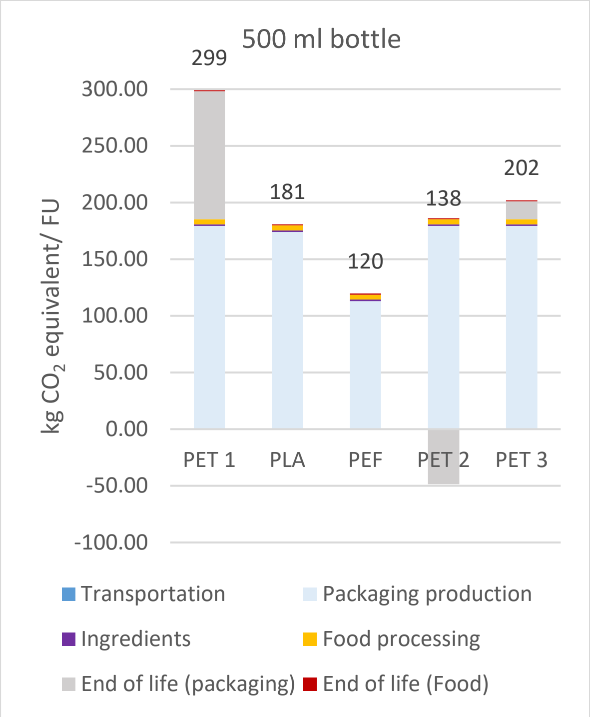

Figure IV GWP impact of packaging including food waste for 500 ml bottle, orange juice

Future research

Monolayer packaging and its oxygen barrier property are considered in this project. Adapting the approach for multilayer packaging and considering other barrier properties will be advantageous for future research. The food items considered in this project have a lower GHG emission and the food waste generated, therefore, has a lower GWP impact. It would be interesting to adapt the method given in this project for a more complex food item and then see the impact of food waste on packaging LCA.

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Lund, June 2021

Divya Nair

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List of abbreviations

CO_2	Carbon dioxide
CO_2e	CO2 equivalent
DMT	Dimethyl ester terephthalate
EG	Ethylene glycol
EU	European Union
FDCA	2,5-furandicarboxylic acid
FU	Functional Unit
GHG	Greenhouse gas emissions
GWP	Global warming potential
HDPE	High density polyethylene
IoD	Quality factor
IoFs	Indices of failure
LCA	Life cycle assessment
O_2	Oxygen
OTR	Oxygen transmission rate
PEF	Poly(ethylene 2,5-furandicarboxylate)
PET	Poly(ethylene) terephthalate
PLA	Poly(Lactic)acid or Polylactide
PS	Polystyrene
RH	Relative humidity
SDG	Sustainable development goals
STEPS	Sustainable Plastics and Transition Pathways
TPA	Terephthalic acid
TR	Transmission rate
UN	United Nations

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1 Introduction

This chapter introduces the aim of this project and what are the objectives behind the project. The chapter gives an insight into the structure of the project.

1.1 Background:

1.1.1 **Food packaging and Barrier properties**

Packaging is often seen as a necessary evil or an unnecessary expense. Many consumers view it as a colossal waste of resources and a threat to the environment. However, the packaging ensures the safe delivery of goods to the end consumer in the best condition intended for their use. It protects contents from contamination and spoilage, making it easier to transport and store goods. Packages serve as a symbol of their contents and a way of life, but they are also potent symbols of wastefulness. (Robertson, 2016) One of the primary functions of food packaging is to protect its contents from outside environmental factors such as water, dust, gas, impacts, shocks, etc., which could harm the product inside. Food packaging helps prevent food spoilage and increases the shelf life of food. One of the important parameters that influence the selection of food packaging materials is barrier properties. Barrier properties protect the food from getting in contact with substances outside the package and thereby prevents spoilage during the intended shelf life. Food deterioration can occur due to food oxidation, moisture loss or gain, loss of desired flavourings etc. Barriers help to minimize food spoilage by reducing the penetration of the above-mentioned factors through the packaging material.

Barrier properties are obtained either by the use of active or passive protection or by a combination of both. Active protection is achieved using additives in packaging material, while passive protection is achieved by adding layers with better barrier properties to existing packaging. The layers used in food packaging vary depending on the type of food to be protected. The materials used to improve barrier properties are usually made of, but not limited to, glass, steel, low-density polyethylene (LDPE), polyethylene (PE), polyamide (PA), Aluminium etc.

1.1.2 **Biopolymers**

Food packaging results in high plastic demand and is therefore regarded as one of the main contributors to plastic waste, challenging plastic waste management globally (Dilkes-Hoffman et al., 2018). One of the disadvantages of using conventional plastics in food packaging is the possibility of toxins from packaging migrating into the food (Grujić et al., 2017). Biopolymers are gaining popularity in food packaging due to increased demand for the use of materials made from renewable sources. The appeal for biopolymers in food packaging also stems from their potential ability to biodegrade and they are expected to have a lower environmental impact than fossil-based polymers. Biopolymers are of various types and are according to their origin and production methods, could be either biodegradable or non-biodegradable. Biodegradable biopolymers can at the end-of-life be treated in industrial composting facilities, and research has shown that biopolymers produced from starch degrade 10-20 times faster than fossil-based plastics. (Grujić et al., 2017)

1.1.3 **STEPS and Life cycle assessment**

Increasing demand for using renewable resources across the food value chain has generated interest in the use of biopolymers in food packaging. STEPS (Sustainable Plastics and Transition Pathways) is a Swedish research program that focuses on developing and promoting sustainable solutions for plastics using renewable materials. The research program is divided into three work packages (WP) namely WP 1, 2 and 3 and this project is part of the work done in WP 3. In WP 3, one of the tasks is to develop an environmental evaluation method/approach for bio-based polymers. WP 3 will also concentrate on identifying the sustainability aspect of biobased polymers and assessing the materials in collaboration with industry stakeholders.

Life Cycle Assessment (LCA) is used to evaluate the environmental impact of products throughout their life cycle. LCA is frequently used to compare the environmental impact of bio-based polymers and fossil-based polymers. (Zhang et al., 2019) Consideration of the barrier properties of biobased polymer for food shelf-life prediction is part of the LCA method being developed in WP 3.

1.2 Purpose and Objective:

1.2.1 **Purpose**

This project will analyse the influence of the barrier properties of the packaging material on shelf life and thereby food waste. Biobased polymers are usually extracted from biomass like proteins, polysaccharides and fats and are considered safe due to their origin. However, there is a risk that these biopolymers will also support microbial growth. Their stability should also be considered during the food shelf-life assessment. (Robertson, 2009a)

High moisture conditions affect some barrier properties of biopolymers such as gas and water vapour transmissions. The barrier properties can be improved by coating them with a thin layer of synthetic polymers. (Siracusa and Rosa, 2018) When LCA of biobased polymers and fossil-based polymers are compared with each other, the production and use of biobased polymers are shown to have a lower environmental impact with regards to the reduction of GHG (Greenhouse gas) emissions and fossil fuel use (Hatti-Kaul et al., 2020).

Studies on agricultural and food production system have shown that the major environmental impact of packed food is often the food item inside the packaging and not the packaging material (Verghese et al., 2012). Also, the demand for packaged food will increase in future resulting in increased shelf-life related food waste therefore inclusion of the environmental impact of shelf-life-related food waste in packaging LCA is required (Conte et al., 2015). Incorporating this element into packaging LCA can aid in the creation of a better packaging solution. The inclusion of food waste in LCAs comparing materials with different barrier properties, would support the development of alternative packaging materials with overall low environmental impact and prevent burden-shifting.

1.2.2 **Objective**

The objective of this project is to evaluate and compare the shelf-life offered by food packaging made of biopolymers and fossil-based polymers. A simple shelf-life estimation tool was developed to estimate the shelf-life of food packed in polymer packaging. The results of the tool were used to estimate differences in food waste between the different polymers which were integrated into the LCA of the packaging materials.

The research questions of the project are:

- How is the shelf-life prediction of packed food performed? What are the factors that are considered while predicting shelf-life?
- How can shelf-life estimation be integrated into packaging LCAs to consider differences in food waste due to shelf-life expiration?
- How will the integration of food waste related to shelf-life expiration influence the environmental impact of the packaging material?

To answer the research question following steps were taken,

- Review the way shelf-life prediction is done and how they include the barrier property of the packaging.

- Gather information on the oxygen permeability of the polymers studied in the project through literature searches, and then develop a simpler shelf-life estimation approach for integrating it in LCA.
- Use secondary data to link shelf-life with food waste and use this value while performing the LCA.
- Compare and analyse the environmental impact of the packaging materials with and without including food waste connected to shelf-life expiration.

1.3 Structure of the report:

The project report consists of five chapters, including the Introduction chapter. Recent research on the use of biopolymers in food packaging, shelf-life prediction model and the LCA method, are analysed in the literature review chapter. The outcome of the literature review is then used in the Methodology chapter to define the approach to be used to develop a model that incorporates shelf-life prediction in food packaging LCAs. The results obtained through the shelf-life estimation tool and the LCA is presented and discussed in the Results and Discussion chapter. The concluding chapter, i.e., the conclusion, summarizes the outcome of the project and suggests areas for future research.

2 Literature

This chapter focuses on giving background on the terms used throughout the project. This chapter is divided into four parts. The first part introduces food packaging material and then presents the different types of packaging material considered in this project. The next part presents barrier properties and how they influence the shelf-life of food. The third part is about life cycle assessment (LCA) and how the integration of food shelf-life in LCA can support the development of new packaging materials. The last part of the chapter discusses existing models used for shelf-life determination and LCA.

2.1 Food packaging

Food packaging is classified into three types: primary, secondary, and tertiary. A primary package comes into direct contact with a food product and provides the first, and typically the most important, protective barrier. The secondary package is made up of a collection of primary packages, and its main role is to protect the primary package or product inside the package from external shocks or other factors. A tertiary package is made up of several secondary packages and is mostly used during product transportation. Consumers usually only see the primary package, as the secondary and tertiary packages are removed before the product is placed on the shelf. (Robertson, 2009a) An example of the primary, secondary and tertiary package is shown in Figure 1.

Verghese et al. (2012) has highlighted that properties of the packaging material, physical and chemical, are critical in deciding the level of protection it offers to the food during food transportation and storage. The combination of preservation techniques and packaging is key in extending the shelf-life of food and ensuring its availability throughout the year (Verghese et al., 2012). Each food category has its period range during which it stays acceptable for consumption, which is why the packaging selection must be in such a way that it does not compromise the shelf-life. Packaging design is therefore a key step along with product development in the food industry. (Conte et al., 2015)

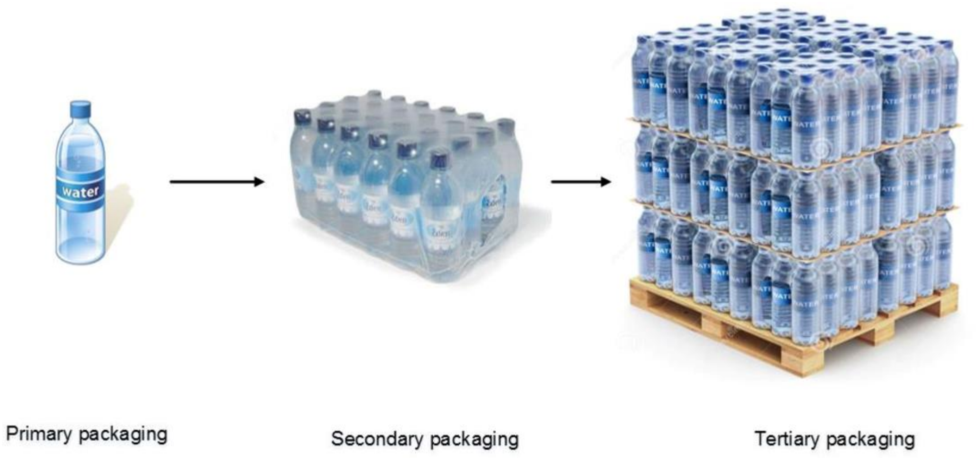


Figure 1 Primary, Secondary and Tertiary packaging of bottled water (Krokhalev, 2017)

Robertson (2016) has classified the roles of packaging into four main types: protection, containment, convenience and communication. Protection is considered to be one of its primary functions and means protecting the food inside from external influences like dust, water, shock etc. The containment means that the packaging must be designed and developed in such a way that all the product inside it is well contained and is not wasted due to leaks or spills. The convenience function could be of various types. This function could be met when the packaging marks portion sizes thereby helping consumers measure the food, it could be from a storage perspective, where once the packaging is opened it can be resealed to protect the food until next use, or from a transportation perspective, it could be designing the packaging size in a way that more primary package could be fit in a secondary and tertiary package thereby reducing the number of trips required to transport the good (Robertson, 2016). Although all these functions are interlinked, the project will focus on protection as the primary packaging.

The food packaging materials currently being used can be made of, but not limited to, glass, metals, polymers, paper etc. The packaging materials that are studied in this project are Poly(ethylene) terephthalate (PET) and biopolymers i.e., Poly(ethylene 2,5-furandicarboxylate) (PEF) and Polylactide (PLA).

2.1.1 **Poly(ethylene) terephthalate (PET)**

Poly(ethylene) terephthalate or PET is a thermoplastic that is widely used in the food packaging industry. Thermoplastic polymers are those that soften when heated and harden when cooled thus making them suitable for recycling. PET production is by esterification or trans-esterification, Figure 2, shows the reaction between two petroleum-based monomers, ethylene glycol (EG) and TPA (terephthalic acid) or DMT (dimethyl ester terephthalate).

PET is a thermoplastic, which is transparent, rigid and is recyclable with a glass transition temperature (T_g) between 67 °C to 80 °C. (Robertson, 2016) When compared with other fossil-based polymers, PET is inert and shows a higher gas barrier property. PET has a high resistance to mechanical impact and is lightweight which is why it is the most preferred plastic packaging in the food industry. (Nisticò, 2020) As PET is a fossil-based polymer, it is not biodegradable and PET waste needs to be either incinerated or recycled.

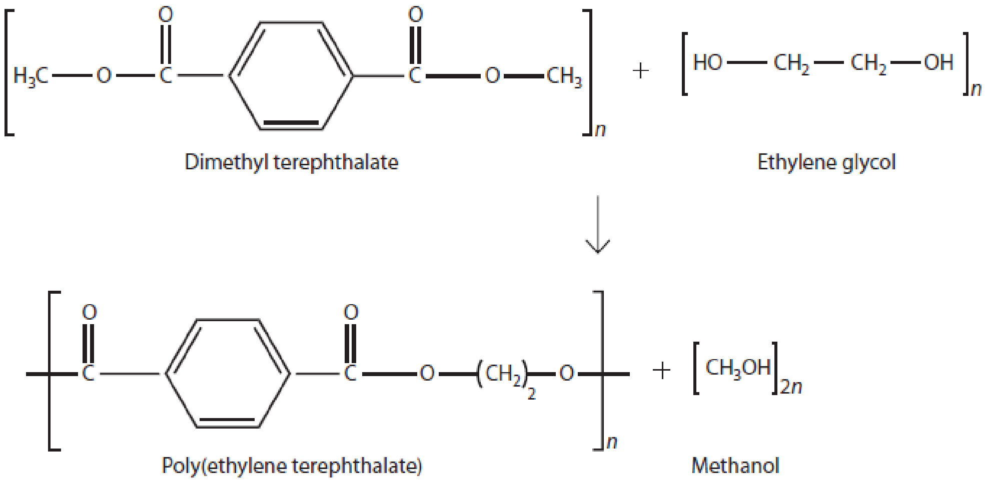


Figure 2 Transesterification reaction for the production of PET (Robertson, 2016)

The PET recycling industry is efficient, and some companies offer recycled PET as an alternative to virgin PET. Although the recycling and use of recycled PET help to reduce the environmental impact of PET, the consumers still prefer biobased polymers over fossil-based polymers like PET. (Nisticò, 2020) Concerns about pollution caused by plastics, the use of fossil fuels in their production, and the adverse effect of plastics on human health are all plausible reasons why consumers prefer biopolymer over recyclable fossil-based polymers (Hottle et al., 2017).

