Applicability of bio-based polymer packaging in the meal kit context

A case study with HelloFresh

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Abstract

Bio-based plastics are increasingly considered as sustainable alternatives to fossil-based plastics. Up until now, their application in the food packaging industry has been limited. The purpose of this study is to investigate the applicability of bio-based polymer packaging films for bakery products, herbs and spices in the meal kit industry context and to assess their contribution towards a more sustainable packaging approach. Six different bio-based packaging film types (starch-based, cellulose based, polylactic acid (PLA), polyhydroxyalkanoates (PHA), bio-based polyethylene (BioPE) and bio-based polybutylene succinate (BioPBS) were compared regarding their product compatibility under current HelloFresh specific supply chain conditions. Except for PHA and BioPBS, all materials can be applied for herbs, while bakery and spices are only compatible with high-barrier cellulose-based films. Additionally, BioPE is applicable for bakery products, if they are stored at frozen conditions. The environmental impact was evaluated based on a beginning-of-life (BoL) and an end-of-life (EoL) assessment. In terms of BoL, bio-based polymers outperform their fossil-based counterparts. BioPE presents a global warming potential as low as -1,6 kgCO_2eq/kg polymer, compared to 1,9 kgCO_2eq/kg polymer for fossil-based PE and bio-based PHA reveals the lowest cumulative energy demand of 1,1 MJ compared to 69 MJ for PET amongst the fossil-based. As to the EoL, the most frequently intended EoL scenario is industrial composting, which was identified to be unrealistic: France is the only country, amongst Germany, the Netherlands and the UK, where composting plants are compatible with bio-plastics. Similarly, none of the countries provide designated recycling streams for bio-plastics. BioPE is preferred as a recyclable option. However, if excessive food contamination residues avert recycling, cellulose-based films are recommended as a compostable alternative.

Keywords: bio-based polymers, bio-plastics, compostability, food packaging, sustainable packaging

Executive Summary

Introduction and Research Questions

Plastic – a ubiquitously utilized material of modern lifestyle. It offers the perfect combination of unequalled functional properties, low cost and broad applicability. Yet, the environmental impacts of plastic production and waste are slowly becoming too big to repair. As an alternative, bio-based plastics are increasingly penetrating the market, promising reduction of resource depletion by decoupling the production from fossil feedstocks. Besides, compostability is a catching asset, leaving consumers to believe that a material will simply biodegrade in nature.

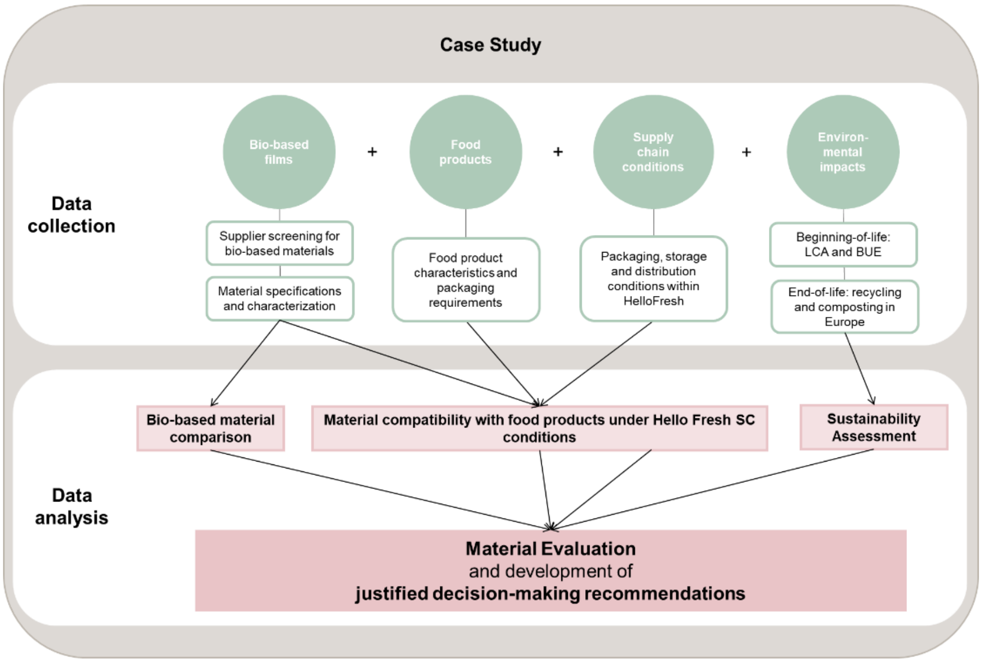
Hitherto, the applicability of bio-plastics has rarely touched upon the field of food packaging, due to limited barrier and mechanical properties. The aim of this thesis is to study:

1. *The extent to which bio-based packaging films are applicable for food packaging in the meal kit industry context* and
2. *In how far the application of bio-based materials contributes to a more sustainable packaging approach*

The study was conducted in cooperation with HelloFresh as an exemplary large-scale meal kit provider. The applicability was investigated for 3 product categories: Bakery products (BAK), fresh herbs (HERB) and ground spices (SPI).

Methodology

The study was conducted as a case study, split into three analysis parts.



A selection of 6 material types (starch-based, cellulose based, polylactic acid (PLA), polyhydroxy alkanoates (PHA), bio-based polyethylene (BioPE) and bio-based polybutylene succinate (BioPBS) were compared in terms of bio-based content, level of compostability, recyclability, industrial availability and transparency. Barrier properties (oxygen transmission rate (OTR) and water vapor transmission rate (WVTR)) were compared to conventional plastics. Furthermore, the shelf-life determining factors of the food products were identified, as well as the product specific storage and distribution conditions within HelloFresh. Based on that, packaging requirements were determined. The requirements were then aligned with the bio-based material barrier properties to identify potential material candidates. Moreover, the *Norner* barrier calculator tool was used to simulate the shelf life performance of the product-packaging systems, taking the supply chain conditions and packaging sizes into consideration. Currently applied packaging materials at HelloFresh were used as reference materials for this simulation. The environmental assessment was split into two parts: the beginning-of-life (BoL) phase and the end-of-life (EoL) phase. The BoL was evaluated by means of the global warming potential (GWP) and cumulative energy demand (CED) as well as the biomass utilization efficiency (BUE). In terms of EoL assessment, post-consumer plastic packaging waste recycling was compared to the likelihood effective compostability by evaluating insights about composting plant operations in Germany, France, the Netherlands and the UK.

Eventually, overall material preference recommendations were determined.

Results and Discussion

The study proved that most currently available bio-based films exert overall weaker barrier properties compared to conventional plastics. Following the product characterization, BAK and HERB products theoretically benefit from weaker barrier properties offered by bio-based materials, especially lower water vapor barriers, providing naturally occurring anti-mist properties. SPI on the other hand require both high gas and water vapor barriers.

Nevertheless, the study revealed limited applicability of bio-based films at current shelf life conditions at HelloFresh. Logistical challenges and procurement strategies do not allow just-in-time delivery for all product categories, thus the required shelf lives for the considered products were found to be 30 days for BAK, 8-10 days for HERB and 12-18 months for SPI.

To avoid the risk of food waste, it is of high priority to provide adequate product protection in order to reach the required shelf life. Therefore, the following material candidates were identified: HERB category is predicted to be compatible with all considered materials, except BioPBS and PHA, while the compatibility for BAK and SPI is limited to two identified high-barrier cellulose-based films. Additionally, BioPE is expected to be applicable for BAK, provided that BAK products are stored at frozen conditions for the majority of the supply chain duration. Practical shelf life tests need to be conducted to verify the predictions.

With regards to the environmental assessment, the BoL analysis has shown that most bio-based polymers outperform fossil-based counterparts in terms of GWP and CED. Starch-based and cellulose-based polymers proved to be most efficient in terms of biomass utilization amongst their bio-based competitors.

However, the outlooks for EoL options for bio-based materials, are rather disillusioning. Most bio-based packaging materials are intended to be disposed in industrial or home composting facilities, except for BioPE which is considered as a drop-in material that can be recycled in existing recycling streams. Yet, the study proved that compostable plastics, despite carrying the compostability certifications, are rarely compatible with composting facilities in Germany, the Netherlands, France and the UK at current stage. Effective composting is hence an unlikely scenario, resulting in the materials being sent to landfill or incineration. Similarly, recycling is not an option, since compostable materials require designated recycling streams, which have not been implemented in Europe's waste infrastructure yet.

Considering the small likelihood of compostability, recyclability in existing recycling streams turns out to be a preferred material feature. Yet, the probability of effective recycling is reduced once considering a packaging *film* which is likely to be *contaminated with food residues*. The choice of material and hence the choice of EoL is thus dependent on the product to be packaged. BioPE is preferred as a recyclable option. However, if excessive food contamination residues avert recycling, cellulose-based films are recommended as a compostable alternative.

Conclusion and future research recommendations

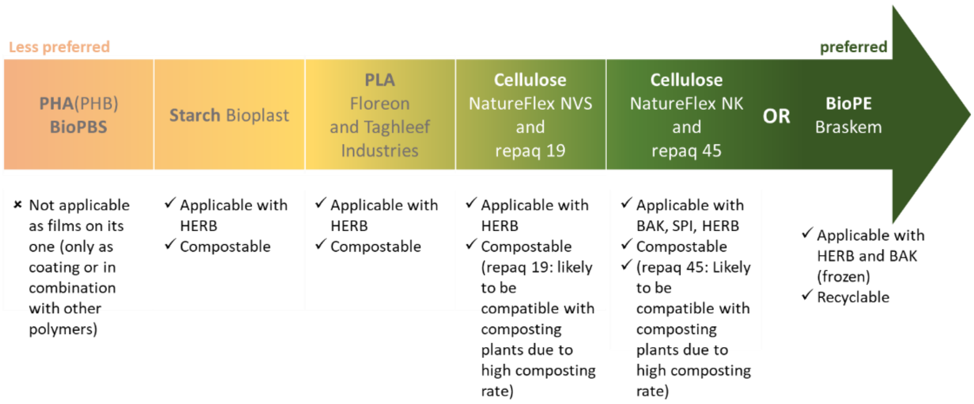
The following decision making priorities were set:

product protection >>> **arbitrary packaging reduction**

recyclability >>> **compostability**

bio-based >>> **fossil-based**

The below material preference recommendation was developed.



Investigations bio-based material applicability for further food products is recommended, especially for products with low chances of recyclability, such as meat and dairy. Further, opportunities for recyclable and/or recycled materials should be investigated. Concerning the meal kit industry, it is also recommended to explore potential optimization of the secondary packaging, e.g. improving volume and weight efficiency or the potential of implementing a packaging return system.