2.1.2 **Biopolymers**

Robertson (2016) while trying to classify biobased packaging material has highlighted that only those packaging materials which are derived or produced from materials that are annually renewable could be considered as biobased. Robertson (2016) goes on to state that if we were to follow this description then paper packaging could not be classified as biobased as the raw material required for paper packaging is not annually renewable and requires anywhere between 25-65 years to be renewed. The biobased polymers (or biopolymers) used as a packaging material is further classified into three main categories by Robertson (2016) and is shown in Figure 3 A biopolymer can be both biodegradables, for example, PLA, or non-biodegradable for example, polymers made from sugarcane such as green PE. The biopolymers under consideration in this project are Poly(ethylene 2,5-furandicarboxylate) (PEF) and Polylactide(PLA) falls under Category 1 and 2 respectively.

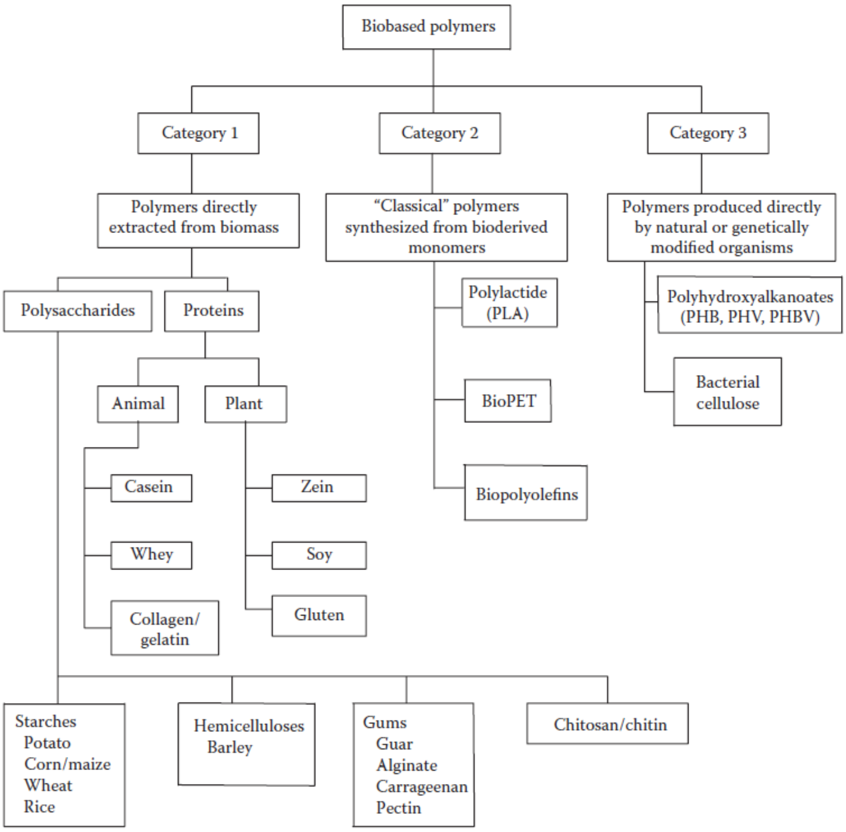


Figure 3 Biobased packaging material classification based on their origin and production(Robertson, 2016)

The biopolymers are now being considered as an alternative to fossil-based polymers from GHG emission and food safety perspective. The biopolymers are considered to have a lower environmental impact as they are produced from renewable material, and they are considered to be safe for food packaging due to the natural origin of its raw materials, for example, starch, which is already present in food (Holm, 2009). However, despite the industry and many consumers preferring to use biopolymers over fossil-based polymers, the use of biopolymers are still very limited mainly due to economic issues, as they are more expensive (Nisticò, 2020).

2.1.2.1 *Poly (lactic acid) or Polylactide (PLA)*

Polylactide (PLA) is one of the most widely studied biopolymers and its commercial production is relatively larger than other biopolymers (Robertson, 2016). Lactic acid from which PLA is derived is produced either by fermentation or chemical synthesis. The fermentation process is cheaper and involves the fermentation of carbohydrate which are obtained from biomass like molasses, corn etc. (Robertson, 2016, Auras et al., 2004). PLA is prepared either by condensation of lactic acid or polymerization reaction which involves lactide formation (Ring-opening polymerization or ROP). The cheapest method is direct condensation, however, the water formation at the end of the reaction affects the molecular weight of the polymer and therefore ROP, Figure 4, is the widely used process to commercially manufacture PLA. (Auras et al., 2004, Robertson, 2016)

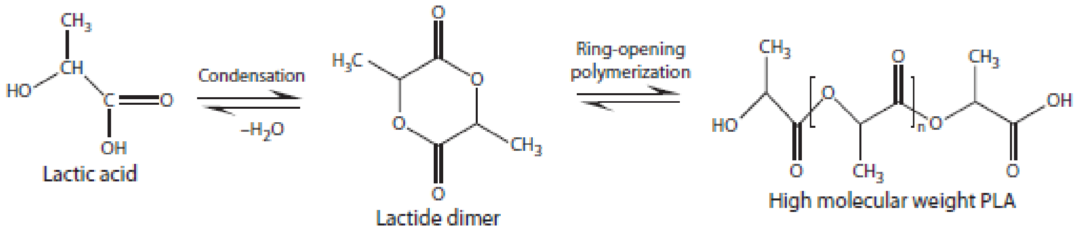


Figure 4 Reaction scheme showing conversion of Lactic acid to PLA (Robertson, 2016)

The amorphous form of PLA, like PET, is commercially used and PLA has a pale-yellow colour with a T_g value ranging from 58°C to 80 °C. PLA is a biodegradable polymer and the mechanical and physical properties of PLA is dependent on how the polymerization process is conducted and can be modified as per requirement. (Auras et al., 2004) Although few studies support the recyclability of PLA, it is not yet established (Auras et al., 2004). The commercial production of PLA uses the fermentation process, and its production quantity is relatively large. Therefore, PLA is more economically feasible than other biopolymers.

Due to its high molecular weight, PLA has thermoforming properties and its OTR is 10 times lower than fossil-based polymers like Polystyrene (PS); being hydrophobic like PET, amorphous PLA films absorb a very low amount of water (Auras et al., 2004, Robertson, 2016). The light transmission rate of PLA is very low while its mechanical strength is similar to PET and blending of PLA with other biopolymers or incorporation of nanocomposites have shown to improve the barrier property of PLA (Auras et al., 2004). All these factors have made PLA suitable for use in food packaging, especially for short shelf-life products.

2.1.2.2 *Poly(ethylene 2,5-furandicarboxylate) (PEF)*

PEF similar to PLA is a biobased polymer that is produced by the synthesis of sugars (C6 or fructose) present in plant-based feedstocks (Nakajima et al., 2017, Loos et al., 2020). PEF is produced when Ethylene glycol (EG) reacts with FDCA (2,5-furandicarboxylic acid) by a polymerization reaction. One of the known PEF manufacturing processes is shown in Figure 5 and in this reaction, FDCA from fructose reacts with EG and the side product methyl levulinate is produced, which is useful for producing another biopolymer. (Nakajima et al., 2017)

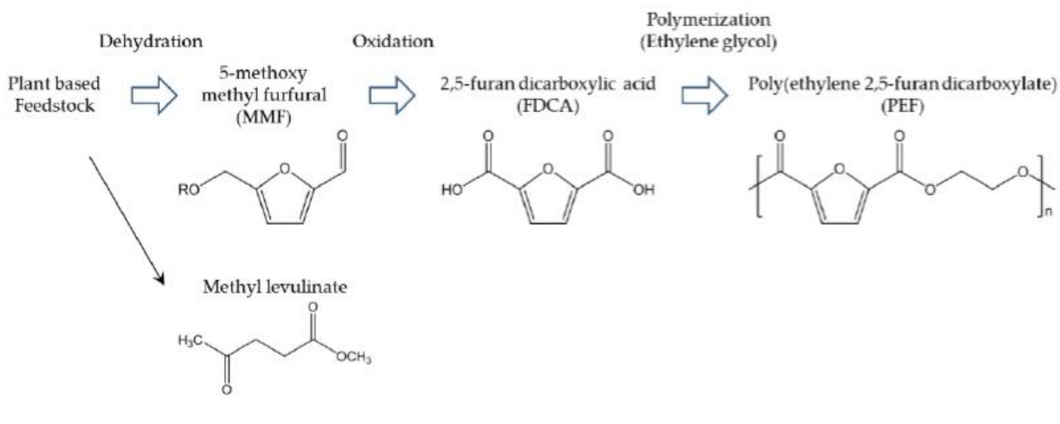


Figure 5 PEF production process (Avantium) (Nakajima et al., 2017)

High molecular weight PEF is noted to have a much higher barrier property than the other biopolymers. As a result, it is regarded as a desirable alternative to PET for the packaging of carbonated drinks (Loos et al., 2020). The review on PEF by Loos et al. (2020) has also highlighted that it has a better gas barrier property than PET, and its CO_2 transmission rate being nearly 30 times lower than PET, thereby making it an ideal choice for carbonated soft drinks packaging. PEF is a colourless biopolymer with 80°C T_g and mechanical strength comparable to PET. PEF is also a recyclable biopolymer that is biodegradable under accelerated conditions; however, its biodegradability under environmental conditions is still being investigated. (Loos et al., 2020) PEF is an ideal alternative to conventional food packaging because it has a better gas barrier property than fossil-based polymers, comparable mechanical strength, and is made from renewable resources. However, the economic aspect of PEF is not feasible since it is not yet manufactured in large quantities.

2.2 Food packaging and barrier properties

Qualitative deterioration of food happens when there is a mass transfer between the food product and the environment. The use of food packaging with the appropriate barrier properties will help to prevent this deterioration. Food packaging is frequently linked to food safety, plausibly due to the role that the barrier property of packaging plays in ensuring that the environment within the packaging is unsuitable for microbial growth, thus preventing food spoilage (Robertson, 2009a). Packaging also guarantees that certain components are not transferred to or from food, such as moisture loss or gain, and that the food retains its quality attributes, such as flavour or juiciness. The choice of appropriate packaging materials is also crucial because when potentially poisonous material from packaging materials migrates into food, it can poison the food inside. (Robertson, 2009a)

The ability of a material to transfer substances from a high concentration side to a low concentration side is referred to as its barrier property (Labthink, 2006). In the case of packaging materials, the substances could be gas, water, liquids, or other particles. Permeation, or permeance, in simple terms, is the number of molecules that can pass through a film and the rate of permeation, therefore, depends on the thickness of the film; Permeability coefficient, P, on the other hand, is independent of the thickness of the film as it is permeation at a constant thickness (Robertson, 2011, Morris, 2017). A general permeation process through a packaging material, for example, plastic film, is shown in Figure 6. The transmission rate (TR) is the amount of permeant that is transported through a film of unit area per time. Permeability, P, is the property of the polymer while TR is the property of the packaging and permeant under specific test conditions. The different TRs that are measured for a packaging material include Oxygen Transmission rate (OTR), Carbon dioxide Transmission (CO_2TR), water vapour transmission rate (WVTR), Moisture vapour transmission rate (MVTR). (Morris, 2017) To summarise, when packaging material is said to have a high oxygen barrier property, it means that it has low oxygen permeance, which results in a low OTR and P.

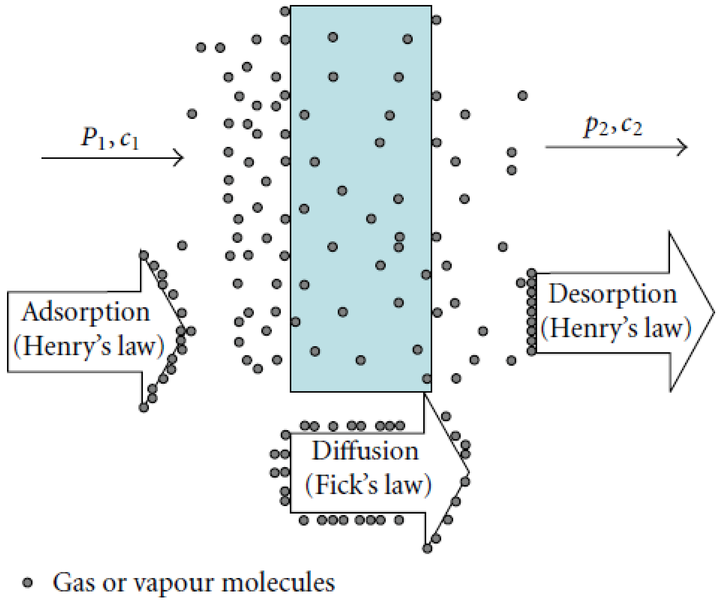


Figure 6 Permeation of gas or vapour molecule through a plastic film (Siracusa, 2012)

The barrier properties of biopolymers are generally considered to be inferior compared to fossil-based polymers, especially in a high relative humidity (RH) environment. Polysaccharide-based films are poor barriers against water vapour and other polar substances at high RH. However, they are good barriers against oxygen (O_2) and other nonpolar substances such as aromas and oils at low to intermediate RH. WVTRs of the starch-based film are four to six times greater than those of conventional films made from fossil-based polymers. (Robertson, 2012) Other biopolymers, like PEF, have shown really good gas barrier property and are therefore one of the newly developed biopolymers whose performance is similar to PET.

PET offers a good gas barrier property and is widely used in soft drinks packaging due to its low carbon dioxide (CO_2) permeability. Furthermore, it provides good protection against aroma components, and the permeability of PET is unaffected by RH. (Nisticò, 2020) These are a few of the reasons why PET is so common in the food industry. However, as described in the preceding chapter, PEF offers greater food protection and has significantly lower CO_2 and O_2 permeability and could therefore replace PET if its price were reduced.

2.2.1 **Food waste**

Before delving into the relationship between shelf-life and food waste, it is important to understand the distinction between food waste and food loss. According to FAO (2019), food loss and waste have become major issues and raising concerns about these issues is part of the 2030 Sustainable Development Goals. Food loss and food waste are two distinct words that refer to food wasted at various points in the food supply chain. (FAO, 2019) Food loss is associated with decreased food quality or quantity as a result of acts by food suppliers in the food supply chain; however, it excludes everything from the retail level to consumer actions and behaviour. Food waste, on the other hand, is described as a decrease in food quantity or quality caused by consumer actions, retailers, food suppliers. Almost one-third of all food produced in the world is wasted somewhere along the supply chain. Reduced food loss and waste would result in the more effective use of land and water resources, which will benefit the environment. (FAO, 2019)

Food waste accounts for 17 per cent of EU GHG emissions and is a significant contributor to the EU's overall negative environmental impacts. An estimated 100 million tonnes of food is wasted in the EU per year, and rising demand for perishable food and ready-to-eat food items will only exacerbate the challenge of reducing food waste. Food waste is an ethical, economic, and environmental issue, which is why the EU and UN have set a target to reduce food waste by 50 per cent by 2021 and 2030, respectively.(Spada et al., 2018, Scherhaufer et al., 2018)

2.2.2 **Impact of shelf-life on food waste**

Shelf-life refers to the quality of food and there is no simple definition of shelf-life that is generally accepted. Shelf-life can be described as the time or period from which food is produced to the time it becomes unacceptable in terms of nutritional loss, consumer preferences, for example, sensory attributes, or safety aspects (Fu and Labuza, 1993). As stated in the introduction chapter, food packaging protects its contents from outside environmental damage like water, vapours, gases, dust, shock vibrations force etc. For many food products, the protection offered by the food packaging is critical and once the integrity of the food package is compromised the food deteriorates quickly.

Knowledge of deteriorative reactions in food is the first step while developing packaging as packaging can help in slowing down these reactions thereby maintaining the desired quality attributes of food. Food packaging chiefly prevents the deterioration that happens due to extrinsic factors like atmospheric O_2, RH, light, dust, mechanical stress, etc. by providing a barrier against these factors. (Robertson, 2011) By preventing deterioration, packaging, along with preservation techniques and low storage temperature, helps in extending the shelf-life of food.

According to Zhang et al. (2019), shelf life has a major influence on food waste and a small extension in shelf-life can help reduce the waste generated. Spada et al. (2018) analysed the food item returned from the market due to shelf-life expiration and related it with the food shelf-life. The statistical analysis was carried out for food items in the Italian market and the authors found that the wastage of food products with shelf life between 30-50 days could be significantly reduced if shelf-life was extended. The article highlighted that the food retailers are more focused on preventing the food wastage of short shelf-life products and that long shelf-life products stay on the shelf longer and are bought by consumers eventually. This could be the reason why medium shelf-life products (shelf-life between 30-50 days) could benefit more from a shelf-life extension. (Spada et al., 2018). The shelf-life extension also plays an essential role in reducing food loss since it extends the period during which food retains its quality criteria and may thus reach a larger number of customers (Conte et al., 2015).