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Lund, June 2019

Theresa Stolberg

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List of acronyms and abbreviations

a_w	water activity	JIT	just-in-time
BAK	bakery	LCA	life cycle assessment
BC	bacterial cellulose	MAP	modified atmosphere packaging
BDO	1-4-butanediol	MEG	mono ethylene glycol
BD	biodegradables/compostables	NaCas	sodium caseinate
bioPE	bio-Polyethylene	NPS	net promoter score
bioPET	bio-Polyethyleneterephtalate	O_2	oxygen
bioPP	bio-Polypropylene	OLA	oligomeric lactic acid
BoL	beginning-of-life	OPP	oriented polypropylene
BOPP	biaxial-oriented-polypropylene	OTR	oxygen transmission rate
BUE	biomass utilization efficiency	PA	polyamide
CaCas	calcium caseinate	PBAT	adipate-*co*-terephthalate
CED	cumulative energy demand	PBS	poly(butylene succinate)
CPP	cast-extruded polypropylene	PEG	poly(ethylene glycol)
DC	distribution center	PGA	polyglycolic acid
EoL	end-of-life	PHA	polyhydroxyalkanoate
EVOH	ethylene vinyl alcohol	PHB	Poly-3-D-hydroxybutyrate
Gly	glycerol	PHBV	polyhydroxybutyrate-co-hydroxyvalerate
GWP	global warming potential	PLA	poly lactic acid
HERB	herbs	PP	polypropylene
HFSS	horizontal form fill seal	PTT	polytrimethylene terephthalate

RH	relative humidity
ROP	ring opening polymerization
SA	succinic acid
SC	supply chain
$SiOx_2$	silicon dioxide
SPI	spices
VFFS	vertical form fill seal
WV	water vapor
WVTR	water vapor transmission rate

1 Introduction

The introductory chapter provides the reader with background information which aim to clarify the motivation for this thesis. Further, the research questions, objectives and delimitations will be elaborated.

1.1 Background of Study & Problem Identification

After having spent 197 days in space, observing the earth's development from 400 km above the planet's surface, German astronaut Alexander Gerst apologized to his unborn grandchildren with the following words: *"I hope that we can still get the hang of it and improve a few things to avoid being remembered as the generation that selfishly and ruthlessly destroyed your livelihood."* He recorded his speech shortly before leaving the International Space Station (ISS), to return back to earth in November 2018. In his statement he emphasizes *"how vulnerable the planet's biosphere is and how limited the planet's resources [...] are".* (Gerst, 2018)

Resource depletion, which can also be described as the consumption of resources faster than they can be replenished, is an ever-increasing issue in today's society. While both, non-renewable and renewable resources are affected by over-consumption, those non-renewable, i.e. fossil-based resources, are much more severely threatened. (Mittal & Gupta, 2015)

As of 2016, the plastic industry consumes approximately 8% of the global oil production and is forecasted to rise up to 20% by 2050 (World Economic Forum, 2016). Following these numbers, the plastic industry accounts for one of the major fossil fuels utilizing industries. Global production of fossil-based plastics has surpassed 381 million tons in 2015 (Geyer et al., 2017) and is expected to continue growing (World Economic Forum, 2016).

Plastic products are present in daily life in diverse applications ranging from textile, construction, toys, household devices, medicine, electronics, packaging etc. Plastic owes its broad variety of applications to several material properties such as light weight, cheap prices and extreme durability. However, durability, one of its greatest assets, is lately revealing to turn into its biggest disadvantage. Plastics accumulation is losing control, pictures of plastic filled oceans are commonly known, alleged recycling streams cannot keep up and the market for recyclates is saturated (Plastics Europe, 2008). In fact, as stated by World Economic Forum (2016), only 14% of all plastics collected globally are eventually recycled as planned. Reasons for this are lacking recycling infrastructure but also the frequent use of multi-layer laminate materials and/or food contaminated materials which both complicate the recycling process significantly.

Amongst all circulating plastics, packaging plastics are by far those which experience the shortest serviceability and a high throw-away culture, considering that they act merely as a short-term protecting and/or containing aid and are disposed once they have fulfilled their purpose (Molenveld et al., 2015). Yet, the packaging industry is by far the one using the largest amount of fossil-based plastics, accounting for nearly 40% of applications (see Figure 1) half of which is used to package food (Robertson, 2012). A similar amount is thus expected to be plastic waste. (Carus & Aeschelmann, 2017; Molenveld et al., 2015)

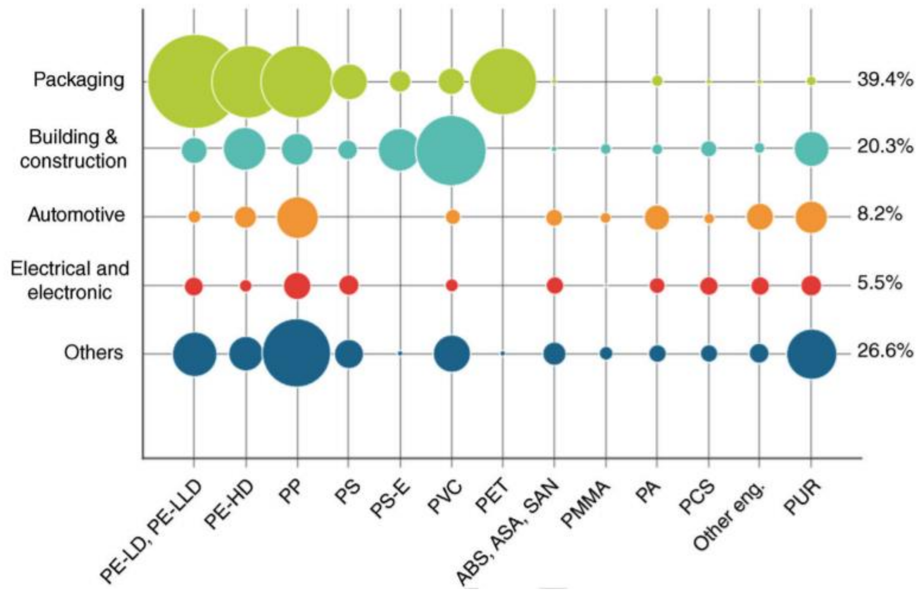

Figure 1. Application of plastics (Lackner, 2015)

However, today's society's increasing desire for convenience, makes the existence of packaging indispensable. Due to unique and vastly beneficial properties as well as low prices and light-weight characteristics, fossil-based plastics, are one of the most versatile materials on the market. Especially in the food industry, where protection and barrier properties are of immense importance, plastic packaging remains omnipresent (Álvarez-Chávez et al., 2012).

The rising demand for plastics and the resulting exploitation of fossil-based resources to an extent at which the earth's capacities are severely threatened (Bertolini et al., 2016) is driving the need to find alternatives to conventional plastic materials. Besides, limited availability of these resources, lead to steadily increasing prices (Molenveld et al., 2015).

Increasing amount of research has been invested into more sustainable alternatives with the potential to alleviate the overdependence of petroleum resources. In this context, bioplastics have been attracting more and more attention. The term *bioplastics* refers to a polymer-material which is *bio-based* and/or *biodegradable*. Two terms which should not be confused let alone be used interchangeably, as *bio-based* indicates the materials origin (made from renewable resources), while *biodegradable* defines the end-of-life (EoL) distinction.
Equally, in the search for more sustainable alternatives, industrial biotechnology is gaining increasing interest as a means of a less energy consuming manufacturing technology hoping to contribute to a reduction of greenhouse gas emissions. (Shamsuddin et al., 2017)

Growing consumer awareness of environmental impacts of packaging materials has also contributed to a growing demand for more sustainable solutions. Biopolymer packaging solutions have been more and more adopted in recent years by various industries, including the food and beverage industry, also to attract consumers (Mordor Intelligence, 2018). As demand is rising, the global bioplastics production capacity is expected to increase from 1.7 million (2014) to 6.1 million tons in 2021 (European Bioplastics e.V., 2019; Guidotti et al., 2017).

However, despite the promising potential of bio-based materials to reduce resource depletion, their overall contribution to sustainability remains arguable, especially when considering the EoL stage. Current European waste infrastructure differs from country to country and in many countries, it remains questionable whether the property of being biodegradable can at all be taken advantage of to the desired extent. (Álvarez-Chávez et al., 2012)

Furthermore, the primary function of packaging is to protect what it contains to avoid product waste as much as possible. Especially in the food industry, the packaging's function of protection is of highest priority to avoid food loss. So far, the use of biopolymers as raw materials for food packaging has been limited due to comparatively poor barrier properties and protection performance. (Peelman et al., 2016; Vilarinho et al., 2018)

One branch of the food industry which has earned heaps of criticism for its utilization of packaging lately is the meal kit industry. In fact, negative customer complaints regarding packaging have increased significantly within the period of one year, according to a study conducted by HelloFresh in 2017. Nevertheless, to safely execute the meal kit concept and to overcome the involved logistical challenges, the use of packaging materials is inevitable. At the same time the meal kit industry follows a delivery-based and just-in-time business model, making it subject to excellent supply chain management skills, but also providing it with the competitive edge towards common grocery stores. Especially storage and distribution conditions can differ greatly to those of conventional grocery store supply chains. The meal kit industry could thus offer a field with more potential for the utility of bio-based polymers.

1.2 Research Questions & Objectives

This thesis aims to assess the potential applicability of bio-based polymers as a packaging material for different food product categories in the meal kit industry context. Furthermore, it will be explored in how far the use of bio-based polymers contributes to a more sustainable packaging approach.

1. *In how far are bio-based packaging films applicable for food packaging in the meal kit industry context?*
2. *In how far does the application of bio-based films in the meal kit context contribute to a more sustainable packaging approach?*

To answer these questions the following objectives have been set:

- To obtain a deep understanding of the nature and diversity of bio-based polymers
- To explore the state-of-the-art of bio-based polymer material development
- To identify bio-based polymer films suppliers in Europe

- To characterize existing bio-based packaging materials and compare them amongst each other
- To identify food product category packaging requirements
- To assess the material performance in interaction with different food product categories
- To collect storage and distribution conditions along the meal kit supply chain
- To explore the environmental impact of bio-based packaging materials from a beginning-of-life (BoL) and EoL perspective

The below diagram (Figure 2) depicts a schematic overview of the intended study approach.

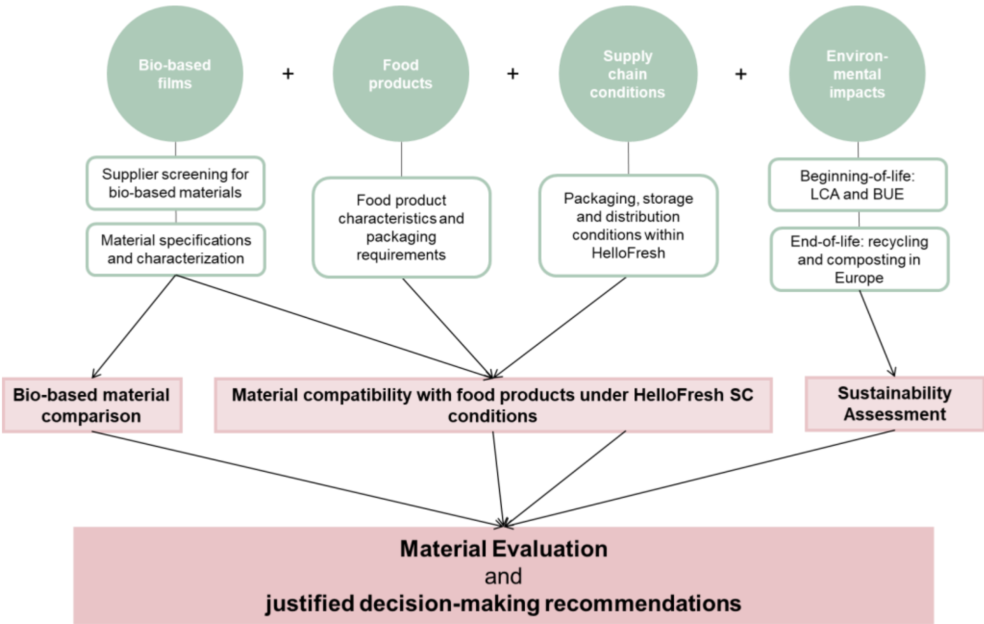

Figure 2. Schematic overview of overall study approach

The study is conducted in cooperation with HelloFresh SE as an exemplary industrial partner, on the basis of which holistic recommendations and decision-making guidelines applicable to the entire industry will be elaborated.

1.3 Delimitations

The following delimitations have been set for the study:

- The applicability of bio-based polymers is investigated for *primary* packaging purposes only, following the primary interest of HelloFresh
- The research focus is on bio-based packaging *films*, as opposed to rigid packaging alternatives, due to time constraints
- The research focus is on bio-based packaging films, that are *food-grade*
- The chosen product categories will be from HelloFresh’s product portfolio
- The number of investigated products for the product-material compatibility will be limited to 3, due to time constraints
- The environmental impact assessment is limited to a beginning-of-life assessment and an EoL assessment of the packaging material only, hence not considering the product’s impact
- The EoL assessment will be conducted for four European countries only, due to time constraints

2 Theoretical framework

This chapter provides a theoretical foundation on four topics which are relevant for the study. Firstly, the roles of packaging, particularly in the food industry and important considerations in packaging development will be described. Secondly, the meal kit industry framework will be elaborated, including an introduction of the industrial partner. Lastly, the state-of-the-art of bio-based polymers is given, followed by an insight into the consumer perception towards bio-based products.

2.1 Roles of Packaging

Packaging is an essential component of virtually every supply chain. As defined by Paine (1981) in three key statements, packaging is

I. *a coordinated system of preparing goods for transport, distribution, storage, retailing and end use*
II. *the means of ensuring safe delivery to the ultimate consumer in safe and sound condition at minimum cost*
III. *techno-economic function aimed at minimizing costs of delivery while maximizing sales*

As further summarized by several researchers (Hellström, 2007; Hellström & Olsson, 2017; Pålsson, 2018), packaging in general has been allocated six disparate functions:

1) **Protection**: to protect the content from physical, chemical, biological and climatic impacts
2) **Containment**: to hold content
3) **Apportionment**: to provide manageable sizes
4) **Unitization**: to optimize material handling through modularization
5) **Communication**: to fulfil legal and commercial demands, to enable product identification

6) **Convenience**: for simple and convenient product use

2.1.1 Food Packaging

According to Robertson (2012), packaging's roles of protection, containment, communication and convenience are of main importance in the *food* context, particularly for primary packaging (i.e. the direct product packaging). All functions must be considered simultaneously when developing new packaging solutions (Robertson, 2012). The researcher, however, will consider apportionment as a highly relevant role for food packaging as well, as this is strongly related to reduction of food loss. Besides that, apportioned packages are a key characteristic for meal kit businesses.

Protection

It is the packaging that is responsible to make sure that the product arrives at the end-user in safe and sound conditions by protecting its content from mechanical, biological and climatic hazards (Robertson, 2012). Packaging itself is a method of preservation with great potential to reduce food loss to a large extent (Wikström & Williams, 2010). It contributes to obtain maximum shelf-life by preventing microbial contamination and physical destruction, as well as to enable optimal quality maintenance (referring to appearance, aroma, taste and texture) (Krochta, 2006) for as long as possible. One of the key packaging properties that contributes to shelf life maintenance to a large extent are the material's barrier properties. Depending on the chemical structure and the composition of the material, packaging walls are likely to be somewhat permeable to gases and water vapor, which in turn can detrimentally affect the product's quality and safety. The two main parameters determining barrier performance are water vapor transmission rate (WVTR) and oxygen transmission rate (OTR). The lower both values are, the lower is the gain/loss of water vapor or oxygen respectively. While the required water vapor barrier depends on the moisture content and the water activity (a_w), the required oxygen barrier is related to product components which are sensitive to oxidation, such as lipids. (Siracusa, 2012)

Containment

The role of containment may seem obvious, yet it is explicitly expressed as a crucial responsibility of packaging. Nearly all products must be hold in something in order to be shifted around and to enable efficient handling. Durability is an important factor to allow product transport as a collective unit. As a containing aid, packaging also contributes largely to protecting the environment from pollution possibly caused by the product. (Krochta, 2006)

Communication

"A package must protect what it sells and sell what it protects". The function of communication serves not only for commercial purposes but also to fulfil legal demands and to mediate relevant product information to the end users. Besides, packaging enables product identification both in terms of branding relevant on a supermarket level, and in terms of logistics for warehousing, track and trace and efficient distribution purposes. (Robertson, 2012).

Convenience

Packaging plays a key role in meeting consumer demands for convenience, especially in the food industry. This encompasses the function of apportionments, i.e. packaging products in desirable and manageable amounts fitted to the intended consumer needs. Furthermore, a package should be convenient in terms of use, e.g. provide easy-to-open, pouring, reclosing or easy-to-empty features etc.) (Robertson, 2012)

Apportionment

The function of apportionment is meant to provide consumers with food packed in manageable sizes, meaning to meet appropriate quantity demands, depending on consumption patterns. By doing so, suitably executed apportionment can lead to reduced product waste, by avoiding packages that contain too much content to be consumed within the intended time period and shelf-life of the product. (Hellström & Olsson, 2017; Pålsson, 2018)

2.1.2 **Packaging Development**

The roles of packaging and the protective benefits can only be fully exploited if appropriate packaging material and design choices have been made according to the given product and related conditions. In the specific field of food packaging, the choice of appropriate materials which do not compromise food taste, appearance and quality is added to the challenge. At the same time, keeping the costs as low as possible while developing effective packaging remains the general aim of packaging development. (Mkandawire & Aryee, 2018; Molina-Besch, 2018)

To obtain optimal food packaging, Harte et al. (1987) once identified three key factors that need to be considered: product characteristics, individual package properties as well as storage and distribution conditions.

Product characteristics

It is essential to know a food product's individual physico-chemical characteristics when choosing a packaging material. Important intrinsic food properties include pH, a_w, sugar content, salt and spice content, added preservatives or antioxidants, initial microbial load and natural pigments (Olsson, 2018). Food products must be protected from any kind of deteriorative reactions, which can be of chemical, physical, enzymatic or microbial nature, as much as possible. Table 1 shows an overview of changes leading to deterioration categorized under the four factors.

Table 1. List of deteriorative factors for food products

Type of deteriorative factor	***Deteriorative changes***
Biochemical	Enzymatic reactions caused by Temperature increase Water activity Substrate alteration
Chemical	Non-enzymatic browning Lipid hydrolysis Lipid oxidation Protein denaturation Protein cross-linking Protein hydrolysis Natural pigment degradation Aroma loss through oxidation Loss of vitamins Glycolytic changes
Physical	Softening Toughening Loss of water holding capacity Wetting Agglomeration Emulsion instability Breakage/crushing Moisture loss/gain Aroma loss (volatility)

(Micro)biological	Microbial contamination and growth influenced by Initial microbial load pH Water activity Nutrients Storage temperature Relative humidity Concentration of gases in headspace (O_2, CO_2)	

(Adjusted from Krochta, 2006; Petersen et al., 1999)

Properties of the individual package

Packaging materials can be characterized with different parameters: Barrier properties, processability, mechanical properties, risk of material component migration into the product etc. are key factors to be taken into consideration when making material choices. Barrier properties refer to the resistance of gas permeability, (O_2, CO_2, N_2,), water vapor, aroma and light permeability. Mechanical properties include tensile strength, tear strength, puncture resistance, etc. The food product is in direct interaction with the packaging material, which, depending on the type of food product, can alter the material performance. Therefore, both product specific characteristics as well as storage and distribution conditions are required to know to be able to define necessary package properties. (Petersen et al., 1999) The fact that all materials interact with the contained product in some or other ways, has led to food packaging being subjected to strict laws and regulations ensuring food and essentially consumer safety. (Krochta, 2006) Besides intrinsic material properties, other factors such as closure, integrity and surface-to-volume ratio can largely influence a product's shelf life. I.e. The larger the package's surface area, the more interaction with the environment is enabled, therefore more potential for gas exchange or light income.

Storage and distribution conditions in the supply chain

Besides intrinsic factors mentioned above, food product behavior is dependent on extrinsic factors determined by the environment. Climatic conditions like temperature, humidity, light intensity, gas atmosphere but also any type of physical stress, such as vibration, compression or shock, that the product is subjected to during transport or storage can lead to product deterioration. Bruising can cause chemical or biological deterioration and can result in the product appearing inferior in quality. Storage and distribution conditions are strongly dependent on individual supply chain conditions. The conditions can either be advantageous in terms of required protection measures but may also demand for more advanced protective actions. Individual supply chain conditions are of essential knowledge to make well informed decisions on packaging materials and design. (Olsson, 2018; Petersen et al., 1999)

2.1.3 Sustainable Packaging Development

Besides fulfilling functional responsibilities, the environmental responsibility is gaining more and more importance when developing packaging. In fact, Pålsson (2018) extended the second point of the by Paine (1981) established packaging definition with *"[…]and at minimum environmental impact"*. (Pålsson, 2018)

"Sustainable development" is becoming a common product development approach, amongst packaging developers. It can also be referred to as "*a model of economic and social development in which the earth's resources are exploited, processed and utilized in a way that one meets the needs of the current generation without compromising or jeopardizing the ability of future generations to meet their needs"* (Haruna, 2016).

On a first instance one might hence tend to *reduce* packaging as much as possible. However, when developing packaging, one must keep in mind that it is not merely the packaging itself that causes environmental impacts, but also – and in some cases primarily– the product it contains. In Europe, *food production* accounts for roughly 20-30% of the environmental impact, of which meat and dairy production bear responsibility for the largest share, due to land and water use. *Packaging* for food products, in comparison, make up only 5-10% of the entire environmental impact of a food product. (Wikström & Williams, 2010) This emphasizes the power of packaging and its function to protect what it contains, as it prevents the invested amount of energy, water and land used for food production going to waste.

If one reduces packaging to an extent that it fails to fulfil its function of protection, therefore causing food waste, the probability that one has merely shifted the environmental burden is high. The aim should thus be to *optimize* the packaging rather than *reducing* it, in order to obtain an overall more sustainable result. (Verghese et al., 2015; Verghese & Lewis, 2007)

However, as was mentioned as a delimitation in 1.3 this thesis will solely focus on the *packaging's* environmental impact. To assess this, it is crucial to observe a packaging's entire life cycle, beginning with the sourcing of raw materials and production processes and ending in the materials disposal and further processing steps.

Figure 3 illustrates a simplified overview of a typical life cycle of a packaging material product, split into 3 general stages: BoL (in brown), use phase (in green) and EoL phase (in pink).