As previously discussed, food packaging can help increase the shelf-life of food by offering better barrier protection. However, the packaging alone cannot help in reducing food waste. Consumer behaviour plays a vital role in reducing food waste and more emphasis must be given to raise awareness among the consumers regarding food consumption and waste to mitigate the food waste and global warming challenge (Scherhaufer et al., 2018).

2.3 Life cycle assessment (LCA)

Life cycle assessment (LCA) is a systematic way to assess the environmental impact of a product and it is done through a cradle-to-grave approach. In other words, LCA evaluates the potential impact that a product may have on the environment throughout its lifecycle. The framework used for conducting the assessment is adapted from ISO 14040/44. The key steps in an LCA assessment are goal, scope and definition, inventory analysis, impact assessment, interpretation and as shown in Figure 7 all these steps are interconnected. (Hann, 2020) By using LCA it becomes easier to understand where most impact happens while producing food and the packaging system can be designed to minimize this impact (Verghese et al., 2012).

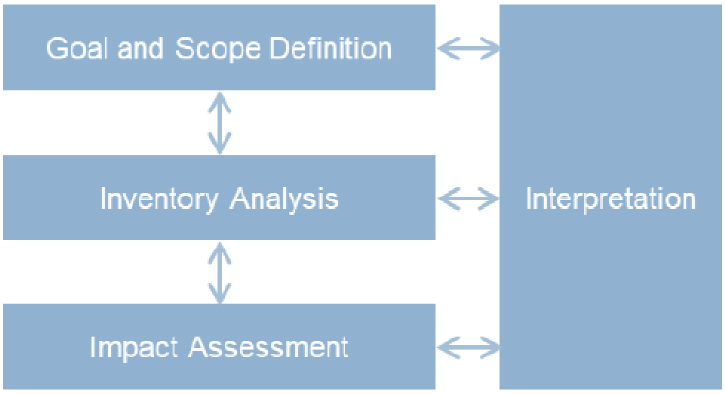


Figure 7: A simplified interpretation of main steps in the LCA tool (Hann, 2020)

LCA has been used widely in food and beverage packaging with Coca Cola being the first company to do so in 1969, for single-use packaging. LCA, has since then, being used to understand the environmental impact of the packaging material by considering the material used, the package size and thereafter suggest a better waste management system. However, the LCA of packaging material is mostly focused on the packaging and not many take into consideration the interaction between the food and packaging material. Consideration of this interaction is important as studies on agricultural and food production system have shown that the major environmental impact of packed food is often the food item inside the packaging and not the packaging material. (Verghese et al., 2012)

The primary purpose of food packaging is to prevent food deterioration and hence while selecting a packaging, the preference is given to packaging alternatives that protect the food better even if it is slightly higher energy demanding than the alternative less energy-intense option. (Verghese et al., 2012) With recent development in food packaging, life cycle studies must consider the influence packaging has in extending the shelf-life of the food. Verghese et al. (2012) has emphasized the importance of including the impact of shelf-life extension, provided by packaging material, will have on the environment and has suggested this to be a more holistic approach to determine the environmental impact of a packaging system. Conte et al. (2015) and Coffigniez et al. (2021) has also favoured this suggestion and has indicated that the absolute LCA for packaging would be the one that considers the direct and indirect impact (through decreased shelf-life and food loss) of the packaging on the environment as well as consumer behaviour.

2.4 Review of shelf-life prediction and life cycle assessment methods

2.4.1 **Shelf-life prediction**

The shelf-life of the food is mainly controlled by three main factors which are food packaging, the distribution and storage environment of the food and, the food itself (intrinsic factors) (Robertson, 2009a). This would mean that controlling intrinsic factors like pH, water activity, enzymes, microbial growth could help to control the shelf-life and so will extrinsic factors like temperature, relative humidity (RH), light, gas concentration, mechanical stress etc. The factors that influence the shelf-life of packed food are depicted in Figure 8.

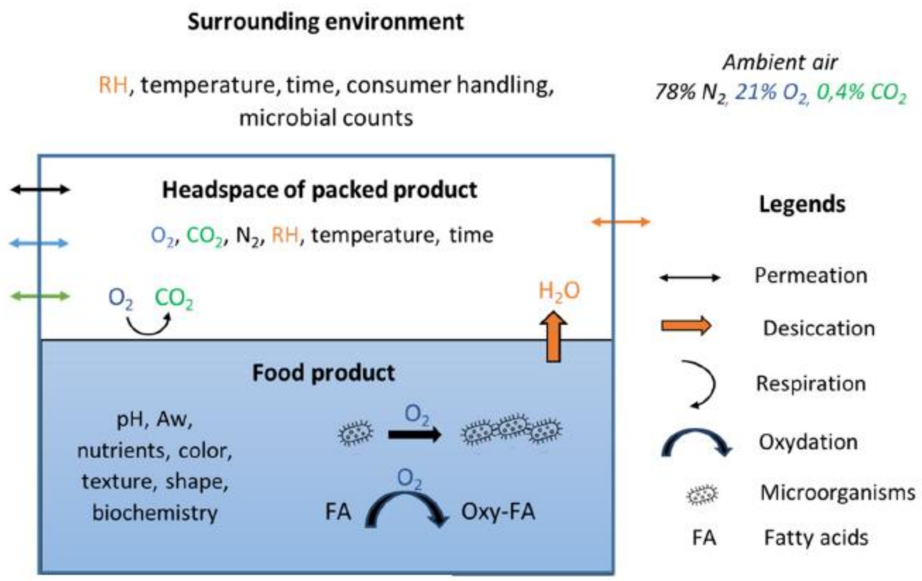


Figure 8 Factors influencing deterioration of packed foods (Coffigniez et al., 2021)

The shelf-life definition has highlighted the acceptability part of food which is usually the quality indicator. An ideal shelf-life prediction model, Figure 9, will incorporate consumer preference, product deterioration due to intrinsic factors and the mass transfer happening through the packaging material (Coffigniez et al., 2021). This project only considers the shelf-life affected due to the barrier property offered by the packaging material and therefore fits the quality and transfer-reaction model shown in Figure 9.

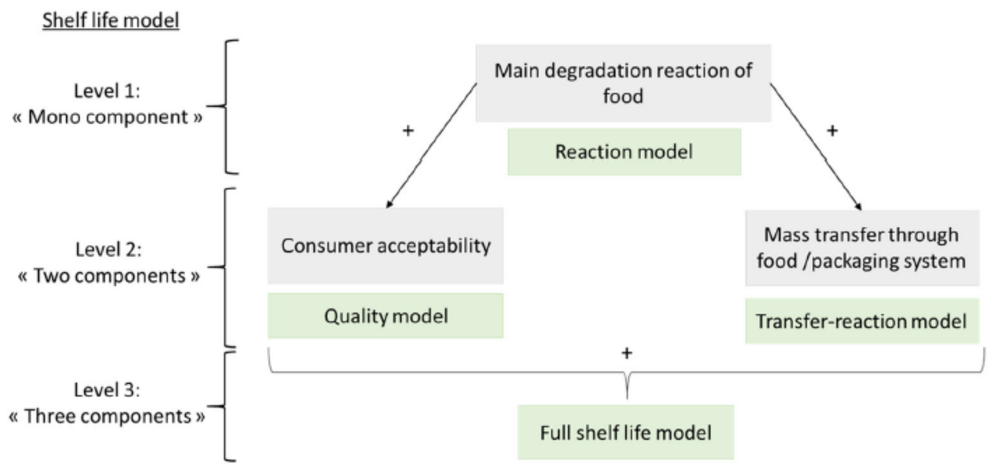


Figure 9 Shelf-life approach combining all key factors (Coffigniez et al., 2021)

According to Robertson (2009b), quality factor (IoD) is a series of measurements that aids in understanding and analysing the quality-related change that occurs in food as a result of processing and storage conditions. As a result, the IoD value is based on a food intrinsic factor and is required to quantitatively analyse the deterioration reaction in food. To predict the shelf-life that the packaging can provide, knowledge of IoD and the concentration of IoD at which deterioration occurs is necessary. (Robertson, 2009b) In the case of citrus fruit, for example, the IoD is the decrease in ascorbic acid content from an initial concentration of A to a final concentration of B. The values A and B are used in the shelf-life prediction model to determine the time it takes for food to reach value B while using a packaging material. IoD is analogous to Indices of failure (IoFs), and identifying and quantifying IoFs is the first step in packaging design (Robertson, 2009b).

The oxidation reaction in food has a detrimental impact on the nutritional content, and one of the most desirable properties of packaging material is the protection of food from atmospheric O_2 (Robertson, 2009b). The shelf-life prediction models reviewed for this project are those that take into account quality loss in liquid food caused by the oxygen permeability of the packaging material.

Profaizer (2007) proposed a finite element model to estimate CO_2 ingress into PET bottles using the permeability method. For the simulation, the gas-polymer matrix model was used because it is suitable for PET bottles. At room temperature, the values from the computer-simulated model were compared to the observed values for CO_2 ingress in 0.5 L PET bottles of varying weights. The model accurately predicted the permeability of gas via PET bottles. (Profaizer, 2007) However, the study only suggested that calculating permeability through simulations could aid in the design of packaging materials and did not go into detail on how this permeability value could be used to estimate the shelf-life of the liquid food within the package.

Ahrné et al. (1996) proposed a mathematical model that considered ascorbic acid loss and formation of p-vinyl-guaiacol (PVG) as a quality indicator for shelf-life prediction of aseptically packed orange juice stored at a temperature from 4 – 50 °C. The influence of factors such as the initial dissolved oxygen, light intensity and oxygen permeability of the container wall was also considered in this model. The quality indicator values were obtained through experiments and this value was then used in a kinetic equation. The degradation of these quality indicators was observed through experiments and then the values were compared with values predicted through kinetic equation (computer simulation). (Ahrné et al., 1996) The model observed the total number of days it took for the quality indicator to deteriorate and reach an unacceptable limit.

The models discussed so far identified the quality indicator and observed, through accelerated tests, the time it took for the quality indicator to deteriorate when using a packaging material. These models resembled the one-component model depicted in Figure 9. Burgess et al. (1990), on the other hand, used calculation and experiment to measure the oxygen permeability and OTR of the packaging material and then attempted to estimate the shelf-life provided by the packaging material. Burgess et al. (1990) used the colour transition from red to brown as a quality indicator. The oxygen value at which the ketchup colour changes from red to an undesirable brown was determined via the experiment. Simultaneously another experiment was performed to measure the OTR and permeability coefficient of the Gamma squeeze bottle. These experimental findings were then combined to predict the shelf-life of ketchup stored in these gamma bottles. The IoD was the change in oxygen concentration until the ketchup reached the minimum permissible red colour. (Burgess et al., 1990)

The method used (Burgess et al., 1990) demonstrated the simplest way to link the permeability of packaging material with the quality factor of food. This model was modified and used in the project to estimate the shelf-life of food packed in polymer material.

2.4.2 **Life cycle assessment considering food waste**

The relation between food shelf-life and food waste is not linear and therefore quantification of shelf-life related food waste can be tricky. Spada et al. (2018) through empirical method tried establishing this link between shelf-life and food waste. However, it only considered food returned from the market and the method only worked for products with medium shelf-life.

Conte et al. (2015) used experimental data to integrate food waste into the LCA of packaging material for cheese. By using the findings of a previous study, the probability of food waste due to shelf-life expiration was estimated. Food waste was predicted to be highest when the shelf-life offered was 0 and lowest when the shelf-life offered was equal to the highest value determined by the experiment. This value was then used to assess the environmental impact of packaging selection. Conte et al. (2015) analysed and compared four multilayer packaging materials with three different headspace scenarios, i.e., atmospheric packaging, vacuum packaging, and modified atmospheric packaging. The impact assessment was carried out for two scenarios: Attributional, which only considered the impact of packaging, and Consequential, which considered both packaging and food. The finding was that in the Attributional approach, the thickness and recyclability of the packaging material determined the environmental impact. In the Consequential approach, the ability of the packaging to minimise food waste was more significant in deciding the environmental impact of packaging.

The study considered the waste disposal scenarios of incineration and recycling for packaging but did not consider the disposal scenario for food. (Conte et al., 2015)

Dilkes-Hoffman et al. (2018) also had a similar conclusion, only in this case the food waste generated due to shelf-life expiration was assumed by the authors and not taken from an empirical relation. The assessment and comparison were done for two types of food, cheese and beef, and the packaging material considered were multilayer biodegradable packaging and fossil-based packaging. The conclusion highlighted that when food waste was considered, the contribution of food to environmental impact was nearly 50 per cent and that packaging design must focus on reducing food waste. The landfill was the only waste disposal scenario considered in the study for both food and packaging. (Dilkes-Hoffman et al., 2018)

The study by Conte et al. (2015), Dilkes-Hoffman et al. (2018) was on a similar line with the difference being that the first study used data from experiments in a realistic scenario for fossil-based packaging while the latter focused on biodegradable packaging material and used a hypothetical scenario. The project has adopted the method used by Dilkes-Hoffman et al. (2018), due to it being based on hypothetical scenarios and showing the comparison between biodegradable and fossil-based packaging.

Based on the literature review, Figure 10 shows the approach that was taken in this project. The project uses this approach for liquid food products and the food items that are studied in this project is blackcurrant juice, ketchup and orange juice. A detailed discussion on each step will be given in subsequent chapters.

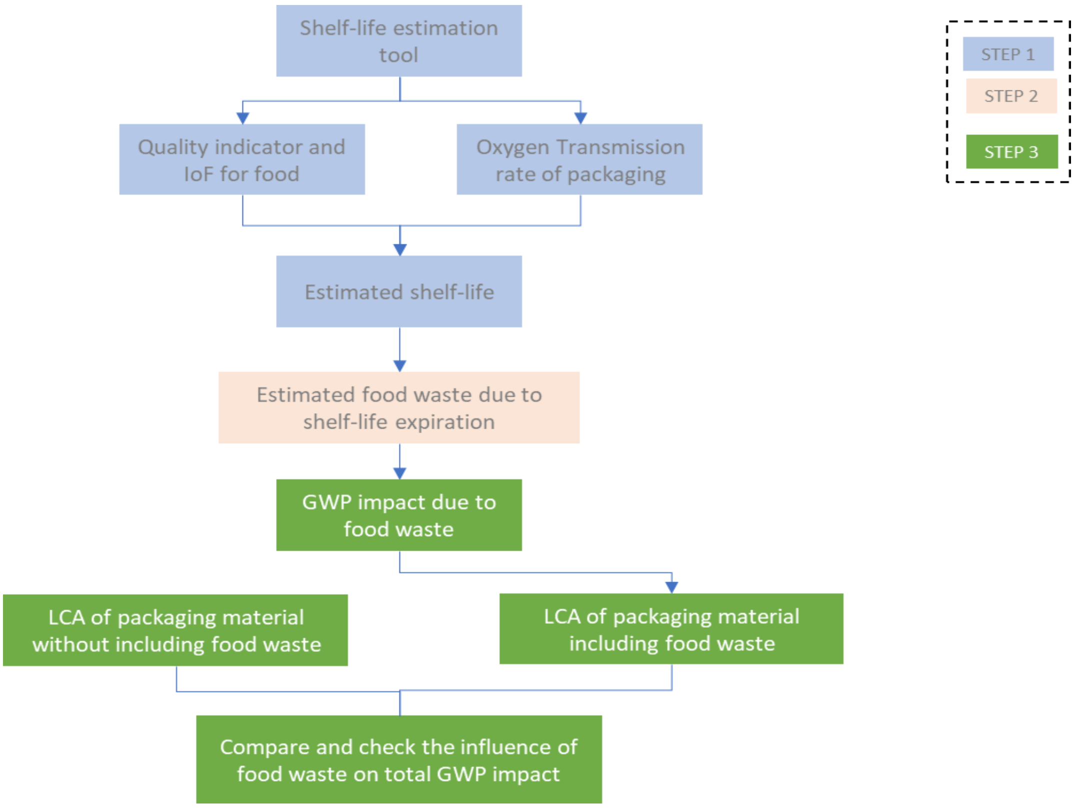


Figure 10 Approach taken to integrate shelf-life into LCA of polymer

3 Methodology

This project aims to develop a simple shelf-life estimation tool that could be used while doing the LCA of food packaging material. This chapter discusses the steps taken to achieve this objective. The first part presents the shelf-life estimation tool designed to be integrated into the LCA, the second part presents the LCA of the packaging material and the third part presents how the tool is validated.