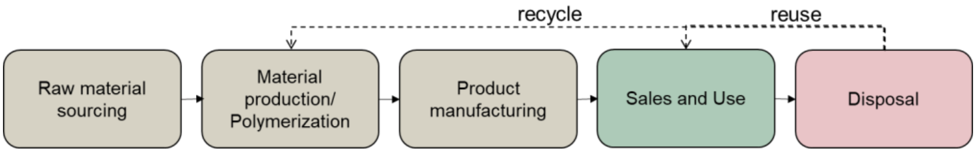

Figure 3. Generic life cycle of packaging products (modified from European Commission, 2019; Landsgesell, 2010)

A valuable sustainability tool, commonly known as life cycle assessment (LCA), has been developed for holistic identification and quantification of environmental impacts related to a given product, process or service. It aims to raise knowledge about the interaction of materials, products and processes with the environment throughout its entire life cycle. By obtaining a life cycle perspective, it contributes to avoid shifting the environmental burden between life cycle stages or between different impact categories. LCAs can support packaging development decisions and help to identify strategies to obtain the most environmentally friendly outcomes. (Verghese et al., 2012)

LCA can be conducted e.g. for a cradle-to-gate scenario, which usually encompasses all beginning-of-life stages until a finished product is sent for sales and use. A gate-to-gate LCA considers only a specific portion of the life cycle which has to be more precisely defined for each individual case. A cradle-to-grave LCA usually encompasses the entire life cycle, including the EoL stage. (Verghese et al., 2012)

2.2 Meal Kit Industry

The meal kit industry is exploding with over 170 companies (including niche operators) actively globally as of 2016 and a CAGR of 20,5% during 2018-2022. (BordBia, 2018; Mintel, 2018; Research and Markets, 2018)

The industry strongly follows the trends of health and wellness, and elevated convenience (BordBia, 2018; Mintel, 2018). Today's consumers want to eat well in as little time as possible, with minimum self-effort. At the same time, they request maximum transparency of what they eat (Frawley Branding, 2017). By providing pre-portioned, high quality cooking ingredients for a particular meal, ordered by the consumer through an easily manageable interface with appealing design, and delivered to the customer's doorstep, meal kit companies found their niche for a successful business model.

Besides providing maximum convenience, the concept is also designed to reduce food waste as much as possible. According to HelloFresh internal speakers, a significant amount of food waste commonly occurring in traditional grocery stores can be avoided by ordering the exact quantity of product required as per received customer orders, hence following a just-in-time production approach. Further, food waste is assumed to be curtailed at consumer level by providing them merely with the exact amount of product needed for the preparation of the intended recipe. However, this is a best-case-scenario assumption, since one does not have any control over how much left-over food effectively ends up in household waste. Such assertions should hence be considered with care, at least until facts provide tangible prove. Besides supposed food waste reduction, the concept has proven to be financially beneficial as a good amount of overheads commonly accompanying traditional grocery stores can be avoided, by eliminating the middlemen. For successful execution of the business model, meal kit companies are heavily reliant on timely product delivery from suppliers as well as efficient fulfillment and distribution processes. (The above information has been obtained from HelloFresh internal speakers and through observations within the company)

Yet, what might appear as a flawless concept, also entails its drawbacks. Perfectly portioned ingredients are inevitably accompanied by large amounts of varying packaging materials. Almost every ingredient is granted its own sachet. An issue, which is recently causing many eco-friendly customers to lose their appetite in meal kits. The meal might have been easily prepared and delicious in taste, yet the remaining bulk of packaging material that needs to be disposed of leaves a strongly negative aftertaste. Besides the primary packaging materials, one is left with the cardboard shipping box, ice packs, a bulky insulation bag and numerous plastic and paper bags that facilitate recipe distinction. It is the amount of material that accumulates as well as the uncertainty of how to properly sort them, that causes dissatisfaction amongst consumers. Besides, they feel fooled, when on the one hand being told they contribute positively to the environment by reducing food waste, yet by taking advantage of the service they stimulate the need for disturbing amounts of packaging. (Information retrieved from blog posts about meal kit box experiences as well as HelloFresh internal consumer feedback analyses). Packaging waste has become a major concern amongst consumers and amongst meal kit companies alike, as the trend towards environmental awareness and sustainability is growing (Mintel, 2018).

Within meal kit companies, the reduction of food loss has already been paid attention to by providing only the necessary amount of product. On top of that, the supply chain conditions and the required shelf life differ considerably to those in conventional grocery market supply chains. It is thus expected that the meal kit industry offers a potential ground for sustainable packaging solutions, which might not be applicable in conventional food supply chains.

2.2.1 **HelloFresh SE**

The case study of this thesis is conducted with HelloFresh SE, the global market leader in the meal kit industry. Being currently present in 8 countries in Europe (Germany, Austria, Switzerland, France, Netherlands Belgium, Luxemburg, UK), across the entire USA, Canada, Australia and New Zealand, it has become the world's most renowned and successful meal kit provider within a period of 7 years. After foundation in 2012, founders Dominik Richter and Thomas Griesel successfully raised an innovative, tech-oriented company with a powerful supply chain setup and efficient fulfilment processes. As of end-2017 the company group reports 1.45 million active customers and a revenue of more than €900 million, to which the US market alone contributes with €286 million. In terms of meals delivered, that equals just below 140 million meals per year. (HelloFresh SE, 2018)

2.2.2 **Sustainable Packaging approaches within HelloFresh**

Despite its marveling success and growth rate, the company is facing challenges. HelloFresh continuously gauges customer satisfaction with the overall product and service by collecting a net promoter score (NPS). It indicates the customer willingness to recommend the product/service to others. These customer surveys have revealed explicit discontent with the amount of packaging involved in the service. In fact, in Germany, the amount of negative complaints related to the quantity of packaging has risen a significant amount (numbers held confidential) in the past year, according to a negative comment frequency analysis conducted by HelloFresh.

Following this observation and with the aim to prevent dwindling customer lifetime values, HelloFresh has initiated several sustainability focused projects, on the one hand to meet the customer's demand for a sustainable lifestyle, but certainly also to improve the product and service to be entirely justifiable. In this context HelloFresh is continuously working on more sustainable packaging solutions, for both primary and secondary packaging.

The HelloFresh DACH (Germany, Austria, Switzerland) team has recently concluded a project with the following five sustainability commandments as a guideline to support the internal development of sustainable packaging solutions:

1. Reduce packaging
2. Replace fossil-resources with renewable resources
3. Reduce the use of virgin materials
4. Use recyclable materials
5. Use biodegradable materials, as long as it is not at the expense of recyclability

(HelloFresh DACH, 2019a)

Besides the commandments, two “must-have” criteria, were defined which must be considered for any type of packaging development: the maintenance of *quality* and *food safety*. According to the KANO theory of consumer satisfaction, must-have attributes are defined as being taken for granted when fulfilled (do not cause positive excitement), however result in dissatisfaction when not fulfilled (Löfgren & Witell, 2005).

With the aim to assess the applicability of bio-based polymers within the meal kit industry, this thesis contributes to the fulfilment of commandment Nr. 2.

2.3 Bio-based polymers

In the twentieth century, the polymer industry was governed by petrochemical-based resources. Even though negative effects were noticed, the industry did not undertake any changes until the negative impacts raised increasing concern and induced the replacement of petroleum-based polymers around the 1980s (Nakajima et al., 2017). Ever since, polymers from renewable resources and biodegradable polymers began to develop. According to Nakajima et al. (2017) *“the development of biodegradable polymers is recognized as one of the most successful innovations in the polymer industry to address environmental issues”*.

Around 170 billion tons of biomass, i.e. renewable resources, are naturally produced every year, of which a mere 3.5% (6 billion tons) are effectively utilized, mostly as a raw material for food production (Robertson, 2012). The remaining unutilized rest thus hides unexploited potential for various applications. The key force driving the development of bio-based materials is the urge to sustain non-renewable resources by substituting them with renewables. (Robertson, 2012)

2.3.1 **Terminology**

First of all, a clear differentiation between the terms 'bio-based polymer' and 'bio-based plastic' is necessary to avoid confusion. A *polymer* can be defined as a chemical or natural substance consisting of multiple repeating structural units. Polymers are commonly synthesized through a polymerization or fermentation process, in which monomers are added one after another to build a chain. (Bradford et al., 2017) A *bio-based* polymer, e.g. starch or cellulose, is hence a chain of monomers derived from renewable resources such as corn or sugarcane, thus differentiating itself from *fossil-based* polymers, e.g. nylon or polyethylene, which are derived from fossil fuels such as petroleum or natural gas. A bio-based *plastic* on the other hand is a material made from the polymers, often blended with fillers and other additives. In short, a polymer acts as the basic building block for a plastic. (Carus & Aeschelmann, 2017; Gironi & Piemonte, 2011)

The term *bioplastics* refers to materials being bio-based and/or biodegradable. While *bio-based* indicates what kind of resource the polymer originates from, that is a plant or other biological, renewable resource, (e.g. starch, cellulose or poly-lactic acid), the term *biodegradable* refers to the EoL stage of the polymer-material, in which case it can degrade and return to nature, regardless of the origin of its monomers. (Molenveld et al., 2015; Reddy et al., 2013). Whether a polymer is biodegradable or not depends solely on its chemical structure rather than the origin of its building block (Chen, 2014). It should thus be noted that a fossil-based polymer can certainly be biodegradable while a bio-based polymer may as well not be biodegradable.

Furthermore, *biodegradable* must be distinguished from the term *compostable. Compostable* plastics are defined as those which are broken down to natural matter in industrial composting environments at a rate equivalent to other compostable materials (Reddy et al., 2013). In comparison, the term *biodegradable* as such is not yet defined by a certain timeframe or environment.

Table 2 summarizes the aforementioned terminology.

Table 2. Terminology (Modified from Reddy et al., 2013)

Term	***Explanation***
Bioplastic	A plastic derived from biological/renewable resources and/or degrades by microbial action/biological activity
Bio-based plastic	A plastic derived entirely or partially from biological/renewable resources
Fossil-based plastic	A plastic derived from fossil, non-renewable resources
Degradable plastic	A plastic which undergoes major structural changes in predefined environmental conditions
Biodegradable plastic	A plastic which degrades due to the action of naturally occurring microorganisms (e.g. bacteria, fungi, algae) to yield carbon dioxide, water, inorganic compounds and biomass or which reduces its molecular weight by biological activity
Compostable plastic	A plastic that degrades in a composting environment in a defined timeframe to yield carbon dioxide, water, inorganic compounds and biomass at a rate similar to known compostable materials, without leaving any toxic residue (>90% metabolic biodegradation into CO_2 within 180 days, >90% dry-weight disintegration after 90 days)

2.3.2 **Certifications**

Companies can obtain formal certifications and labels approving the bio-based content and compostability. Formal certifications are processed are controlled by DIN CERTCO and TÜV Austria (formerly Vinçotte), a German and Belgian authorized certifier respectively. Either of the following labels (Figure 4) can be obtained to authenticate the bio-based content of a product (European Bioplastics e.V., 2019)

Figure 4. Example of bio-based label from DIN CERTCO (left) (also available with lower bio-based content) and TÜV AUSTRIA (right)

If a packaging material meets the requirements for the European standard EN13432 for industrial compostability, it is entitled to be labelled with the seedling-logo

(Figure 5), which certifies conformity with the referenced standards. The logo has become an established, distinctive trademark in several European countries including Germany, the Netherlands, Belgium, Switzerland and the UK, declaring that the material will decompose entirely in an industrial composting plant under controlled temperature, humidity and time conditions. (European Bioplastics e.V., 2019)

Figure 5. Seedling-Logo certifying that a product is industrially compostable based on the European norm EN13432

Besides the seedling-logo, the OK compost INDUSTRIAL label (Figure 6) certifies, that a material is fully biodegradable in industrial composting facilities. Industrial composting facilities are strictly harmonized and controlled with regard to temperature, material particle sizes, moisture content, aeration, pH and carbon/nitrogen ratio. (European Bioplastics, 2009)

In contrast, it is impossible for authorities to monitor these parameters in home composting environments, where composting is often less consistent and more time-consuming due to lower and less stable temperatures. Home conditions are in full responsibility of individual households, thus vary to a great extent (European Bioplastics e.V., 2016) No international standards have been defined specifying home composting conditions. TÜV Austria has however defined a simplified certification scheme. The OK compost HOME label (Figure 6) certifies biodegradation in garden/home composting conditions. Since the effective degradation behavior depends heavily on the given composting environment, a mere certification does not simultaneously assure good degradation performance in every home composting environment. (European Bioplastics, 2015)

Similarly, there is no defined standard for biodegradability in marine conditions. The TÜV Austria OK biodegradable MARINE label (Figure 6) is merely based on a non-standardized certification scheme. (European Bioplastics, 2018)

Figure 6. OK compost INDUSTRIAL and OK compost HOME and OK biodegradable MARINE (from left)

Table 3 summarizes the required conditions for the biodegradability levels.