3.1 Tool development process

The tool estimates the shelf-life that packaging can provide to food and is intended to be used while performing the life cycle assessment of polymer food packaging materials. The shelf-life estimated by the tool will then be used to estimate the food waste generated by using a particular polymer packaging material, which will then be used to evaluate the overall environmental effect of the packaging. The tool's scope is limited to liquid food products whose nutritional value or visual appearance/colour is degraded by oxygen entering the package due to the polymer's oxygen permeability. PET, PLA, and PEF were considered while developing the tool. The shelf-life estimation tool developed here is an MS Excel-based tool and the method used to design the tool is described in the following sub-chapters.

3.1.1 Initial Planning and Discussion

A discussion with an industry representative and a researcher was undertaken to gain a better understanding of the shelf-life prediction approaches used in the industry. The first discussion was with a shelf-life expert from Tetra Pak, and it was important in determining the project's approach. The purpose of the discussion was to gain a better understanding of the industry's approach to calculating shelf-life and how it can be adapted for this project. The discussion served as a basis for defining the tool’s content and approach. The discussion suggested using an existing model for estimating the shelf-life of liquid foods in plastic bottles and then extrapolating the model to estimate the shelf-life of food stored in PET, PLA, and PEF bottles. The first version of the shelf-life estimation tool was developed after this discussion.

The second discussion was with a packaging expert from the University of Helsinki. The first version of the tool was presented, and the feasibility of including bottle closures of different materials was discussed. Another outcome of this discussion was the incorporation of oxygen in the headspace of the container even if the food is filled aseptically. The specifics of these discussions are not covered in this report; however, their impacts in designing the tool are addressed in the subsequent chapters.

3.1.2 **Development of Shelf-life estimation tool**

The first step in developing the tool was to determine the food types for which the shelf-life would be estimated, as well as their IoFs. Orange juice was chosen when developing the tool because its nutritional quality is influenced by the oxygen permeability of packaging. The initial approach to designing the tool is based on Burgess et al. (1990) shelf-life prediction model for ketchup. This model was modified for orange juice packaged in 500 mL and 1000 mL bottles, and the quality indicator was changed from the change in colour of ketchup to the amount of ascorbic acid in the juice.

The values used to estimate shelf-life was extracted from different research articles. Table 4 summarises the oxygen permeability values obtained from the literature. TetraPak (2017a) provided the minimum ascorbic acid content required in orange juice as well as the amount of oxygen that causes ascorbic acid loss. The dimensions of the bottle were taken from the manufacturer's website and then modified to achieve the target of bottle shape as shown in Figure 12. The dimensions i.e., body and neck height, base and neck radius, was then entered in Norner calculator to check the shape the bottle takes, and the values were adjusted to achieve the desired shape. The dimensions were then used as an input to calculate the surface area and volume of the bottle. The equations used to calculate the surface area and volume of the bottle are presented in Chapter 3.1.3.

The assumption used for the shelf-life estimation is that the liquid inside the bottle is a well-mixed system that is kept at 23 °C in a monolayer bottle. One of the reasons why only a monolayer bottle was used in the project was the difficulty of acquiring details, regarding the type and thickness of each layer used in a multi-layer bottle, through a literature review. The second assumption is that the atmosphere inside the bottle is inert, and oxygen transfer is presumed to occur from the atmosphere to the liquid through the package.

Orange juice must contain at least 200 mg/L of ascorbic acid, according to the AJIN report, and a value less than this indicates a loss of orange juice quality (TetraPak, 2017b). As a result, 200 mg/L of ascorbic acid served as an indicator of orange juice's end of shelf-life. Calculations showed that 1 mg of oxygen results in a loss of approximately 11 mg of ascorbic acid in orange juice (TetraPak, 2017c). These values were correlated to calculate the amount of oxygen that would cause a quality loss in orange juice.

Although the assumption is that food is aseptically packed, the second discussion with the researcher at Helsinki University suggested that the probability of oxygen remaining in the headspace should not be overlooked. Furthermore, when the quality loss happening is through aerobic degradation, the factors that contribute to the aerobic degradation are the OTR of packaging, oxygen in the headspace and dissolved oxygen in juice (TetraPak, 2017c). As a result, the second version includes total oxygen content, which is calculated using dissolved oxygen in juice and oxygen in the headspace. The dissolved oxygen value for orange juice was obtained from Ros-Chumillas et al. (2007), and oxygen in the headspace, as an outcome of the second discussion, is assumed to be between 0.5 and 1 per cent.

Once the tool for orange juice was completed, other food items that undergo nutritional loss due to the oxygen permeability of polymer were explored. The tool was further explored for blackcurrant juice, which contains ascorbic acid and whose shelf-life is determined by the decrease in ascorbic acid value. The ascorbic acid content of unfortified blackcurrant juice ranges from 60 to 190 mg/100ml (Mattila et al., 2011). Since juice can lose some of its nutritional qualities during processing, the lower end of the ascorbic acid value range was chosen for blackcurrant juice. The ascorbic acid value at the end of the shelf-life for blackcurrant juice was calculated assuming that the ascorbic acid value at the end of the shelf-life should be 40 per cent or less than the initial value. This assumption was based on the ascorbic acid content of orange juice at the beginning and end of its shelf life.

In addition to orange and blackcurrant juice, the developed tool was also used to estimate the shelf-life of ketchup. The quality indicator for ketchup was the change in colour and the oxygen required to bring this change was taken from Burgess et al. (1990).

3.1.3 **Equations used in the tool**

Packaging materials made of polymer materials allow the permeation of gases, vapours, dust and other low molecular weight compounds. The process of permeation of gas through a film or polymer is as shown in Figure 6 and the amount of gas or vapour permeating through a film can be calculated using Fick's law as shown in Equation 1. Q is the quantity of gas or vapour permeating through a film, X is the thickness of the film, A is the surface area, t is the time. D and S are the diffusion and solubility coefficient respectively and p_1 and p_2 are the pressure on each side of the film and $p_1 > p_2$. (Robertson, 2009a)

$$Q = \frac{DS(p_1 - p_2)At}{X} \qquad 1$$

Permeability coefficient, P, is the product of D and S and the new equation will be as shown in Equation 2. The transmission rate, TR, is the amount of permeant passing through a film and is calculated using Equation 3.

$$P = \frac{QX}{\Delta pAt} \qquad 2$$

$$\boldsymbol{TR} = \frac{\boldsymbol{Q}}{\boldsymbol{At}} \qquad 3$$

The focus of this project is to understand the oxygen permeability of PET, PLA and PEF and OTR of the packaging. The OTR of each of these materials is calculated using Equation 3.

Oxygen causes two major quality loss in orange juice namely vitamin C degradation and browning (colour change) (TetraPak, 2017b). Ascorbic acid degradation, due to oxygen permeating through the package, is the IoFs considered in this project to estimate the shelf-life of blackcurrant and orange juice.

The amount of oxygen absorbed which would cause quality loss of the juice was calculated considering the surface area of the bottle. The surface area and volume of the bottle are calculated using Equation 4 and 5, respectively, where the variable a is the neck radius, b is the base radius, h_1 is the height from the base to neck and h_2 is the neck height of the bottle. (Heckman, 2020) Total oxygen content inside the bottle was calculated using Equation 6 (Jue Song, 2018). Finally, the shelf -life of the food, in days, is then estimated using Equation 7.

$$\boldsymbol{Surface\ area\ of\ bottle = \pi(a+b)\sqrt{h_2^2 + (b-a)^2} + 2\pi b h_1 + \pi b^2} \qquad 4$$

$$\boldsymbol{Volume\ of\ bottle = \frac{1}{3}\pi h_2(a^2 + ab + b^2) + \pi b^2 h_1} \qquad 5$$

$$\boldsymbol{Total\ oxygen\ content\ = O_2 concentration\ in\ headspace\ \times headspace\ vol. + Dissolved\ O_2 \times Vol\ of\ product\ \times 0.766} \qquad 6$$

$$\boldsymbol{Shelf-life\ of\ food = \frac{Amount\ of\ oxygen\ leading\ to\ quality\ loss}{OTR\ of\ polymer + Total\ Oxygen\ Content}} \qquad 7$$

In the case of multiplayer packaging, the total permeability (P_T) can be calculated using Equation 8, where L_x and P_x is the thickness and permeability of individual layers and L_T is the total thickness of the packaging film (Abbott, 2021).

$$\boldsymbol{P_T = \frac{L_T}{\frac{L_1}{P_1} + \frac{L_2}{P_2} + \ldots\ldots + \frac{L_x}{P_x}}} \qquad 8$$

3.2 Life cycle assessment of the polymer

As a first step in performing the LCA of the polymer, the system boundary was established. For the PLA bottle, the amount of food waste generated across the hypothetical supply chain, shown in Figure 11, was calculated and correlated with the estimated shelf-life of food. This value was then used as a baseline for calculating the waste generated by other polymers. The final GWP (Global Warming Potential), CO_2 equivalent, of each polymer was calculated by including both food and packaging waste. The following sub-chapters specify the method used to calculate food and packaging waste as well as the GWP of the polymers.

3.2.1 **Scope of the LCA and Functional Unit**

The purpose of this LCA is to gain an understanding of how changes in food waste due to decreased or increased shelf-life impact the polymer's overall GWP. A hypothetical supply chain, as shown in Figure 11, was considered for this. The functional unit (FU) was 1000 kg of packaged food purchased by consumers, and the mass flow calculations are shown in Table 2. All supply chain steps within the scope of this LCA take place in South Sweden. The polymer granulates and preforms are manufactured in Malmö, then transported to a food manufacturer in Eslöv, where the preform is blow moulded to bottles and filled with a liquid food product, before being transported to a retailer in Helsingborg, where the product is purchased and consumed by customers.

The scope does not include the farming and manufacturing steps for the consumed food, but the amount of ingredients that need to be cultivated to produce the amount of liquid food wasted is considered. Similarly, the scope ends at the retail level, but packaging waste produced at the customer end is taken into account in the end-of-life scenario. The ingredients considered for ketchup are tomato and sugar. 1 kg of ketchup requires approximately 6 per cent added sugar (Wohner et al., 2020), and this quantity of sugar is included in the ketchup ingredients. Since sugar is a key ingredient in ketchup, the impact of the cultivation of sugar (for the wasted ketchup) is also considered in the assessment.

The LCA first assessed the environmental impact of changing the packaging material in the hypothetical supply chain without taking food waste into account. It then assesses the environmental impact of the packaging material after taking into account the food waste generated in retail as a result of differences in provided shelf-life. The environmental impact category assessed is GWP(100 years) and is measured in Kg CO_2-equivalent (CO_2e) emissions. The inputs for GWP emissions are shown in Table 1.

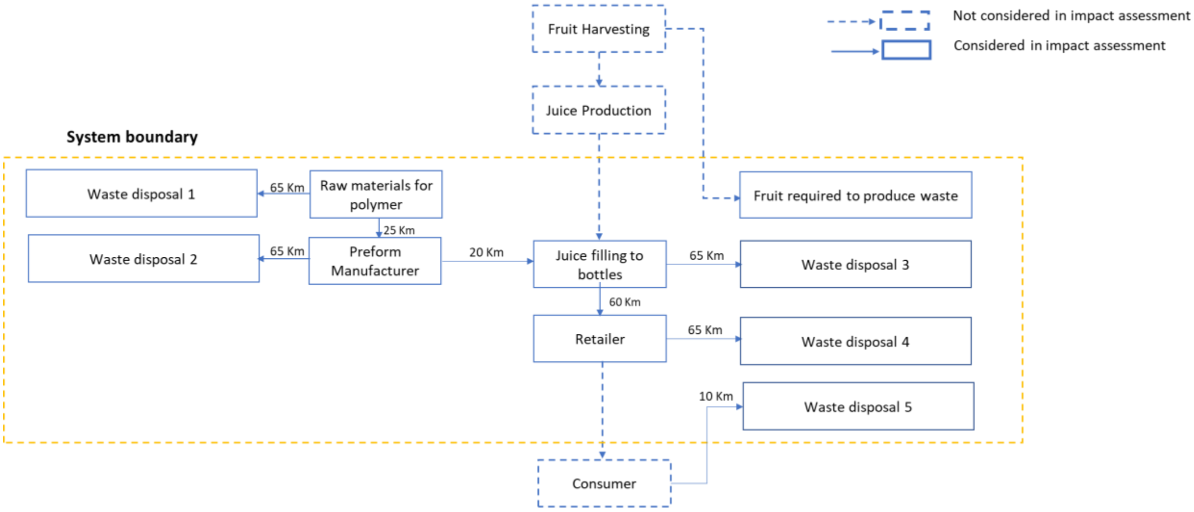


Figure 11 Hypothetical supply chain and system boundaries considered in LCA

Table 1 Inputs and GWP 100 year impact data for LCA system

Process	***Description***	***$KgCO_2$ e/Kg***	***Reference***
Production of ingredients	*Orange, cultivation*	*	*Ecoinvent database (Wernet et al., 2016)*
	Tomato, cultivation	*	
	Sugar production	*0.63*	*(García et al., 2016)*
Production of packaged food	*Juice production*	*1.10*	*(Doublet et al., 2013)*
	Ketchup production	*1.05*	*(Williams and Wikström, 2011)*
Production of Packaging	*PLA granulate, production*	*	*Ecoinvent database (Wernet et al., 2016)*
	PEF, production	*2.05*	*(Eerhart et al., 2012)*
	PET granulate, production	*	*Ecoinvent database (Wernet et al., 2016)*
	PET recycled granulate, production	*	
Waste processing	*PET municipal incineration*	*	*Ecoinvent database (Wernet et al., 2016)*
	PET recycling (cut-off)	*	
	Wastewater treatment, the conventional method	*0.26*	*(Monteith et al., 2005)*
Storage at retailer	*Food waste (juice and smoothies) at 0.4 %*		*WRAP report (Lee et al., 2015)*
		$KgCO_2e$/ tKm	***Reference***
Transportation, road	*Transport, freight, lorry >32 metric ton, EURO3*	*	*Ecoinvent database*

**Ecoinvent data not disclosed due to license agreement*

3.2.2 **Food and Packaging considered**

The project only considers the primary packaging in the LCA. The shelf-life given by PLA, PET, and PEF are compared first, and then the estimated shelf-life values are used to estimate food waste in retail, and finally compare the environmental impact of these polymers. The shelf-life estimation and LCA were carried out on three different food items: ketchup, orange juice, and blackcurrant juice.

3.2.3 **Waste processing (end of life) scenarios**

Incineration, recycling and wastewater treatment are the waste disposal scenarios considered here. The waste generated is sent to the same waste management facility in South Sweden. PEF and PET can be recycled, while PLA is biodegradable and can be composted. According to Förpacknings & Tidnings Insamlingen (FTI), the recycling rate for plastic packaging in Sweden in 2018 was around 42 per cent. This rate, however, includes both the plastic that is incinerated for energy recovery and plastic that is recycled into a new product. It is estimated that about 15 per cent of plastic is recycled into new products. (TidningsInsamlingen, 2019)

Directive 94/62/EC amendment Directive 2018/852 has also mandated that EU nations must recycle 50 per cent of plastic by December 2025 and according to Tojo (2011), in Sweden, 70 per cent of PET bottles collected through a deposit system is recycled. Therefore, another scenario with 100 per cent recycling of PET was included in the LCA. However, ketchup is not packed in transparent bottles and currently, only colourless PET bottles are considered recyclable in Sweden (TidningsInsamlingen, n.d). Therefore, for ketchup, the scenario with 100 per cent recycling of PET was not considered.

According to Förpacknings & Tidnings Insamlingen (FTI), the technology for processing biodegradable polymers are not yet available and therefore, incineration was the only waste disposal scenario considered for PLA and PEF.

At the consumer level, liquid food waste is washed down the drain and packaging waste is disposed of at a household waste management station. The amount of food waste produced at the consumer end due to shelf-life expiration is difficult to gather and, as a result, is not considered in the LCA. The WRAP report contains information on the liquid food waste produced at retailers due to shelf-life expiration. However, due to a lack of knowledge on the end-of-life scenario, it is assumed that the liquid food is drained into drains and the packaging goes to incineration.