Table 3. Required conditions for the different biodegradability levels

Biodegradability level	*Requirements and conditions*
Industrially compostable according to EN13432	**European Standard:** **Biodegradation requirement**: >90% metabolic conversion into CO_2 within 6 months (compared to reference sample) at ca. 58°C composting conditions **Disintegration requirement**: max. 10% remaining dry weight after 3 months Usual conditions for industrial composting facility: 50-70°C, aerobic, thermophilic bacteria (European Bioplastics, 2009)
Home compostable	No international standard specifying home composting conditions. The following certification scheme was defined by TÜV Austria: **Biodegradation requirement**: >90% metabolic conversion into CO_2 within 12 months at ambient temperatures (compared to reference sample) at ambient composting conditions **Disintegration requirement**: max. 10% remaining dry weight of test material after 6 months Usual conditions for home composting facility: 20-45°C, aerobic, psychrophilic to mesophilic bacteria (European Bioplastics, 2015)
Marine biodegradable	No international standard specifying marine composting conditions. The following certification scheme was defined by TÜV Austria: **Biodegradation requirement:** >90% metabolic conversion into CO_2 within 6 months (European Bioplastics, 2016)

(European Bioplastics, 2018)

2.3.3 End-of-life of bio-based materials

Composting certifications and the according labels used on packaging provide a means to communicate a materials sourcing and the intended EoL option for a product. A reasonable number of bio-based packaging materials carry the compostability certification according to the European Standard EN13432, hence are designated for compost as their EoL stage.

In the EU, a large portion of municipal waste is biodegradable waste, consisting largely of organic food waste. By collecting organic biodegradable matter a significant amount of waste can be diverted from landfill. Instead of contributing to greenhouse gas emissions (in case of landfill), organic matter can be biologically decomposed to eventually result in a stabilized product which can be further used as soil stabilizer or fertilizer. (Williams, 2005)

As described in Table 3 there are two types of on-land composting possibilities: industrial and home composting. Besides significant differences in compost plant sizes, the major and most crucial difference is the prevailing temperature and the consequential presence of microorganisms. Lower temperature and psychro- and mesophilic microorganisms in home composting facilities decelerate the process, essentially resulting in significantly longer degradation durations. (European Bioplastics, 2015; Williams, 2005)

While certifications and labels indicate the intended EoL, they do by no means ensure that the intended EoL will also be the effective scenario. Where a packaging product is eventually processed depends on the disposal in households in the first place, followed by the waste infrastructure which determines the collection systems and sorting rules and lastly, on the compatibility of the product with the composting and recycling facilities.

The European Commission (2019) conducted a study on the environmental impacts of bio-based products in which they compared the intended EoL scenario (industrial composting or recycling) to an assumed real EoL scenario (a mix of landfill, incineration, recycling and industrial composting). The LCAs were conducted for cradle-to-grave scenarios and considered 16 impact categories (global warming potential, acidification, eutrophication, stratospheric ozone depletion amongst others). The results were broken down to 5 major life cycle stages to signify which life cycle stage has the strongest influence on the environmental impact. As can be seen in Figure 7, results differed depending on what kind of bio-based product was considered. For most products, the “polymer and material production” stage appears to contribute the largest portion to the environmental impact. As for “Packaging films" however, results showed that in case of a mixed EoL scenario, the EoL stage is responsible for 50% of the environmental impact, whereas in case of intended EoL, the EoL only weighs about 20% of the environmental impact. (European Commission, 2019) It is thus assumed that the EoL has a significant influence on the environmental impact of bio-based packaging films.

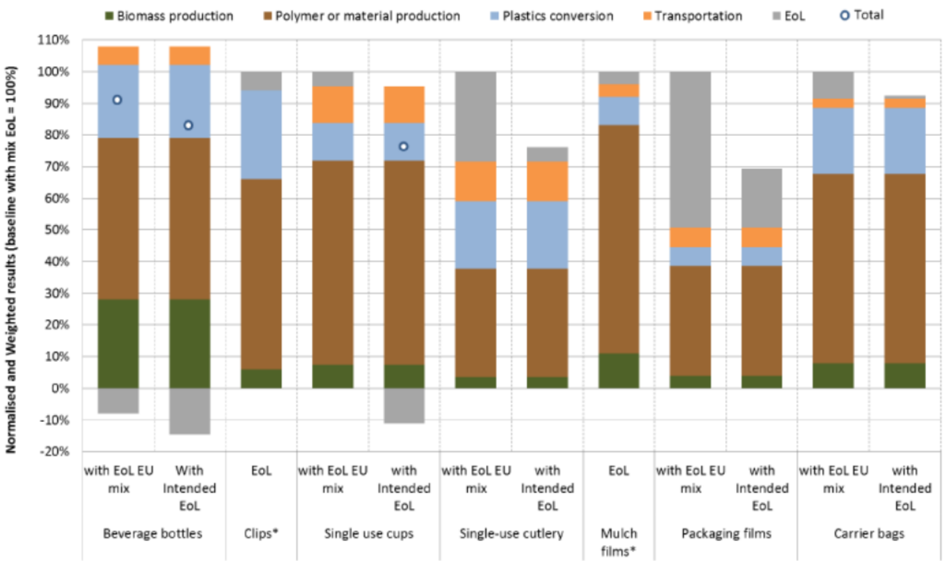

Figure 7. Weighted result of cradle-to-grave LCA of seven bio-base products. The weighting is based on 16 impact categories and distributed into major life-cycle stages. (European Commission, 2019)

2.3.4 State-of-the-art of biopolymers

Bio-polymers have been deeply studied in the recent decade, with the hope to develop a replacement for conventional petroleum-based packaging materials. They can be classified into 3 main categories related to their origin and method of production:

A. **Biopolymers extracted from biomass**, which can be any type of natural material such as polysaccharides, proteins or lipids.
B. **Biopolymers synthesized by classical chemical synthesis (fermentation) from bio-derived monomers**
C. **Biopolymers directly produced by natural or genetically modified microorganisms**, which are synthesized intracellularly and extracted afterwards

(Khosravi-Darania & Buccib, 2015; Rastogi & Samyn, 2015)

Figure 8 represents a schematic overview of the polymer classification.

The following section gives an overview of the state of the art of some of the most studied and most applied biopolymers in the food packaging industry to date. It focuses on food grade biopolymer materials with which film manufacturing is possible. Biopolymers which are primarily used for rigid plastic production (bottles or others) will not be discussed. The section aims to cover the nature of the polymers, in terms of biological source and chemical structure and features, different production methods as well as recent developments regarding improved applicability for food packaging. A more detailed investigation on barrier properties, which have been identified as a crucial quality parameter for effective utilization of biopolymers in the food industry (Vartiainen et al., 2014), will be part of the individual material assessment in the results section.

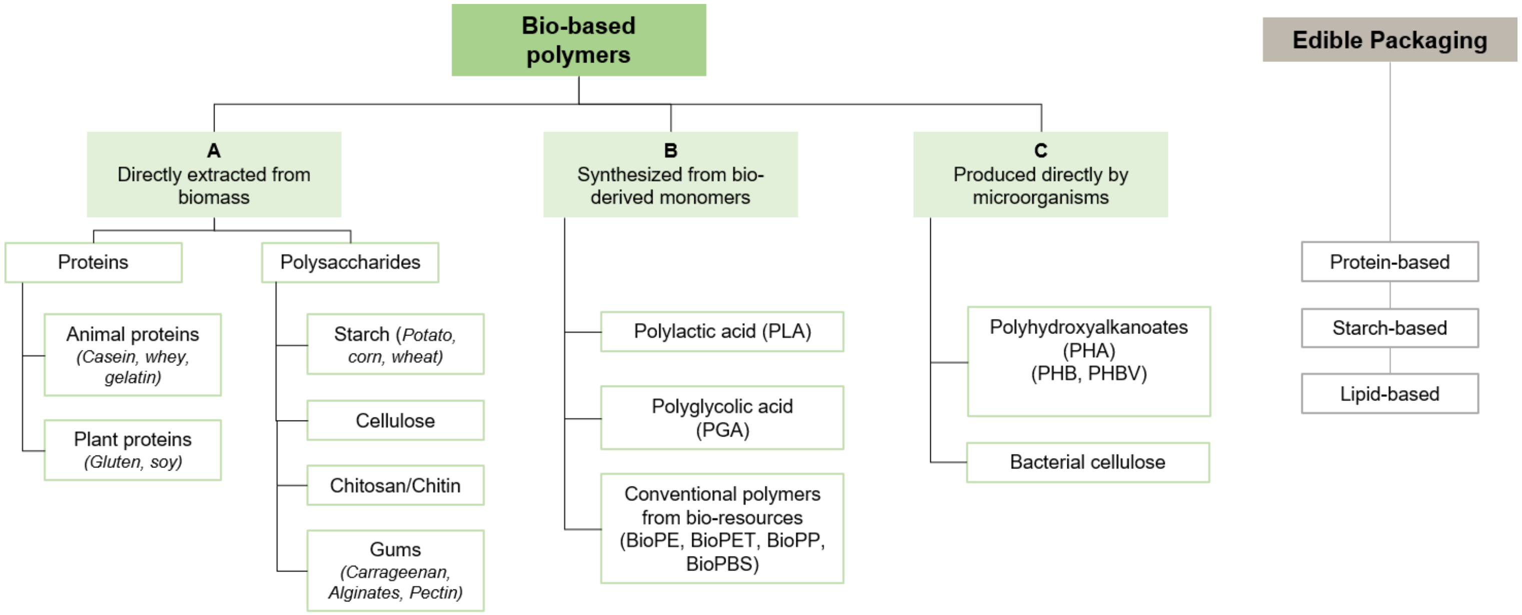

Figure 8. Overview of bio-based polymers classified by their method of production (modified from Rastogi and Samyn, 2015; Robertson 2013)

2.3.4.1 Starch based plastics

Starch is a polysaccharide. In fact, it is one of the most accessible and inexpensive polysaccharides known to man. It is a renewable resource which is entirely biodegradable. It is obtained from various plants and grains, most commonly potato, tapioca and corn. Starch is a crystalline material with thermoplastic characteristics (which means it is moldable at high temperatures and solidifies when cooling down). Properties of starch materials are directly related to the ratio of amylose/amylopectin (see Figure 9), which are the two glucose polymers which starch is composed of. A predominance of amylose provides a starch-based material with high strength and improved flow properties, which are preferred properties for the production of thermoplastic starch (Greene, 2014; Prabhu & Prashantha, 2018). At the same time, high amylose content also reduces the materials flexibility. (Mohammadi Nafchi et al., 2013)