3.2.4 **Estimation of food waste based on differences in the shelf-life**

According to a WRAP report, 0.4 per cent of liquid food waste is produced at the retail level (Lee et al., 2015). Approximately 48 per cent of household food and drink waste is attributed to packaged foods that are not consumed within their shelf-life (Lee et al., 2015). Since most liquid food items are washed down the drain, there is insufficient data to determine the amount of liquid food waste produced in the home. According to a survey conducted by the Swedish

National Food Agency (2016), roughly 23 per cent of total food waste is washed down the drain, with juice and other drinks accounting for 10 per cent of this waste. Based on the findings of this survey, the amount of liquid food waste produced at the consumer level is estimated to be around 2 per cent. Since this 2 per cent does not specify if the waste generated is due to shelf-life expiration, it was only used to quantify how much packaging material and food must be produced per functional unit. According to Dora et al. (2020), the amount of packaging-related food loss at the processing stage is around 5 per cent and this value is used to estimate the packaging waste generated in the processing step. The waste generated at preform manufacturer is around 2 per cent (Tomiran et al., 2015) and this value is also used to estimate the waste generated at polymer supplier. Table 2 used all these values to quantify the food and packaging waste produced during the supply chain steps. The food waste generated at the retailer due to shelf-life expiration is calculated to be 3.87 and 3.92 Kg (per FU), for the 500 ml and 1000 ml package respectively.

PLA and PEF are the biopolymers considered in this project and the estimated shelf-life for PLA is the shortest while PEF provides the longest shelf-life. PET is the only fossil-based polymer considered and it offers a shelf-life that is in between PEF and PLA. Therefore, the food waste generated due to shelf-life expiration at retailers (based on Lee et al. (2015)) was assumed to be valid for PET. This value was then used as a baseline to quantify waste generated in retail due to differences in the shelf-life by PLA and PEF.

Table 2 Mass flow of supply chain

Process from Figure 11	***V= 500 ml, normalized to FU***			***V= 1000 ml, Normalized to FU***			***Calculation***
	Packaging (kg)	*Food (kg)*	*Total (Kg)*	*Packaging (kg)*	*Food (kg)*	*Total (Kg)*	
Consumer (A)	*36.00*	*964.0*	*1000.0*	*25*	*975*	*1000*	***FU***
Retail (B)	*50.20*	*967.9*	*1018.1*	*25.1*	*978.9*	*1004*	*Total weight = Total A + 0.4 % A*
Food processing (C)	*52.71*	*1016.3*	*1069*	*26.3*	*1027.9*	*1054.2*	*Total weight = Total B + 5 % B*
Preform Manufacturer (D)	*53.24*	*-*	*53.2*	*26.6*	*-*	*26.88*	*Total weight = Total C + 2 % C*
Polymer supplier (E)	*53.77*	*-*	*53.8*	*26.9*	*-*	*27.42*	*Total weight = Total D + 2 % D*

3.2.5 **Impact analysis- GWP potential of polymers**

For the impact analysis, the amount of packaging and food waste produced in the supply chain was multiplied by the individual component's Kg CO_2e emissions. The environmental impact of switching food packaging for different foods packaged in PET, PEF, and PLA was then analysed and compared for two scenarios, namely with and without food waste.

3.3 Validation of tool and LCA

The shelf-life estimation tool developed here is used to provide an understanding of the protection provided by the packaging material and to be used for the packaging material's LCA. The second version of the tool was shared with a packaging expert from the University of Helsinki to get feedback on its usability and to understand estimated values that could be considered in polymer LCAs. The accuracy of this tool was not evaluated as it is intended to be a simplified version of the shelf-life calculation software used by the industry. The process and results were discussed with Tetra Pak LCA experts to evaluate if the LCA method used by including food waste can be used by them.

4 Results and Discussion

This chapter is divided into three parts. The first part gives details on the shelf-life estimation process and summarizes the input values and assumptions used to estimate the shelf-life. The second part presents and discusses the shelf-life results for PET, PEF and PLA. It then tries to link the estimated shelf-life with food waste generated due to shelf-life expiration. The third part of the chapter presents and discusses the results from the LCA of the packaging material and the difference in the environmental impact of the packaging material with and without considering food waste. In the final part, first, the method used in this project is compared with existing work in this context, then the outcome of the discussion with industry and researcher is presented and finally, a reflection is given on the relevance of this project with UN sustainable development goals.

4.1 Shelf-life estimation data

Fruit juices under consideration have been pasteurised and contain vitamin C (unfortified). The amount of oxygen required to reach IoFs is the first variable in the estimation tool. Ascorbic acid degradation is the IoFs considered here for fruit juices. Table 3 specifies the minimum ascorbic acid requirement for each fruit juice. IoFs for ketchup is a change in colour from red to brown, and the oxygen value when this colour change occurs is given in Table 3. The oxygen permeability of the polymer is the tool's second variable. For 23°C, the oxygen permeability of the polymer was taken from the literature. Table 4 provides the oxygen permeability value (OPV) for PET, PEF, and PLA at 23°C. Since the permeability value of PLA is approximately 6 times that of PET (Holm, 2009), the values marked with *a* are used to estimate the shelf-life.

The third variable is the bottle dimension. The bottle shape as shown in Figure 12 was considered and the dimensions were changed to meet the volume requirement of 500 ml and 1000 ml. The surface area and the volume calculated by using the formula given in chapter 3.1.3 was verified using Norner (2019). The thickness for the monolayer PET bottle used for aseptic packaging of orange juice is 0.600 mm (Ros-Chumillas et al., 2007) and this value was used for other polymers as well. The values are shown in Table 5.

Table 3 Indices of failure for food

Food	*Indices of Failure*	*Value*	*Reference*
Blackcurrant juice	*Decrease in ascorbic acid*	*264 mg/L*	*(Mattila et al., 2011)*
Orange Juice	*Decrease in ascorbic acid*	*200 mg/L*	*(TetraPak, 2017b)*
Ketchup	*Colour change*	*Redness 15.7*	*(Burgess et al., 1990)*

Table 4 Oxygen permeability values for polymer from literature

Polymer	*OPV ($cc^{1}m^{1}m^{-2}Day^{-1}atm^{-1}$) at T=23°C*	*Reference*
PET	*1.40E-3*	*(Morris, 2017)*
	9.19E-4 [a]	*(Robertson, 2011)*
PLA	*1.18E-2*	*(Morris, 2017)*
	9.19E-3 [a]	*(Bao et al., 2006)*
	1.93E-2	*(Norner, 2019)*
PEF	*7.03E-4*	*(Nakajima et al., 2017)*
	4.81E-4 [a]	*(Norner, 2019)*

a: values considered in the shelf-life estimation tool

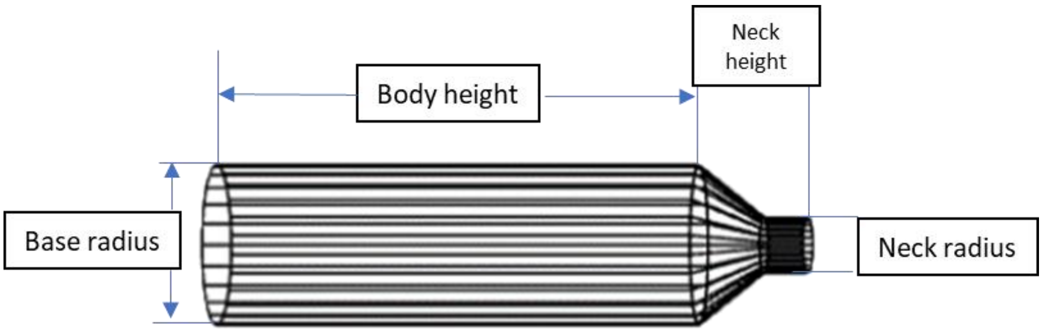


Figure 12 Bottle shape considered in the tool, an image created using Norner Calculator(Norner, 2019)

Table 5 Dimensions for 500 ml and 1000 ml bottle

Variables	*Unit*	*500 ml bottle*	*1000 ml bottle*
Body height	*cm*	*22.00*	*22.00*
Base radius	*cm*	*2.598*	*3.684*
Neck radius	*cm*	*1.100*	*1.300*
Neck height	*cm*	*3.000*	*3.000*
Thickness	*cm*	*0.060*	*0.060*
Calculated surface area	*m^2*	*0.042*	*0.061*
Calculated volume	*m^3*	*0.506*	*1.041*
Surface area, Norner calculator	*m^2*	*0.043*	*0.062*
Volume, Norner calculator	*m^3*	*0.503*	*1.006*

As ascorbic acid degradation in fruit juices is caused by oxidation, the first step in estimating shelf life is determining the amount of oxygen (in mL) needed to reach the minimum ascorbic acid requirement, Table 6. Table 4 was used to obtain the permeability value at 23 °C, which were then entered into Equation 3. The bottle's dimensions were modified to reach a volume of 500 ml and 1000 ml, and these dimensions were used in Equation 4 to measure the bottle's surface area. For all food items, an oxygen content of 1 per cent in the headspace and a headspace volume of 10 ml were assumed. Robertson and Samaniego (1986) conducted experiments and concluded that the dissolved oxygen content in market products is so low that it cannot lead to any quality deteriorative reactions. Using Equation 6, the total oxygen content was determined by assuming the dissolved oxygen value to be 0. Finally, the shelf-life was calculated using Equation 7.

Table 6 Estimation of Oxygen required to reach IoF value

Food	*Indices of Failure*	*Oxygen required (ml/L)*	*Reference*
Blackcurrant juice	*Decrease in ascorbic acid*	*19*	*Calculated*
Orange Juice	*Decrease in ascorbic acid*	*14*	*Calculated*
Tomato ketchup	*Colour change*	*69*	*(Burgess et al., 1990)*

4.2 Estimated shelf-life result

The shelf-life estimated using the first version of the developed tool is shown in Table 7. The shelf-life was estimated without considering the oxygen content in the headspace.

Table 7 Estimated shelf-life - 500 ml and 1000 ml bottles

	Estimated shelf-life (days) at T = 23 °C		
Volume (V) = 1000 ml	*PET*	*PLA*	*PEF*
Blackcurrant juice	*96*	*10*	*184*
Orange juice	*74*	*7*	*142*
Ketchup	*349*	*35*	*666*
Volume (V) = 500 ml	*PET*	*PLA*	*PEF*
Blackcurrant juice	*68*	*7*	*129*
Orange juice	*50*	*5*	*95*
Ketchup	*255*	*25*	*487*

The second version estimated shelf-life with 1 per cent oxygen in the headspace and a headspace volume of 10 ml. Table 8 shows the estimated shelf-life for the food at 23 °C for 500 ml and 1000 ml, respectively. According to Table 8 the shelf-life increases with increasing bottle volume. The estimated shelf-life for PEF in Table 7 and Table 8 corresponds to the higher oxygen permeability provided by PEF as compared to PET (Burgess et al., 2014). The estimated shelf-life results are rounded up to the nearest number and this is why the estimated shelf-life of food in PLA bottle is similar in Table 7 and 8.

Table 8 Estimated shelf-life - after considering total oxygen content

	Estimated shelf-life (days) at T = 23 °C		
Volume (V) = 1000 ml	***PET***	***PLA***	***PEF***
Blackcurrant juice	*77*	*9*	*126*
Orange juice	*59*	*7*	*95*
Ketchup	*280*	*34*	*454*
Volume (V) = 500 ml	***PET***	***PLA***	***PEF***
Blackcurrant juice	*50*	*7*	*77*
Orange juice	*37*	*5*	*57*
Ketchup	*186*	*25*	*285*

Figure 13 depicts the estimated shelf-life after taking into account oxygen in the headspace. As the headspace volume and oxygen available in the headspace are the same for all food items, the oxygen permeability of the packaging material is the only factor that can lead to the decrease in ascorbic acid value. The results show that the PEF package provides the longest shelf life, followed by the PET and PLA packages. This is in line with the observation made by Nakajima et al. (2017) that PEF has a very high oxygen gas barrier property and is, therefore, an excellent biopolymer for use in food packaging.

The study by Miller and Rice-Evans (1997) on phenolic antioxidants in apple, orange, and blackcurrant juice found that these antioxidants protect the vitamin C content of these juices from mild oxidation. According to the study, ascorbic acid degradation is greatest in apple juice and lowest in blackcurrant juice. (Miller and Rice-Evans, 1997) Vitamin C stability is also affected by its concentration in food, and it increases with increasing concentration (Herbig and Renard, 2017). Since blackcurrant has a higher concentration of vitamin C, its estimated shelf life is, as a result, higher than that of orange juice.

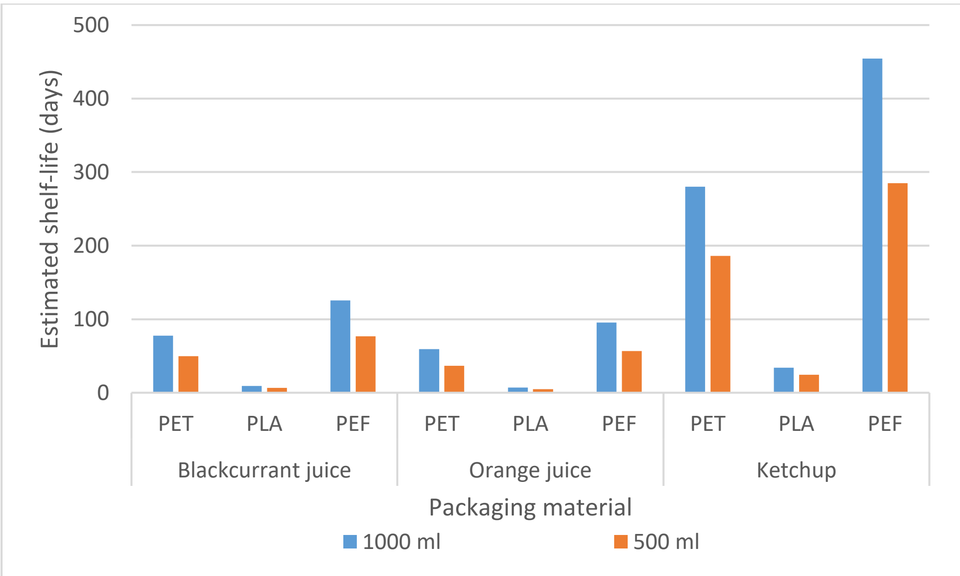


Figure 13 Estimated shelf-life (days) using the developed tool after considering oxygen in the headspace

Figure 13 depicts the effect of package volume on food product shelf-life. The surface area per unit volume ratio influences the food's shelf life. Increased surface area per unit volume reduces food shelf-life, and the smaller the package size, the greater this ratio. (Robertson, 2011) As a result, smaller packages of the same product with the same polymer thickness have a shorter shelf-life, which explains why the products in 500 ml bottles have a shorter shelf-life.

4.2.1 **Linking shelf-life with food waste**

According to the WRAP report, increasing the shelf-life of fruit juices and smoothies by one day will reduce food waste by 0.01 per cent (Lee et al., 2015). This correlation, shown in Equation 9, was used to estimate the amount of food waste generated by other packaging materials due to the difference in shelf-life, for package volumes of 500 ml and 1000 ml. The percentage of food waste at the store, FW_R, varies depending on the type of food being considered. For this project FW_R, as stated before, is 0.01 per cent.

$$FW_{PEF\ or\ PLA} = FW_{PET} - \frac{\%FW_{R,juice} \times (Shelf{-}life\ \ PLA\ or\ PEF - Shelf{-}life\ by\ PET)}{FW_{PET}} \qquad 9$$

The estimated shelf-life from Table 8 was used in Equation 9 to calculate the food waste generated by each packaging material at a different volume and is shown in Table 9.

Table 9 Food waste generated due to end of shelf-life, 500 ml and 1000 ml bottles

Food Type	***Food waste generated (kg/ FU)***		
	V = 500 ml		
	PLA	***PET***	***PEF***
Orange Juice	*3.95*	*3.87*	*3.82*
Blackcurrant juice	*3.98*	*3.87*	*3.80*
Ketchup	*4.29*	*3.87*	*3.62*
	V = 1000 ml		
Orange Juice	*4.05*	*3.92*	*3.82*
Black currant juice	*4.09*	*3.92*	*3.79*
Ketchup	*4.54*	*3.92*	*3.47*

The results show that when compared to PET, the increased shelf-life offered by PEF decreases food waste by an average of 3 per cent for 500 ml bottles and 6 per cent for 1000 ml bottles. While for PLA, which offers a lower shelf-life compared to PET, food waste increases by an average of 5 per cent for 500 ml bottles and 7 per cent for 1000 ml bottles.

4.3 LCA of polymers

Since the LCA's FU is 1000 kg of packaged food, the values calculated for 1000 ml and 500 ml are normalised to the FU and then considered here. The steps for calculating the GWP of packaging material with and without food waste are outlined below.

4.3.1 **GWP impact due to transportation**

The transportation distance was determined by entering the start and end points into Google Map and is shown in Table 10 the hypothetical supply chain. The transportation weight only includes the weight of the packaging material; however, from retailer to consumer, the food waste due to expired shelf life is also included. Table 10, Table 11 and Table 12 show a summary of the destination as well as the transportation impact calculation. Since retail food waste is minimal in relation to packaging waste, the difference in transportation-related emissions for different packaging materials is small. As a result, Table 11 and Table 12 values are used for all three packaging materials.

Table 10 Transportation distance estimated using google maps

Sr No	*Supply chain step*	*Point of Origin-Destination*	*Estimated distance (km)*	*Mode of transport*
1	*Polymer supplier to Preform Manufacturer*	*Malmö-Lund*	*25*	*Road*
2	*Preform Manufacturer to Juice manufacturer*	*Lund-Eslöv*	*20*	*Road*
3	*Juice manufacturer to Retailer*	*Eslöv-Helsingborg*	*60*	*Road*
4	*Retailer to Consumer*	*Helsingborg*	*5*	*Road*
5	*Waste disposal 1*	*Malmö- Eslöv*	*44*	*Road*
6	*Waste disposal 2*	*Lund- Eslöv*	*25*	*Road*
7	*Waste disposal 3*	*Eslöv*	*2*	*Road*
8	*Waste disposal 4*	*Helsingborg - Eslöv*	*55*	*Road*
9	*Waste disposal 5*	*Helsingborg - Eslöv*	*55*	*Road*

Table 11 GWP impact due to transportation, 1000 ml bottle

SR no	*Estimated distance (km)*	*Transportation weight (kg)*	*CO_2e*
1	25	26.88	0.062
2	20	26.62	0.049
3	60	26.36	0.144
4	5	25.10	0.013
5	44	0.27	0.001
6	25	0.27	0.003
7	2	1.32	0.0002
8	55	4.02	0.020
9	55	0.50	0.003
		Total	0.30

Table 12 GWP impact due to transportation, 500 ml bottle

SR no	*Estimated distance (km)*	*Transportation weight (kg)*	*CO_2e*
1	25	53.77	0.125
2	20	53.24	0.098
3	60	52.71	0.288
4	5	50.20	0.025
5	44	0.54	0.002
6	25	0.53	0.003
7	2	2.64	0.000
8	55	4.06	0.020
9	55	0.80	0.004
		Total	0.56

4.3.2 GWP impact of food ingredients

If the food items under consideration are thrown away, it means that the food cultivated to produce those items is also wasted. Table 13 and Table 14 show the total amount of crop cultivated to produce 1 kg of orange juice, blackcurrant juice, and ketchup, as well as the GWP impact.

Table 13 Indirect waste due to ingredients, 1000 ml bottle

Food Type	***Ingredients needed for 1 Kg of final product (juice/ketchup)***	***Ingredients needed for Food waste generated (kg/FU)***		
		PLA	***PET***	***PEF***
Orange	*1.50*	*6.07*	*5.87*	*5.73*
Blackcurrant	*2.00*	*8.18*	*7.84*	*7.59*
Tomato	*1.48*	*6.72*	*5.80*	*5.14*
Sugar	*0.08*	*0.36*	*0.31*	*0.28*

Table 14 Indirect waste due to ingredients, 500 ml bottle

Food Type	***Ingredients needed for 1 Kg of final product (juice/ketchup)***	***Ingredients needed for Food waste generated (Kg/FU)***		
		PLA	***PET***	***PEF***
Orange	*1.50*	*5.93*	*5.81*	*5.73*
Blackcurrant	*2.00*	*7.97*	*7.74*	*7.60*
Tomato	*1.48*	*6.35*	*5.73*	*5.35*
Sugar	*0.08*	*0.34*	*0.31*	*0.29*

Table 15 shows the GWP impact of relative food waste produced at the farming stage, which is calculated by multiplying the amount that goes to waste by the GWP value of producing the food.

Table 15 GWP impact of ingredients that goes to waste

Food type	***Packaging type***	***GWP, V=1000 ml (Kg CO_2e/ FU)***	***GWP, V=500 ml (Kg CO_2e/ FU)***
Orange	*PLA*	*1.579*	*1.542*
	PET	*1.527*	*1.510*
	PEF	*1.491*	*1.490*
Tomato	*PLA*	*1.783*	*1.683*
	PET	*1.538*	*1.519*
	PEF	*1.362*	*1.419*
Blackcurrant	*PLA*	*2.126*	*2.071*
	PET	*2.038*	*2.012*
	PEF	*1.972*	*1.977*

As indicated in Chapter 3.2.4, household liquid food waste is washed down the drain and therefore ends up at the wastewater treatment unit. Due to a lack of data, it is assumed that the retailer's liquid food waste is also sent to the wastewater treatment plant. Table 16 shows the GWP impact of producing the food that goes into waste and Table 17 shows the GWP impact of liquid food that enters the wastewater treatment plant.

Table 16 GWP impact of food processing

Food type	***Packaging type***	***GWP, V=1000 ml (Kg CO_2e/ FU)***	***GWP, V=500 ml (Kg CO_2e/ FU)***
	PLA	*4.453*	*4.349*
Orange Juice	*PET*	*4.307*	*4.259*
	PEF	*4.205*	*4.202*
	PLA	*4.771*	*4.503*
Ketchup	*PET*	*4.116*	*4.064*
	PEF	*3.644*	*3.796*
	PLA	*4.498*	*4.382*
Blackcurrant Juice	*PET*	*4.312*	*4.257*
	PEF	*4.172*	*4.182*

Table 17 GWP impact of liquid food going to wastewater treatment (WWT)

Food type	*Packaging type*	*GWP, V=1000 ml (Kg CO_2e/ FU)*	*GWP, V=500 ml (Kg CO_2e/ FU)*
Orange Juice	*PLA*	*1.052*	*1.028*
	PET	*1.018*	*1.007*
	PEF	*0.994*	*0.993*
Ketchup	*PLA*	*1.181*	*1.115*
	PET	*1.019*	*1.006*
	PEF	*0.902*	*0.940*
Blackcurrant	*PLA*	*1.063*	*1.036*
	PET	*1.019*	*1.006*
	PEF	*0.986*	*0.988*

4.3.3 GWP impact due to packaging

The next step is to determine the GWP impact of packaging materials. Chapter 3.2.4 shows the total packaging waste produced in the supply chain. Regardless of where the waste is generated, all packaging material used in the supply chain will be discarded. As a result, the initial amount of packaging material required for creating a bottle is used to calculate the GWP impact of packaging production, and the values are shown in Table 18.

Table 18 GWP impact of packaging production

Packaging Type	*GWP, V=1000 ml (kg CO_2e/FU)*	*GWP, V=500 ml (kg CO_2e/FU)*
PET	*89.39*	*178.78*
PLA	*86.65*	*173.29*
PEF	*56.21*	*112.42*

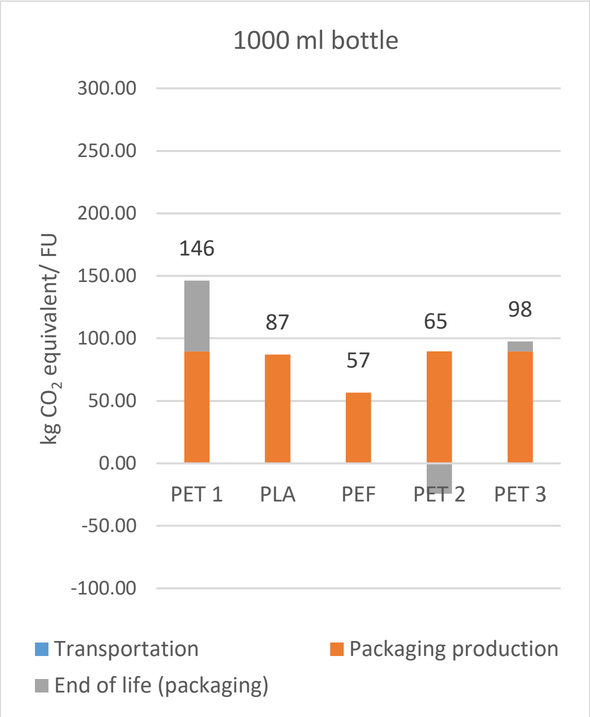
For end-of-life of packaging, as mentioned before, a recycling scenario was also considered for PET bottles. If the recycling scenario is considered for the end-of-life of PET bottle, it would mean that there is some GHG emission reduction during the waste disposal. As this project considered only virgin PET bottles, for understanding the amount of energy saved, the difference in GWP impact of producing virgin and recycled PET was calculated and the value was used to calculate the reduce GHG emissions during PET recycling. The end-of-life scenarios for packaging material and their GWP impact is shown in Table 19. PET 1 refers to 100 per cent incineration, PET 2 refers to 100 per cent recycling and PET 3 refers to the cut-off system model, where the burden of producing the PET is not assigned to those who would be using the recycled PET. The CO_2 emissions from incineration of PLA and PEF are of biogenic source and since this CO_2 has been removed from the atmosphere when the renewable feedstock for the biopolymers was cultivated, it is not accounted for in GWP (Vidal et al., 2007).

Table 19 GWP impact of End of life of packaging material

Packaging Type	*GWP, V=1000 ml (kg CO_2e/FU)*	*GWP, V=500 ml (kg CO_2e/FU)*
PET 1	*56.48*	*112.97*
PET 2	*-24.24*	*-48.48*
PET 3	*7.95*	*15.90*

4.3.4 **LCA of packaging material without including food waste**

Firstly, the CO_2e emissions of PET, PEF and PLA without considering the food waste was calculated and the different contributors to emission in the supply chain were analysed. The total GWP was calculated by adding the impact due to transportation and packaging and the detailed values for 500 ml and 1000 ml bottle is given in A.1.



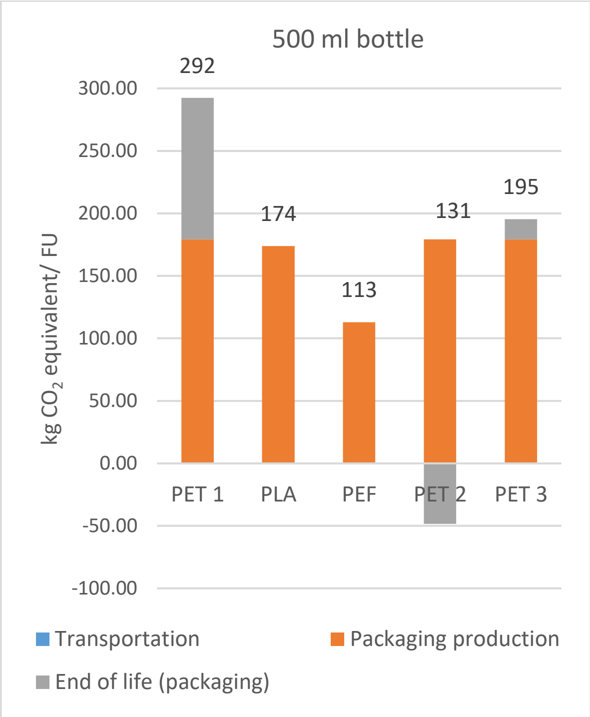


Figure 14 GWP impact of packaging without considering food waste 500 ml and 1000 ml bottles

Figure 14 shows that transportation contributes less than 1 per cent of carbon emissions for all packaging material, regardless of package volume, and is therefore not noticeable in the graph. The EU Directive 94/62/EC on packaging and packaging waste states that food packaging must be as light as possible without compromising food quality or safety. Since the weight of packaging considered in this study meets this criterion, transportation of packaging content has the least influence on the overall environmental impact. However, the GWP impact of a 500 ml bottle is nearly double that of a 1000 ml bottle, which is attributed to the higher amount of packaging material used per functional unit.

For PET 1 bottles, packaging production accounts for 61 per cent of the emission, while end-of-life accounts for 39 per cent of the emission. The overall environmental effect of PEF is 61 per cent lower than that of PET 1 and packaging production contributes to this emission. The environmental impact of PLA is 41 per cent lower than PET 1 and PEF has the lowest environmental impact amongst PET and PLA.

However, when PET 2 and PET 3 is included in this comparison, PET 2 total environmental impact reduces substantially, with its end-of-life accounting to an average of negative 24 per cent. The environmental impact of PET 2 becomes 16 per cent higher than PEF but it is still 25 per cent and 55 per cent lower than PLA and PET 1 respectively. Similarly, for PET 3, although its environmental impact is higher than PET 2 and PEF, it is still 33 per cent lower than PET 1 and is only 12 per cent higher than PLA.

From the results, packaging production seems to be the biggest contributor to the environmental impact of the packaging and is relatively higher for biopolymers. Since the biopolymer industry is relatively young in comparison to the fossil-based polymer industry, the production-related emissions for these polymers are hard to predict and depend on the type of raw materials used for its production as well as the process used to produce it. As the biopolymer industry expands, so will the production quantity, and thus the emission at the production stage will most probably be lower. (Dilkes-Hoffman et al., 2018) Similarly, if recycled PET is used to produce the bottles, its production impact will also reduce thereby decreasing its overall environmental impact.

The second major contributor to the environmental impact of packaging is the waste disposal method. Incineration is only the end-of-life scenario considered for PEF and PLA. PLA, however, is a biodegradable material while both PET and PEF can be recycled. When the recycling scenario for PET was included, the total average emissions of PET reduced by 44 per cent as compared to when PET is only incinerated. The results show that using recyclable fossil-based polymers could help in reducing their environmental impact. Similarly, PEF is also a recyclable biopolymer but, its mechanical recyclability presents a few issues one of which is that it has properties identical to PET, making separation at the waste sorting stage difficult (Loos et al., 2020). When the challenges are overcome, mechanical recyclability of PEF could become a possibility. This could mean that, when recycling biopolymers is achievable, PEF would still be a better alternative to PET and its environmental impact would be much lower than what is shown in the results above.

4.3.5 LCA of packaging material including food waste

If the food waste is considered, then the GWP impact of the packaging material will change with the food type and package volume. The detailed value of GWP impact of the packaging materials after considering food waste is shown in A.2.

The LCA results show that amongst the polymers PEF has the lowest GWP 100-year impact followed by PLA and PET. But when the recycling scenario of PET is also included in this PET 2 has a GWP impact which is 14 per cent higher than PEF, which is 2 per cent lower than when food waste was not included. Figure 15, Figure 16 and Figure 17 show the CO_2e emissions for orange juice, blackcurrant juice and ketchup respectively. The results show that the inclusion of food waste increases the environmental impact of the packaging material but it does not change the overall impact drastically and PET 1 still has the highest impact.