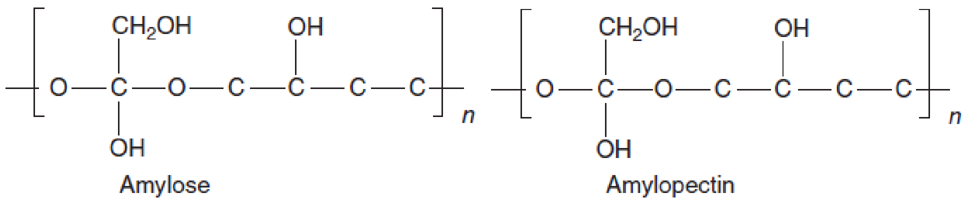

Figure 9. Molecular structure of amylose and amylopectin

Even though starch-based polymers exhibit good oxygen barrier properties, more commonly used polymer materials made from starch are not entirely starch-based, but instead are blended with other compostable polyesters or even petro-based plastics. This is due so some non-beneficial properties of purely starch-based material: highly hydrophilic characteristics, limited mechanical properties and increasing retrogradation over time in presence of water resulting in brittleness. (Ferreira et al., 2016; Khan et al., 2017)

Furthermore, plasticizers, such as glycerol, glycol or sorbitol, or various types of proteins have been studied to achieve a more flexible material with low water vapor permeability and good mechanical strength, to be useful as a thermoplastic packaging material. (Ferreira et al., 2016; Khan et al., 2017; Prabhu & Prashantha, 2018)

Packaging films made from starch-blends are generally not transparent: some are translucent, others even opaque. To improve the films barrier properties it can be combined with cellulose. For improved flexibility, polybutylene adipate-*co*-terephthalate (PBAT), which is biodegradable, yet derived from non-renewable sources up until now (Mallegni et al., 2018) is a good laminate option (van den Oever et al., 2017).

Starch as such is consumed by microorganisms as a carbon source. Starch-based materials can therefore be disposed together with organic waste for biodegradation. Starch blends are even biodegradable in marine environment (van den Oever et al., 2017). Several studies have also proven that the presence of starch in combination with other polymers (e.g. polylactic acid) has a beneficial effect towards an increased biodegradation rate (Prabhu & Prashantha, 2018). However, the compostability only applied as long as the starch is combined with other biodegradable polymers. Blending with non-biodegradable polymers, will render the material both non-biodegradable and non-recyclable. (Greene, 2014)

2.3.4.2 Cellulose based

Cellulose is the main structural component of plant tissue and one of the most abundantly available and broadly used natural materials. Its fibers make up a major component of paper. Cotton and wood pulp, as well as sugarcane bagasse in smaller amounts serve as a major source for cellulose extraction (Ferreira et al., 2016; Reddy et al., 2013). Many advantages such as being cheap, renewable, light weight, durable and possessing good mechanical properties make cellulose a highly attractive polymer in search for conventional plastics substitutes. (Kalia et al., 2011)

Besides being produced from plants, cellulose can also be derived from bacterial synthesis, which is known as bacterial cellulose (BC). BC can be considered a more sustainable type of cellulose as it does not require plant renewal. BC synthesizing bacteria include *Rhizobium* spp., *Agrobacterium* spp., *Acetobacter* spp. *and Alcaligenes* spp. (Arévalo Gallegos et al., 2016) Even though BC has the exact same chemical structure as cellulose derived from plants, it has a much higher degree of purity as it is free from other compounds that are commonly linked to cellulose, e.g. lignin, pectin hemicellulose etc. Its high degree of purity renders BC promising for a variety of applications, including the food industry. (Arévalo Gallegos et al., 2016) Also, recently, researchers discovered that biotechnologically produced cellulose by *Escherichia coli*, contains a sidechain which is not present in cellulose found in plants. This sidechain happens to make the cellulose film denser and hence more resistant to shear forces. (Thongsomboon et al., 2018)

However, most commercially available cellulose-based materials are still derived from renewable wood pulp.

Cellulose is a long straight-chain polysaccharide made of linked D-glucose molecules. The chemical structure of two linked glucose molecules is depicted in Figure 10.

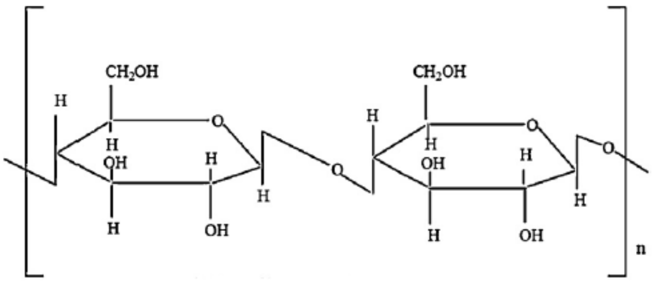

Figure 10. Chemical structure of cellulose (Reddy et al., 2013)

Despite of the large amount of hydroxyl groups, and the resulting hydrophilic nature, cellulose is not water soluble. The array of hydroxyl groups allows for strong hydrogen bonds, which are considered to be the determining factor of the materials physical and chemical properties. (Vilarinho et al., 2018; Khwaldia, 2010)

Cellulose films are not sealable by itself, however can be easily combined with a layer of either a starch-based or amorphous polylactic acid (PLA) layer to render it sealable and remain its transparent character ideal for packaging applications. For improved barrier properties, yet maintaining the compostable properties, a thin layer of aluminium oxide is often applied. (Molenveld et al., 2015) The thermoplastic behavior of cellulose can be greatly improved by chemical modification such as etherification or esterification, leading to cellulose derivatives, of which cellulose acetate and cellulose esters are most commercialized. However, these are not commonly used for packaging purposes. Aside from chemical modification, the addition of plasticizers is also common to overcome material drawbacks. (Ferreira et al., 2016)

The applicability of cellulose packaging films ranges from fresh produce, bakery, sweets to dairy and coffee products, where its high transparency and its 'dead fold' (once folded/twisted the fold is retained) is of great advantage. (van den Oever et al., 2017)

Cellulose-based materials are biodegradable and compostable in various environments.

2.3.4.3 Polylactic acid

Polylactic acid is one of the most well established and cheapest bio-based alternatives to conventional polymers. According to Global Trend Report by the Nova Institute in 2017, PLA is a fast-growing market segment and is predicted to continue growing at an annual growth rate of 10% until 2021 (Carus & Aeschelmann, 2017; Mallegni et al., 2018).

PLA is synthesized either by direct polycondensation of its monomers (lactic acid) or through ring opening polymerization (ROP) of lactide, which is more common for industrial purposes (see Figure 11). (Reddy et al., 2013)

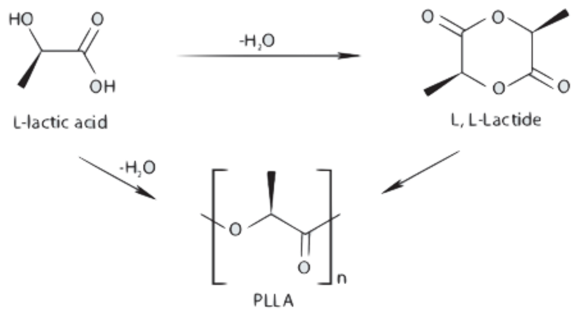

Figure 11. Schematic depiction of two alternative synthesis methods of PLA. Left: condensation polymerization; right: ROP (Storz & Vorlop, 2013)

The monomer, lactic acid, can either be synthesized by carbohydrate fermentation, for which several kinds of biomass such as starch waste, sugar beets or whey can act as a carbohydrate source, or by chemical synthesis. (Inkinen et al., 2011; Vitkevicius, 2017)

Lactic acid has a chiral nature, meaning it can appear as D- and L-lactic acid, resulting in distinct forms of polylactides namely poly(L-lactide) and poly(D-lactide) or a racemic mixture of the two obtaining poly(DL-lactide). The crystallinity of a resulting polymer depends on the amount of bound D-lactic acid monomers. One can thus obtain an entirely amorphous as well as a fully crystalline polymer. (Reddy et al., 2013)

PLA has proven to be a versatile material in various fields of application. Being extremely transparent and glossy, as well as being approved for food contact (Mallegni et al., 2018; Molenveld et al., 2015), makes it easily applicable in the food packaging field. Thanks to its breathing capabilities it is especially suitable for respiring products, e.g. fresh produce and bread (Molenveld et al., 2015). Besides, it has a good aroma barrier (van den Oever et al., 2017). PLA packaging appears in different forms including trays, films, coatings etc. PLA films however are rather stiff, with an increased sensitivity to tearing (van den Oever et al., 2017). The low flexibility can be overcome by blending PLA either with a plasticizer or a flexible polymer, e.g. PBAT (biodegradable, but fossil-based) (Mallegni et al., 2018). PLA's comparatively high water permeability excludes the applicability for liquid products which require long shelf life or those highly sensitive to moisture, unless PLA is combined with layers of other materials such as chitosan and cellulose to obtain an improved water barrier (Halász et al., 2015; Molenveld et al., 2015). Furthermore, researchers are progressing in developing high-oxygen-barrier PLA based films by applying a silicon dioxide ($SiOx_2$) coating to PLA. The coating provides chemically inert properties resulting in excellent oxygen barrier, while not having a negative effect on the biodegradability. (Chaudhry et al., 2010; Huang et al., 2018)

Most PLA materials are biodegradable only in industrial composting conditions (min. 58°C) (Greene, 2014; van den Oever et al., 2017), which is considered as one of PLA's downsides. Researchers are thus driven to optimize the material for a more sustainable EoL.

Carbios, a French Innovative Green Chemistry Company, is actively contributing to the ongoing research. Their initial goal was to identify the organisms that are responsible for the degradation of PLA in the composting environment. Once successfully identified they continued by isolating the responsible enzyme from the organism and eventually embedded the enzyme in the chemical structure of the PLA material during production to obtain a material with implanted decay properties. The breakthrough, enzyme-based technology that renders PLA biodegradable at ambient conditions (PLA is degraded back into harmless lactic acid), has proven to be effective at least on a pre-industrial scale. (Carbios, 2015)

Carbiolice – the joined venture, which resulted from the successful biodegradation technology – produces plastic pellets which carry the degradation enzymes in their formulation, targeting rigid as well as flexible plastics/packaging market. (Carbios, 2019) As stated by Carbios in early 2019, the material is marketable next year. (Spiegel Online, 2019)

Furthermore, *Carbios* has successfully engineered microorganisms, which inhere a metabolic pathway, enabling the production of PLA without the need for building blocks sourced from the environment. (Labiotech.eu, 2016)

2.3.4.4 Polyglycolic acid

Technical Research Centre of Finland (VTT) researchers have recently made progress in developing a technology to efficiently derive the monomer of polyglycolic acid (PGA), glycolic acid, from bio-based feedstock.