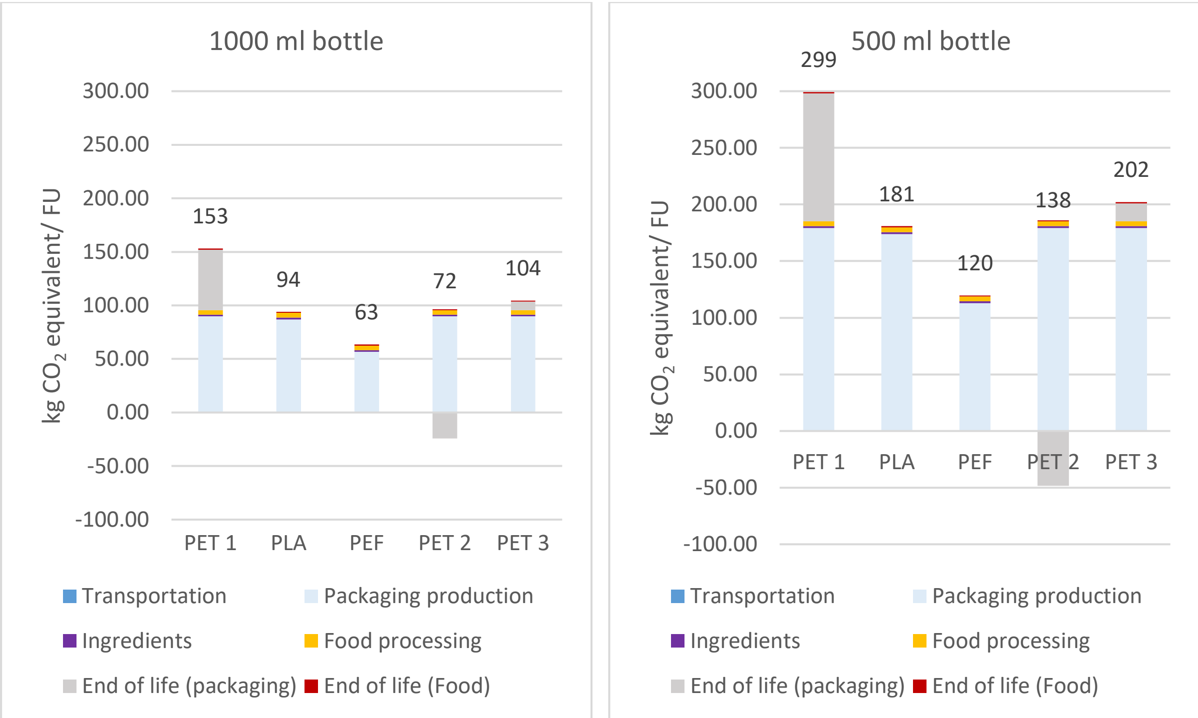


Figure 15 GWP impact including food waste for Orange Juice

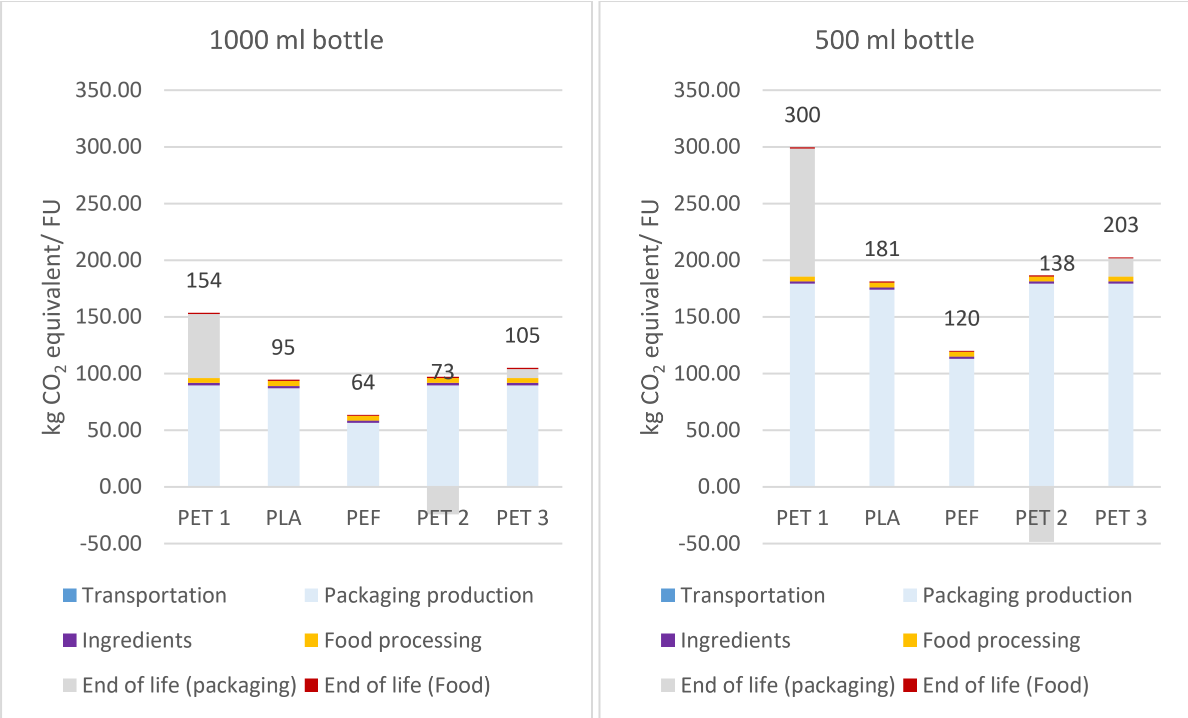


Figure 16 GWP impact including food waste for Blackcurrant Juice

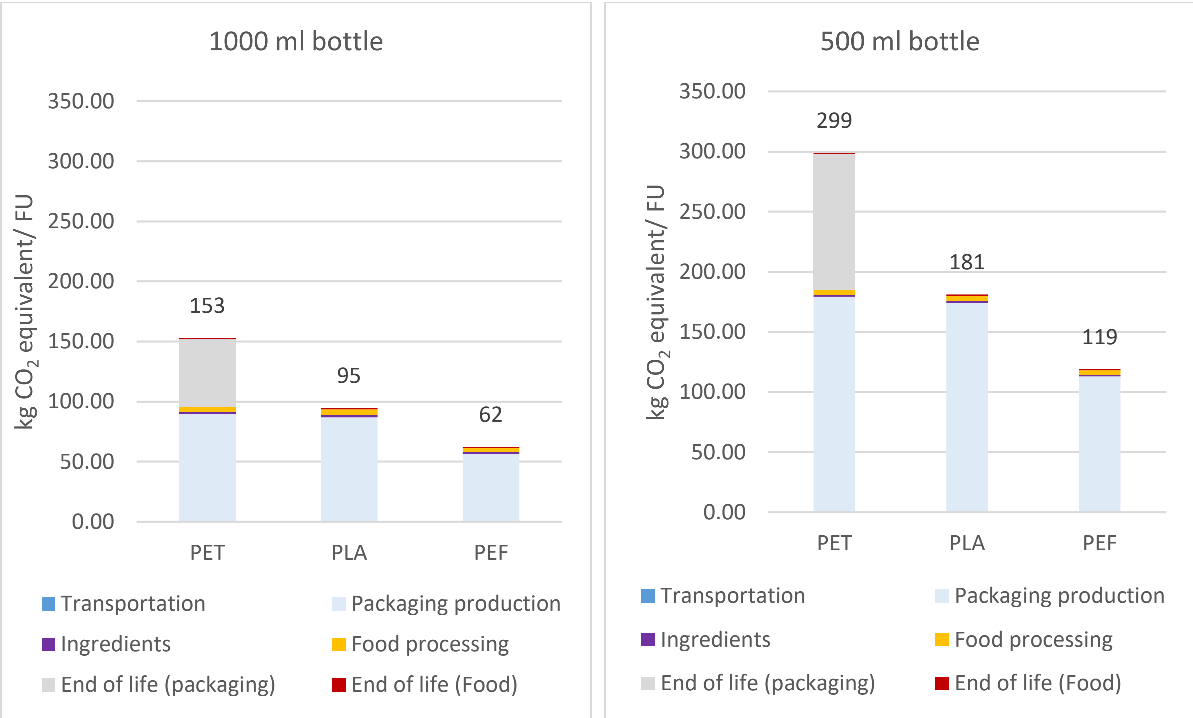


Figure 17 GWP WP impact including food waste for ketchup

Although the amount of food-related waste generated in the 500 ml package is slightly higher than the 1000 ml bottle, the contribution of food-related waste to overall emission is lower for the 500 ml bottle. This may be attributed to the higher requirement of packaging discussed earlier.

When compared to PET 1, the average total environmental impact of PLA after accounting for food waste is 39 per cent lower, which is 2 per cent less than the difference between the two materials when food waste is not taken into account. Similarly, the average total environmental impact of PEF after accounting for food waste is 58 per cent, which is 3 per cent less than the value measured when food waste is not taken into account. The average contribution of food waste to this increased CO_2e emissions is 8 per cent for PLA, 10 per cent for PEF and 4 per cent for PET 1. The results indicate that when food waste is included in the LCA of polymers, the contribution of packaging production decreases, and that including food waste changes the ratio between the impact of food waste vs the impact of packaging vs waste processing. This would also mean that if the product packed has a higher GHG emission, then the impact of food waste could be higher than the one shown in the results.

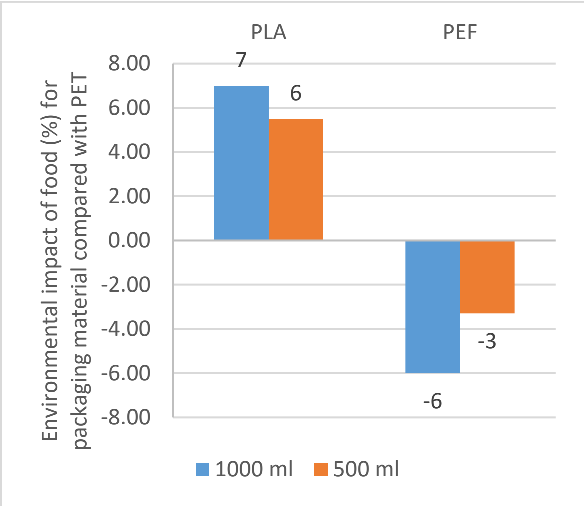


Figure 18 Kg CO_2e difference in emissions for PET and PEF when compared with PLA

According to the results, including the food shelf-life offered by a packaging material will affect the kg CO_2e emissions. An increase in food-related emissions would decrease the contribution of packaging products to the environmental impact of the packaging. As the food products considered here do not have high GHG emissions, the overall impact does not change a lot by including food waste. However, Figure 18 indicates that when packaging production is excluded from the analysis, PEF has a lower environmental effect, in comparison to PET, while PLA has a higher environmental impact.

In the selection of packaging material for any food product, priority is given to packaging material that satisfies the quality, shelf-life, storage temperature requirement without having a large impact on the cost of the product (Ros-Chumillas et al., 2007). The results have shown the importance of considering the shelf-life aspect and with decreasing shelf-life the food waste will increase contributions to the carbon emissions. The results have also shown that polymers made from renewable resources can exhibit better gas barrier properties than fossil-based polymers and could be an excellent material for food packaging. Therefore, while developing new packaging materials the environmental impact of material production and the shelf-life extension provided by the material must be given equal importance.

From the results, it can be said that when the fossil-based polymers are recycled, then the GHG emissions of plastic can reduce. Although only virgin PET is considered as the main packaging material, considering a 100 per cent recycling scenario, the results showed that PET emissions can be reduced significantly. Even without 100 per cent recycling, PET 3 showed that even a smaller per cent of recycling can decrease the impact of the packaging material. The composting of biopolymers is not considered in the project; however, composting of biopolymers contributes to higher GHG emissions, primarily due to biogenic emissions, reducing its environmental efficiency (Hottle et al., 2017). This, along with a better barrier property, allows PET to be considered an alternative to biopolymers such as PLA, but not to PEF, which can be recycled and has a better barrier property than PET. As stated earlier, recycling and composting of biopolymers are not yet available in countries like Sweden, and the production cost of the biopolymers, like PEF, is high. Therefore, encouraging more recycling of PET, in the meantime, can help reduce the burden of packaging on the environment and PET can do that without reducing the shelf-life of food.

4.4 Comparison with existing studies

Dilkes-Hoffman et al. (2018) has demonstrated how including food in the LCA of biopolymer packaging affects the balance between the contribution of packaging waste and food waste caused by the packaging material's low barrier property. The model compared multi-layered thermoplastic (TPS) and Polyhydroxyalkanoate (PHA) combination PHA-TPS with polypropylene (PP) and the food products considered were beef and cheese.

Unlike the method proposed in this project, Dilkes-Hoffman et al. (2018) did not establish any link between increased shelf-life and reduced food waste. The food waste generated at the store was assumed to be 4 and 4.5 per cent for beef and cheese respectively and this waste was not related to the barrier properties of the packaging material. The comparison was made between beef and cheese products, which has significantly higher GHG emissions than juice. The model only considered landfill scenarios for packaging and food waste. Therefore when not considering the food waste, waste treatment of packaging material is the biggest contributor to GHG emissions. (Dilkes-Hoffman et al., 2018)

The method demonstrated in this project and by Dilkes-Hoffman et al. (2018), although it considers an assumed value of food waste due to shelf-life expiration, concludes that the inclusion of food waste does change the ratio of the GHG emission contributors in LCA of packaging material. The production and waste treatment of packaging is the biggest contributor until food waste is included in the LCA. Once food waste is included, the difference in environmental impact is influenced by the food waste generated and the GHG emission of the food. The GHG emission of cheese and beef are much higher than the food considered in this project and therefore by including the food waste generated, the production of the food had a much higher impact on the environment. Figure 19 kg CO_2emissions for 1 kg packaged beef consumed at the house, image is taken from (Dilkes-Hoffman et al., 2018)Figure 19 shows the GWP 100 and GWP 20-year impact assessment done by Dilkes-Hoffman et al. (2018) for beef.

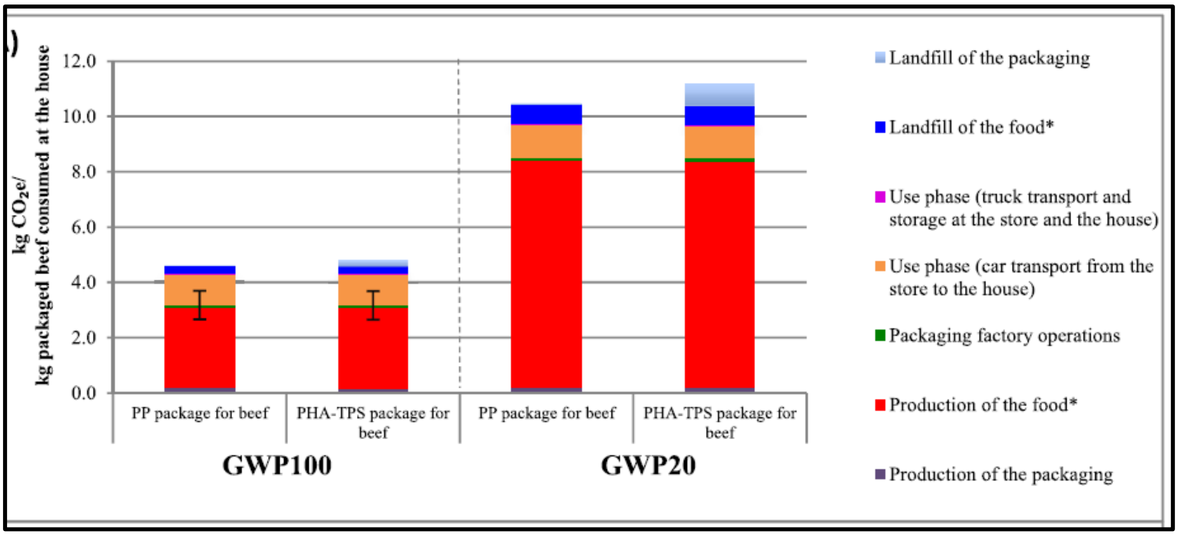


Figure 19 kg CO_2emissions for 1 kg packaged beef consumed at the house, image is taken from (Dilkes-Hoffman et al., 2018)

4.5 Discussion with industry

4.5.1 **Discussion on Shelf-life tool**

The discussion with the researcher from the University of Helsinki focused on whether the values provided by the tool seem reasonable, what could be done to improve the tool, and whether the tool could be used in the LCA of packaging material. The second version of the tool was shared with the researcher before the discussion. In terms of scale, the tool's OTR values were considered to be reasonable. However, the tool's estimated shelf-life value for certain polymers appeared to be unrealistic in reviews. On examination, a calculation error was discovered and was corrected.

While the current tool gave a good overview of the shelf-life offered by different polymers and aids in estimating the performance of the polymer, it should be further developed to integrate temperature variance and the possibility of a small amount of microbial spoilage, making it even more suitable for use in LCA. Therefore, best- and worst-case scenarios for temperature variation could be incorporated in the shelf-life estimation before integrating it into the LCA.

Concerning the tool itself, it was suggested, that the units and other terminology used be identical to those used by industry professionals, and that the tool's design or interface should be more user friendly, with fields that are not relevant from the user's perspective excluded or hidden.

4.5.2 **Discussion on LCA**

The purpose of the discussion with Tetra Pak experts was to present the tool and assess if the approach could be used during the development of food packaging materials. At Tetra Pak, the current practice is to design packaging for a range of products instead of for a specific food item. As a result, the technique was thought to be a reasonable start for designing food-specific packaging and including food waste while designing the packaging was thought to be beneficial. At the moment, the LCA of packaging, food shelf-life determination (due to packaging barrier property), and visually appealing packaging are all achieved in parallel.