Synthesized from hydrolyzed sugar, PGA is a very simple, biodegradable polyester, of which the production closely resembles that of PLA. Compared to PLA however, PGA exhibits good mechanical strength (20-30% stronger than PLA) and good heat resistance. Furthermore, PGA has excellent oxygen barrier properties, which makes PGA a promising polymer for food packaging purposes. (Gädda et al., 2014) According to Ali Harlin, (Professor at VTT's biotechnology and food research laboratory), applying PGA film in food packaging virtually resembles modified atmosphere packaging (MAP) which are commonly used as multilayer food packaging solutions for a variety of foods including meat products. (Environment News Service, 2012)

To date, PGA is mostly considered as a drop-in replacement for PET. Film-suitable products are not yet commercially available. However, the ongoing project REFUCOAT, coordinated by AIMPLAS, a Spanish research Institute, is currently dealing with the development of a hybrid barrier and coating material with high oxygen and water barrier properties. By combining PGA with modified $SiOx_2$, researchers hope to launch an innovative, cost-efficient material for film and tray manufacturing which can substitute aluminium-based (metallized) structures. AIMPLAS aims to replace MAP materials. Furthermore, a combination of polyhydroxyalkanoates (further elaborated in 2.3.4.5) with PGA is expected to be useful for fresh food packaging.

The project is funded by the European Union and is projected to run until 2020. No commercially available products are expected before that time. (Cordis EC, 2019)

2.3.4.5 Polyhydroxyalkanoates

Poly-ß-Hydroxyalkanoates (PHA) are a group of microbially produced polyesters. A variety of microorganisms, including genera such as *Alcaligenes, Bacillus, Pseudmonas* and others, synthesize and accumulate PHA intracellularly through fermentation of carbon substrates under nutrient stress conditions inhibiting growth (Arrieta, Samper, Aldas, & López, 2017; D. z. Bucci, Tavares, & Sell, 2007; Khosravi-Darania & Buccib, 2015; Muñoz De Las Heras, 2017). PHA acts as an intracellular energy and carbon storage for microorganisms, preventing starvation in the case of nutrient absence. The required carbon substrates can be of various origin e.g. starch or organic waste. Depending on the carbon source and the synthesizing microorganism, different polymers can be obtained. PHAs are thermoplastics and biodegradable polymers (Khosravi-Darania & Buccib, 2015).

Poly-3-D-hydroxybutyrate (PHB) is the most basic and most common homopolymer within this group. PHB is partially crystalline and consists of a chain of hydroxybutyric acids units ($C_4H_6O_2$) (see Figure 12) (Khosravi-Darania & Buccib, 2015).

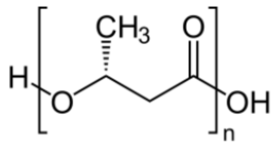

Figure 12. Chemical structure of a PHB monomer. 'n' refers to the total number of monomers per polymer chain. (Khosravi-Darania & Buccib, 2015).

The physical properties are similar to those of polypropylene, a vastly used conventional plastic. However, according to a study conducted by Bucci et al. (2005), PHB has a 50% lower deformation value than conventional PP, implying a lower flexibility of the material. The significantly higher stiff- and brittleness compared to that of PP, resulting from the highly crystalline structure of PHB, have led to more attention being paid to a copolymer called polyhydroxybutyrate-*co*-hydroxyvalerate (PHBV), which proves to be less brittle and therefore hides more potential for various uses. (Khosravi-Darania & Buccib, 2015; Muñoz De Las Heras, 2017). Also, Khosravi-Darania and Buccib (2015) state that the brittleness increases with long storage at room temperature.

PHB nevertheless shows great potential for its use in food packaging thanks to its biodegradability and high crystallinity giving it good barrier properties (to gases and water vapor) (Arrieta et al., 2017). Besides, its light transmission rate is lower compared to that of PLA in visible and UV wavelength regions. (Khosravi-Darania & Buccib, 2015)

Furthermore, Muñoz De Las Heras (2017) studied the baker's yeast, *S. cerevisiae*, as a potential PHB producing microorganism, in search for a more suitable organism for growth in biomass hydrolysates (low pH conditions and presence of fermentation inhibitors). The study yielded promising results, which drives the potential for PHB becoming a sustainable plastic alternative. Yet, further process modifications are required prior to industrial implementation. (Muñoz De Las Heras, 2017)

To date, various PHAs are applied in different forms of food packaging such as boxes, films, coating as well as for medical purposes and pharmaceutics delivery carriers. (Khosravi-Darania & Buccib, 2015) In February 2019, a company called Cove launched a water bottle made entirely from PHA. According to Alex Totterman, the founder of Cove, the bottle does not require industrial composting conditions to break down – microbial activity naturally present in soil and marine environment is sufficient for complete biodegradation (Peters, 2019). However, film blowing of PHA related materials is scarcely mentioned in literature. Instead it seems more frequently applied as performance additive to enhance PLA film properties. (CNBC, 2016) Films made purely from PHAs are rarely offered by suppliers, which is probably related to it degrading quickly upon melting, thus its elastic strength is insufficient to enable successful stretch or blow processes (Cunha et al., 2016).

According to Carus and Aeschelmann, (2017) producers expect highly dynamic development and see great potential in PHAs in the future. Even though the market is currently comparatively small, it is projected to multiply by 2021 compared to 2016, resulting from growing capacities in Asia and the US, as well as the launch of a PHA plant in Italy (Bio-On). (Arrieta et al., 2017; Carus & Aeschelmann, 2017)

PHA based materials are biodegradable by bacteria, fungi and algae in both industrial conditions and in marine environment. (Arrieta et al., 2017; Greene, 2014)

PLA-PHB blends

A number of researchers have reported about PLA-PHB polymer blends (Arrieta et al., 2017; Khosravi-Darania & Buccib, 2015). Blending PHB with PLA opens an opportunity to improve poor processability and formability properties of PHB, which appear to be the strongest drawbacks hindering its utility on an industrial scale. Since however both materials are of brittle nature, the blend turns out to be of limited use for film manufacturing. The addition of third components, especially plasticizers, have been studied and plasticization has successfully been identified to effectively improve the blend's flexibility and even positively affect the two polymers' compatibility. Studied plasticizers include glycerol, oligomeric lactic acid (OLA), poly(ethylene glycol) (PEG) and others. Furthermore, the addition of PEG as a plasticizer also resulted in a positive reduction in oxygen permeability. Overall, PLA-PHB blends have proven to be a beneficial combination of polymers for short-term food packaging purposes, especially where oxygen barriers and low humidity requirements are of interest. (Arrieta et al., 2017; Khosravi-Darania & Buccib, 2015)

Overall, commercial availability of PHA or PHB films is very limited to date.

2.3.4.6 Drop-in bio-based materials Bio-Polyethylene/Polyethylen-terephtalate/Polypropylene

So-called drop-in bio-based plastics have a chemical structure which is identical to their petrochemical components, therefore they can be applied for the exact same purposes.

Commonly available drop-in plastics include bio-Polyethylene (bioPE), bio-Polyethylen-terephtalate (bioPET) and bio-Polypropylene (bioPP). Both bioPE and bioPP can be made entirely from biotechnologically obtained ethanol through fermentation of sugar cane, corn, beet or other renewable raw materials. BioPET on the other hand is made from terephthalic acid and mono ethylene glycol (MEG), of which only MEG could be obtained from renewable resources until recently, when Coca-Cola launched the first 100% bio-based PET bottle using paraxylene as a terephthalic acid precursor. (Greene, 2014; Putranda, 2017) Other drop-in polymers, such as Polytrimethylene terephthalate (PTT) or PBAT can also only be up to 50% bio-based, according to most recent research stages. While drop-in plastics are not biodegradable, they possess the advantage of being mechanically recyclable in existing recycling facilities (European Bioplastics e.V., 2019; Greene, 2014). The following will provide a brief description of bio-based PE. (Carus & Aeschelmann, 2017)

BioPE

BioPE is based on carbon substrates mainly derived from sugar cane. Currently, the largest sugar cane production sites are located in Brazil. Ethanol undergoes two conversion steps prior to obtaining the final structure of Polyethylene (PE), (as shown in Figure 13) which is identical to that of conventional PE derived from petro-based resources.

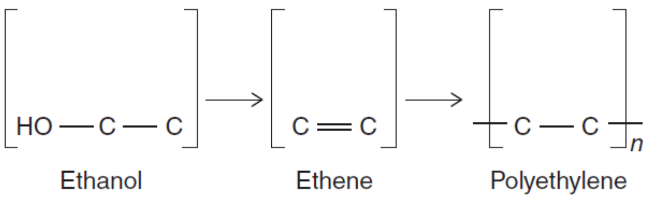

Figure 13. Molecular structure of polyethylene and its precursors (Greene, 2014, Chapter 5)

The mechanical properties of bio-based PE are therefore the same as conventional PE materials, making it a versatile thermoplastic resin for various applications in consumer goods industries. (Greene, 2014, Chapter 5; Plasticoverde - Braskem, n.d.)

In terms of sustainability, sugar cane plantations are often frowned upon due to excessive amounts of land required, however it should be kept in mind that sugar cane plants capture and fix CO_2 from the atmosphere, thus actively contributing to the reduction of greenhouse gas emission. (Plasticoverde - Braskem, n.d.)

2.3.4.7 Bio-Polybutylene succinate

Bio-Poly(butylene succinate) (PBS) is a biodegradable polyester. PBS is a polymer build through poly-condensation of succinic acid (SA) and 1-4-butanediol (BDO). Often, a third monomer, an organic dicarboxylic-acid, is incorporated as well. Its production route is shown in Figure 14 below. Up until recent developments, PBS was produced from petrochemical resources only. However, biotechnological progresses have enabled yeast- or bacteria-based production of both monomers, SA and BDO, from renewable sugar sources derived from e.g. sugar cane, cassava or corn. (Carus & Aeschelmann, 2017; Guidotti et al., 2017; Puchalski et al., 2018) It is expected that in the future, also second-generation renewable feedstocks (not suitable for human consumption) can be used. (Succinity GmbH, n.d.)

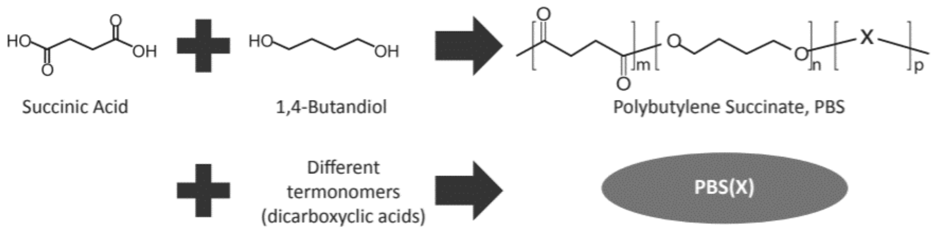

Figure 14. Schematic depiction of PBS synthesis (Succinity GmbH, n.d.)

With the ability of being 100% bio-based and with the outlook towards efficient biotechnological production routes, the market for PBS is expected to grow immensely in the following years.

PBS is considered as a thermoplastic with applications ranging from disposables and packaging for the food industry, as well as agricultural, industrial or automotive purposes. PBS has been approved to be a food grade material. Mechanical properties are similar to polypropylene (PP) (Puchalski et al., 2018) Furthermore, researchers have been working on the development of copolymers, such as polybutylene succinate adipate (PBSA) and others with glycol sub-units with the aim of enhancing the materials flexibility. (Guidotti et al., 2017; Puchalski et al., 2018) Its barrier properties still leave room for improvement. (European Commission, 2015)

2.3.4.8 Edible Packaging

Packaging films, which besides being biodegradable are also edible, are another potential hiding opportunity to reduce waste and resource overdependence. Even though this category will not be touched upon in any of the following parts of this thesis, the researcher has chosen to elaborate it as well, since scientific progress in this field is continuously growing, and consequently also the portfolio for latent future applications, e.g. dissolvable spice capsules.