The complexities involved in determining the food shelf-life are a major constraint, and so using the tool, which only considers one scenario, may have drawbacks. It was also stated that when all ingredients in the food products in the report are taken into account, the carbon footprint of the food products in the report may increase. This point was taken into account, and in the final version, in addition to tomato paste, sugar was added as an ingredient to ketchup and the GWP results explained before includes both tomato and sugar as ketchup ingredient.

4.6 Sustainable Development Goals

According to the UN, Sustainable development is achieved when the needs of the present generation are met without compromising the resources required to meet the needs of future generations. Based on this definition, the UN has identified some key problems that need to be addressed to ensure the future generations will have enough resources and has come up with 17 Sustainable Development Goals (SDGs). (UnitedNations, 2020) The goals are made to achieve a better future by ending poverty, improving the lives of everyone on this planet while simultaneously protecting the planet. (UnitedNations, 2020) The SDGs which are addressed to this project are 12: Responsible consumption and Production, 11: Sustainable Cities and communities, 14: Life below water. SDG goals identified are committed to reducing the marine pollution (debris etc.) which are caused due to activities performed on land, reducing GHG emissions by reducing the food waste generated, improving the environmental impact of cities by having a better waste management system and reusing practices and also to incorporate efficient use of natural resources. (UnitedNations, 2020)

Avoiding unnecessary food loss and waste, by using well-designed packaging, will have a positive impact not just on food security but also on the GWP impact of the food chain. The packaging is key in ensuring that the food is provided with an optimal condition throughout its life. (Coffigniez et al., 2021) This the reason why trying to link the shelf-life provided by packaging with food waste generated is important. The project has shown that the better the barrier property of a material the higher will be its shelf-life and that biopolymers like PEF are an excellent competitor to fossil-based polymers. Using biopolymers instead of fossil-based polymers will also help in decreasing the use of non-renewable sources. Food waste generates GHG emissions which when incorporated into the overall GHG of packaging material may increase or decrease its' efficiency. Therefore, incorporating food waste in the GWP impact assessment of packaging material will give a better insight on how the food packaging should be designed to reduce food wastage while also ensuring more renewable sources are used in its production.

Another concern with food packaging is the waste management system. Packaging waste contributes to around 60 per cent of the estimated 29.1 million tons of plastic waste in Europe and of this only 30 per cent is recycled and the remaining goes to waste (Statista, EU data journalism). Directive 94/62/EC amendment Directive 2018/852 has therefore set some requirements to address the issue of packaging waste management. The Directive 94/62/EC amendment Directive 2018/852 encourages EU countries to focus on measures to recycle and reuse the packaging waste generated and to adopt a waste management practice that will ensure the amount of packaging waste going for incineration is reduced. However, the substitution of fossil-based polymers with biodegradable polymers will develop a problem if there is a lack of adequate composting facility for these polymers. Since biopolymers are not yet suitable for home composting, the waste arising from them could contribute to the existing issue of waste management. Biopolymers can also be recyclable, for example, PEF, but as mentioned in the previous chapter the separation of biopolymers from fossil-based polymers and using it in recycling is currently a challenge. However, the EU council has come up with a new rule which mandates all EU states to have a separate waste collection facility for biowastes by 2023 (EuropeanCouncil, 2018). If this happens, then there will be better sorting, and therefore better recycling and composting, of the biopolymer and this could change the end-of-life scenario related emissions of the packaging materials.

The results in this project show that having a better recycling facility for PET can also reduce the environmental burden of fossil-based polymers. PET recycling is more established, efficient and growing, however, inadequate facilities for the collection or sorting of PET is affecting its recyclability (Nisticò, 2020, TMR, 2019). Therefore, in addition to legislations, setting up better waste sorting and recycling facilities is equally important to meet the SDGs.

All these measures implemented by EU and EU member states will however be irrelevant if consumers are not made aware of the recycling requirements. The environmental impact of substituting PET with a biobased alternative like PEF and PLA is discussed in this project. While PEF can be mechanically recycled, PLA can be sent to the composting facility during waste processing. The project also highlights that recycling fossil-based polymers like PET will also help in reducing their environmental impact and reducing plastic waste. However, the consumers need to be aware of this information or else the packaging waste will end up in incineration facilities.

5 Conclusion

This chapter first answers the research questions presented in the Introduction chapter followed by a reflection. The next part presents the limitations of the approach used in the report and the final part presents recommendations for future research.

5.1 Research question

- How is the shelf-life prediction of packed food performed? What are the factors that are considered while predicting shelf-life?
- How can shelf-life estimation be integrated into packaging LCAs to consider differences in food waste due to shelf-life expiration?
- How will the integration of food waste related to shelf-life expiration influence the environmental impact of the packaging material?

Industry's shelf-life prediction methods integrate experimental findings with computer simulations. Accelerated tests are used to estimate shelf life and are compared to simulation results. This study examined shelf-life prediction methods in which the quality factor was calculated, and the degradation of the quality factor was experimentally observed. The shelf-life is commonly calculated by fitting this value to a mathematical equation, like the one used in this project. In most cases, the permeability coefficient of the polymer, which is necessary for shelf-life prediction, is calculated via experiment. In certain cases, both permeability coefficient and OTR are measured experimentally using accelerated tests.

The LCA of packaging material reviewed in this project tries to incorporate food waste. However, there is a limited number of LCAs that are performed on realistic scenarios. Additionally, few studies try to find a link between shelf-life and food waste generation. The method by Conte et al. (2015) and Dilkes-Hoffman et al. (2018) reviewed and adapted in this project, are few that have tried to relate shelf-life and food waste through experiments or by assumptions and use them to analyse GWP impact of packaging material.

Current shelf-life prediction models consider either deteriorative reaction in food or quality indicator or barrier property of packaging (mass transfer reaction) or a combination of two of these parameters. The model that takes the IoFs of food and then combines it with the mass transfer reaction of packaging material to estimate the shelf-life of food is the simplest and easiest to incorporate into the LCA of packaging material. The permeability coefficient for TR calculation can be derived from existing articles or determined by simulations under various conditions to which the packaging would be subjected. This value can then be used in the TR expression derived from Fick's law. The TR can then be used to predict the shelf life provided by packaging. Based on the literature review, the two-component model may be a suitable approach to begin the shelf-life integration with LCA. As more data is gathered, the model can be improved.

The literature review and the results from this project have shown that the inclusion of shelf-life related food waste changes the environmental impact of packaging materials. The dynamic or the ratio of packaging production to total environmental impact changes. Based on the type of food being assessed, the contribution of food to GHG emissions can go up to 50 per cent of the total emissions (Dilkes-Hoffman et al., 2018).

5.2 Reflection

The project highlights that integrating food waste caused due to lower barrier property of packaging content is important. The approach's findings would enable the packaging design and development team to create a more efficient and sustainable packaging solution. The current practice, in which the shelf-life prediction, packaging design and LCA is performed in parallel, is a challenge in the integration of food waste and LCA. Since there are multiple steps involved in this integration, it necessitates cooperation between experts from various fields, which can be complicated and time-consuming at times. The second challenge is acquiring complete data on food waste produced as a result of shelf-life expiration and quantifying this waste. The various actors involved in these scenarios, as well as the difficulty in predicting consumer attitudes and behaviour, in terms of purchase and consumption, are the main hindrance to obtaining this information.

The simple shelf-life estimation tool developed in this project considers two factors i.e IoFs (or IoD) and mass transfer reaction of packaging material. Using this tool will give a fair understanding of the shelf-life offered by mono-layer packaging material. Although multilayer packaging is not explored in this project, the means of incorporating this aspect in the developed tool is provided in the report. Quantification of shelf-life related food waste is difficult as it requires lots of data. While the collection of data until retailer is possible and is used in this project, consumer behaviour is difficult to analyse and incorporate. However, organizations like the UN, WRAP and also national organizations like the Swedish national food agency are working towards the quantification of this waste.

Comparison of biopolymers with fossil-based polymers is not the primary goal of this project, but it is worth highlighting that the newly produced biopolymers synthesized from biomass have the potential to replace fossil-based polymers. The project has tried to assess the effect inclusion of food waste would have on the environmental impact of the polymers. One of the objectives was to see if including food waste will increase the environmental impact of the biopolymer due to the amount of waste generated by decreased shelf-life. The results have shown that incorporation of food waste has an impact but as the GHG emissions are low for the food products considered in the project, the difference after including food waste is not significant.

The inclusion of a recycling scenario for PET has significantly reduced the environmental impact of fossil-based polymers. While the initial notion was that the fossil-based alternative would perform poorly when compared to biopolymers, the results proved otherwise. In the recycling scenarios (PET 2 and PET 3), PET had a much smaller impact with reduced GHG emissions due to recycling and in the 100 per cent recycling scenario, the environmental impact was lower than PLA. This was after considering a 100 per cent recycling scenario, which may not be completely possible for now. However, it will be interesting to evaluate how PET and PEF perform against each other, in a more practical scenario, once PEF recycling facilities are available and more recycled PEF are used in producing bottles.

5.3 Limitations of the project

The project has developed a shelf-life estimation tool based on values from different scientific articles and reports. The accuracy of estimated shelf-life and GWP (Kg CO_2e emissions) values are dependent on the values given in these articles and reports. The shelf-life estimation is designed for liquid food types by considering one quality factor, ascorbic acid content for juice and colour for ketchup, and therefore while adapting the method for other food types, the modifications must be made to get more accurate results.

The food and packaging in the food supply chain are subjected to a considerable amount of temperature variation, which affects the shelf-life. The project assumes that the food and packages are kept at a constant temperature in the supply chain, which is not the case in a practical scenario. Taking into account one best and one worst-case scenario temperature can aid in incorporating temperature variance into the proposed method. The thickness of PET, PLA, and PEF bottles is assumed to be the same in this project. If the thickness of the PLA bottle is increased, or active or passive protection is introduced, the estimated shelf-life for food packaged in the PLA bottle could be longer.

The primary goal of the LCA was to determine if food waste could be included in the LCA of packaging polymers and which model would be appropriate for the same. As a result, the LCA performed in this project focuses solely on the GWP potential of packaging materials and ignores the energy or water required to produce these materials. The GWP impact of liquid food waste might be underestimated due to factors such as inadequate data on waste management of liquid food products and consideration of only major ingredients., As seen in other models, the environmental impact of food waste can be expected to be higher for other types of food items.

5.4 Future research

According to the writers' knowledge, there have not been many studies that attempt to quantify the differences in retail food waste caused by shelf-life differences between packaging materials with different barrier properties and then included this waste in the life cycle assessment of the food packaging material. The project showed that it is possible to include food waste, generated due to shelf-life expiration, in the LCA of packaging materials. Although in this project, the inclusion of food waste did not amount to a significant change in the total environmental impact of the packaging materials, the studies reviewed have considered foods with higher GHG emissions and their results have shown a significant change after including food waste. Therefore, if LCA is performed for packaging materials containing food products with higher GHG emissions, the results would change significantly and may provide more ideas to improve packaging design and development.

The project only considers monolayer packaging material and the O_2 barrier property of packaging. It would be interesting to see if the method were adopted for multilayer packaging and in addition to O_2, CO_2 and water vapour permeability was also included to understand the protection the packaging would provide to the food being considered. This would provide a better understanding of food waste generation and, as a result, the environmental impact of packaging. It would also be interesting to see the LCA incorporate another type of food product and packaging. This would benefit in comparing and analysing how waste generation varies with food type.

The quantification of food waste due to shelf-life expiration is estimated in reports by organisations like WRAP; however, more effort is required to relate food waste caused due to consumer behaviour so that the overall assessment of packaging-related food waste can be more realistic. More inter-disciplinary research is needed to gain a deeper understanding of the influence of packaging choices on food shelf-life and food waste in households.

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Appendix A LCA values

A.1 LCA of packaging material

Table 20 GWP impact of the packaging material without considering food waste

Process	***kg CO_2eq/FU***				
	V = 500 ml				
	PET 1	***PLA***	***PEF***	***PET 2***	***PET 3***
Transportation	*0.56*	*0.56*	*0.56*	*0.56*	*0.56*
Packaging waste	*178.78*	*173.29*	*112.42*	*178.78*	*178.78*
End of life (packaging)	*112.97*	-	-	*-48.48*	*15.90*
Total GWP	*292.31*	*173.86*	*112.99*	*130.86*	*195.24*
	V = 1000 ml				
Transportation	*0.30*	*0.30*	*0.30*	*0.30*	*0.30*
Packaging waste	*89.39*	*86.65*	*56.21*	*89.39*	*89.39*
End of life (packaging)	*56.48*	-	-	*-24.24*	*7.95*
Total GWP	*146.17*	*86.94*	*56.51*	*65.44*	*97.64*

A.2 LCA of packaging material including food waste

Table 21 GWP impact of packaging material for orange juice

Process	***kg CO_2eq/FU***				
	V = 500 ml				
	PET 1	***PLA***	***PEF***	***PET 2***	***PET 3***
Transportation	*0.56*	*0.56*	*0.56*	*0.56*	*0.56*
Packaging	*178.78*	*173.29*	*112.42*	*178.78*	*178.78*
Ingredients	*4.26*	*4.35*	*4.20*	*4.26*	*4.26*
Food processing	*112.97*	*0.00*	*0.00*	*-48.48*	*15.90*
End of life (packaging)	*1.01*	*1.03*	*0.99*	*1.01*	*1.01*
End of life (Food)	*1.51*	*1.54*	*1.49*	*1.51*	*1.51*
Total GWP	*299.09*	*180.78*	*119.67*	*137.64*	*202.02*
	V = 1000 ml				
Transportation	*0.30*	*0.30*	*0.56*	*0.30*	*0.30*
Packaging	*89.39*	*86.65*	*56.21*	*89.39*	*89.39*
Ingredients	*1.53*	*1.58*	*1.49*	*1.53*	*1.53*
Food processing	*4.31*	*4.45*	*4.21*	*4.31*	*4.31*
End of life (packaging)	*56.48*	*0.00*	*0.00*	*-24.24*	*7.95*
End of life (Food)	*1.02*	*1.05*	*0.99*	*1.02*	*1.02*
Total GWP	*153*	*94*	*63*	*72.30*	*104.49*

Table 22 GWP impact of packaging material for Ketchup

Process		***kg CO_2eq/FU***	
		V = 500 ml	
	PET	***PLA***	***PEF***
Transportation	*0.56*	*0.56*	*0.56*
Packaging	*178.78*	*173.29*	*112.42*
Ingredients	*4.06*	*4.50*	*3.80*
Food processing	*112.97*	*0.00*	*0.00*
End of life (packaging)	*1.01*	*1.11*	*0.94*
End of life (Food)	*1.52*	*1.68*	*1.42*
Total GWP	*298.90*	*181.16*	*119.14*
		V = 1000 ml	
Transportation	*0.30*	*0.30*	*0.30*
Packaging	*89.39*	*86.65*	*56.21*
Ingredients	*1.54*	*1.78*	*1.36*
Food processing	*4.12*	*4.77*	*3.64*
End of life (packaging)	*56.48*	*0.00*	*0.00*
End of life (Food)	*1.02*	*1.18*	*0.90*
Total GWP	*153*	*95*	*62*

Table 23 GWP impact of packaging material for Blackcurrant juice

Process	***kg CO_2eq/FU***				
	V = 500 ml				
	PET 1	***PLA***	***PEF***	***PET 2***	***PET 3***
Transportation	*0.56*	*0.56*	*0.56*	*0.56*	*0.56*
Packaging	*178.78*	*173.29*	*112.42*	*178.78*	*178.78*
Ingredients	*4.26*	*4.38*	*4.18*	*4.26*	*4.26*
Food processing	*112.97*	*0.00*	*0.00*	*-48.48*	*15.90*
End of life (packaging)	*1.01*	*1.04*	*0.99*	*1.01*	*1.01*
End of life (Food)	*2.01*	*2.07*	*1.98*	*2.01*	*2.01*
Total GWP	*299.59*	*181.35*	*120.13*	*138.14*	*202.52*
	V = 1000 ml				
Transportation	*0.30*	*0.30*	*0.30*	*0.30*	*0.30*
Packaging	*89.39*	*86.65*	*56.21*	*89.39*	*89.39*
Ingredients	*2.04*	*2.13*	*1.97*	*2.04*	*2.04*
Food processing	*4.31*	*4.50*	*4.17*	*4.31*	*4.31*
End of life (packaging)	*56.48*	*0.00*	*0.00*	*-24.24*	*7.95*
End of life (Food)	*1.02*	*1.06*	*0.99*	*1.02*	*1.02*
Total GWP	*154*	*95*	*64*	*72.81*	*105.01*