Edible packaging films originate from an ancient meat preservation method. However, once cheap, fossil-based polymers developed, progress in advancing the materials slowed down significantly. (Mkandawire & Aryee, 2018) Recently, the topic has begun to resurface at least on a research level. While presenting promising mechanical, physical, chemical and biological protection properties, researchers even hope for improved food preservation (Bonnaillie et al., 2014). In fact, edible packaging films are not intended to replace conventional or bio-based packaging films for long -time food storage. Instead their capacity of possibly enabling an extended shelf-life and improved economic efficiency is driving their utility. (Robertson, 2013)

Edible packaging films consist of a matrix (structured biopolymer) and additives, such as plasticizers or cross-linkers. Precursors for the matrix-building polymers can be of different nature, including proteins, polysaccharides or lipids either derived from animal (e.g. chitin/chitosan, gelatin), plant (e.g. starch derivatives, pectins, cellulose), or microbial biomass. (Mkandawire & Aryee, 2018; Tulamandi, Rangarajan, & Rizvi, 2016).

Protein based edible packaging

One very commonly used raw material for edible packaging films, are cow's milk proteins. (Bonnaillie & Tomasula, 2015) Cow's milk comprises 3 different types of protein: caseins (Cas), beta-lactoglobulin and alpha-lactalbumin, of which Cas, makes up the major part (~80%) (Bonnaillie et al., 2014). During an acidification process, casein precipitates from the milk and is then neutralized with $Ca(OH)_2$ or NaOH base to re-solubilize. Then the protein reacts with the metal ions (Ca^{2+} or Na^{1+}) to form calcium caseinate (CaCas) or sodium caseinate (NaCas) before being spray-dried. The caseinates exhibit an amphiphilic character, due to hydrophobic, ring-shaped proline residues which are conveniently distributed within the protein structure. (Bonnaillie & Tomasula, 2015) The casein protein structures itself provide several polar functional groups, which render casein films to be a good oxygen barrier (Bonnaillie et al., 2014).

For the manufacturing of film, the caseinates are commonly blended with glycerol (Gly), which serves as a plasticizer to reduce the brittleness and allows for more material flexibility. The result is a transparent, taste-neutral film with good oxygen barriers, a good tensile strength and moderate elasticity, yet a high sensitivity to moisture. The mechanical properties thus depend strongly on humidity conditions present during manufacture, storage and use. Many researchers are working on methods to improve the mechanical properties to mitigate the sensitivity to processing and formulation parameters during manufacturing, to eventually enable commercial production and application of edible films. Similarly, required cost and amount of resources leave room for improvement. (Bonnaillie et al., 2014)

The moisture sensitivity of casein films can be both beneficial and non-beneficial. The water absorption capacity negatively affects the mechanical protection properties. Besides, being mostly water soluble, also impairs the extent of utilization significantly. (Bonnaillie et al., 2014) On the contrary, the water solubility can be exploited in a way that films dissolve easily in hot or cold water. In the case of single use packaging they could be either washed off and/or can dissolve in the meal, leaving zero waste behind.

Several studies have been conducted recently, experimenting with various additives and processing methods with the attempt to optimize the material's potential. Studies included the effect of addition of hydrocolloids, stearic acids, citric pectin and numerous enzymes, trials to cross-link two materials through enzyme treatment with transglutaminase as well as via physical radiation treatment and addition of cross-linkers. Further, high pressure processing to obtain more hydrophobic casein was investigated, as well as casein modification through Maillard reaction and alkali treatment. (Bonnaillie et al., 2014)

2.3.4.9 Summary of bio-based polymers

Table 4 summarizes the key characteristics of the investigated bio-based polymers.

Table 4. Summary of bio-based polymers

Biopolymer	***Key facts***
Starch based	**Feedstock:** potato, tapioca, corn **Building block:** starch **Properties:** crystalline, thermoplastic, hydrophilic, limited mechanical properties, brittleness, translucent or opaque, biodegradable **Other:** often blended with plasticizers or other polymers
Cellulose based	**Feedstock:** cotton, wood pulp, sugarcane bagasse **Building block:** cellulose **Properties:** good mechanical properties, hydrophilic, yet not water soluble, transparent, biodegradable, dead-fold **Other:** bacterial cellulose can be obtained through biotechnological synthesis, potential improvements through aluminum oxide layers, plasticizers, ester- or etherification
PLA	**Feedstock:** sugar beets, starch waste, whey **Building block:** lactic acid **Properties:** breathable, good aroma barriers, stiffness, high water permeability, crystallinity and hence thermal stability depend on amount of bound D-lactic acid monomers, biodegradable **Other:** potential improvements through addition of plasticizers or flexible polymers, combination with chitosan or cellulose, $SiOx_2$ coating
PGA	**Feedstock:** hydrolyzed sugar **Building block:** glycolic acid **Properties:** good mechanical strength, good heat resistance, excellent oxygen barriers, biodegradable **Other:** not available as film
PHA and PHB	**Feedstock:** organic waste, corn, potato, tapioca **Building block:** starch **Properties:** poor processability, high stiff- and brittleness, good barrier properties, biodegradable **Other:** mainly used as performance additive for PLA
BioPE	**Feedstock:** sugar cane, sugar beet, corn **Building block:** ethylene **Properties:** identical to conventional PE, recyclable (not biodegradable)
BioPBS	**Feedstock:** sugar cane, cassava, corn **Building block:** succinic acid, 1-4-butanediol **Properties:** thermoplastic, mechanical properties similar to PP, weak barrier properties
Edible Packaging	**Precursors:** starch, pectins, cellulose, gelatin **Properties:** good oxygen barriers, taste-neutral, transparent, good tensile strength, moderate elasticity, high sensitivity to moisture, weak processing properties **Other:** often blended with glycerol as plasticizer for more flexibility

Furthermore, Figure 15 gives a summarized overview based on bio-based content and biodegradability. Further bio-based polymers with potential for plastic material production can be extracted from animal sources, such as chitin and chitosan. These can be commercially produced through extraction processes, enzyme hydrolysis or fermentative action. However, the production methods have not yet reached industrial scale and are limited in their economic feasibility. (Ferreira et al., 2016)

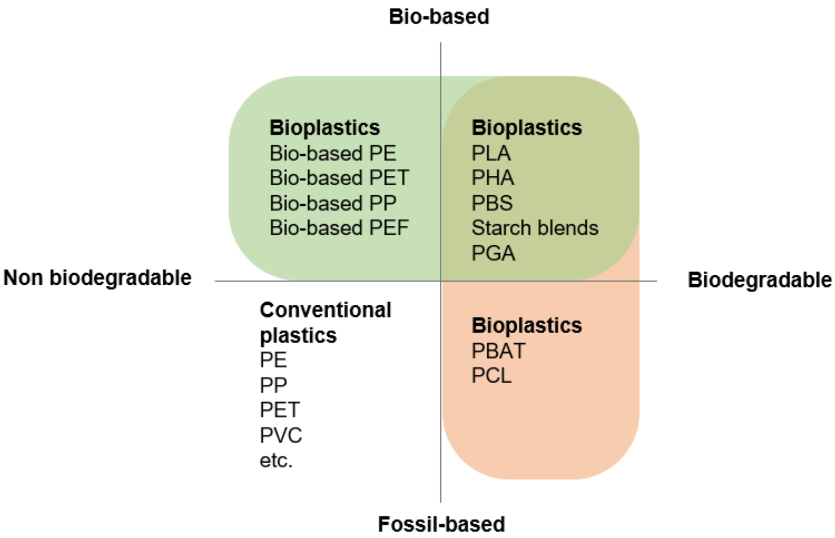

Figure 15. Overview of plastics (modified from Pestorp, 2018)

2.4 Consumer perception towards bio-based packaging

As with all innovative concepts and breakthroughs, the creation of an ideal bio-based future requires not only technological feasibility and economic viability but also social desirability (Olsen, 2015). Therefore, consumer acceptance is just as important as engagement and commitment from professionals in order to achieve a successful trend towards bio-based products.

Researchers from Wageningen University found that a broadly speaking 'care about sustainability' is certainly well spread amongst German and French consumers, as was found in a study conducted to support food companies in making well-informed sustainable packaging approaches. (Meester & Molenveld, 2017)

Also, according to Plastics Europe, *"there is an increasingly negative perception of plastics in relation to health, environment and other issues."* Consumers seek for materials based on sustainable and recyclable resources, which are carbon neutral, and have the lowest environmental and health impacts possible. (Vähä-Nissi, 2017; World Economic Forum, 2016)

While many studies present consumer insight results regarding perception towards ‘environmental packaging’ or ‘environmental friendliness’ in general, consumer insight data specifically targeting *bio-based* products is scarcely available.

However, a two-year project (October 2016-2018), called BIOWAYS, running under the EU’s Horizon 2020 Framework Programme, was conducted with the aim to understand consumer awareness and acceptance specifically for bio-based products. In that context, they wanted to get insights how consumers perceive the benefits of bio-based products and consequences of their use. The study received slightly more than 450 responses from various demographic groups across Europe. (Bioways, 2017)

Results from this survey prove that a large percentage (80%) exclaimed a positive association with bio-based products and a majority (66.6%) of respondents prefer bio-based products over non-bio-based counterparts. At the same time however, the study also revealed a lack of consumer knowledge and clear understanding of what ‘bio-based’ really means. Only a third believe to have appropriate knowledge of bio-based products. Furthermore, comparatively high prices and missing labelling often discourage customers from eventually purchasing the products. This shows that the general existing degree of interest and environmental awareness certainly needs to be supported by more informative action and clear labelling regulations to achieve more consumer engagement with the bio-economy and to prevent misconceptions about existing products. (Bioways, 2017)

A group of respondents also expressed concern about the use of natural resources for non-food purposes affecting the overall availability of food as well as rising food prices. (Bioways, 2017)

All results indicate that a societal desire for sustainable packaging is present, nevertheless a successful transition to a bio-economy is not possible without the implementation of a number of initiatives, focusing especially on a clear labelling and certification framework as well as informative material and resources for appropriate consumer education. (Bioways, 2017; Bonnaillie et al., 2014)

3 Methodology

This chapter explains the author's approach to the study. As a whole, the study is conducted as a case study, which is divided into 2 parts: a data collection part which is further subdivided into primary and secondary data collection, and a data analysis part.

3.1 Overall Study Approach

The study is guided by the following research questions:

1. *In how far are bio-based packaging films applicable for food packaging in the meal kit industry context?*
2. *In how far does the application of bio-based materials in the meal kit context contribute to a more sustainable packaging approach?*

In order to answer these questions, the overall research approach of a case study has been chosen. The aim is to gain knowledge and data through different data collection methodologies. The data is subsequently combined, analyzed and applied to the studied context (meal kit delivery service industry) to eventually provide HelloFresh with justified recommendations towards the applicability of bio-based polymers. Recommendations will be based on a material comparison of identified bio-based packaging films and in how far they match with product and packaging requirements of certain food categories under supply chain conditions within HelloFresh. Furthermore, the environmental impacts of the identified materials will be taken into consideration for the recommendations**.** In this context the BoL and the EoL stages will be analyzed apart from each other, using different types of data.

Figure 16 illustrates how the study approach is split into data collection and data analysis.

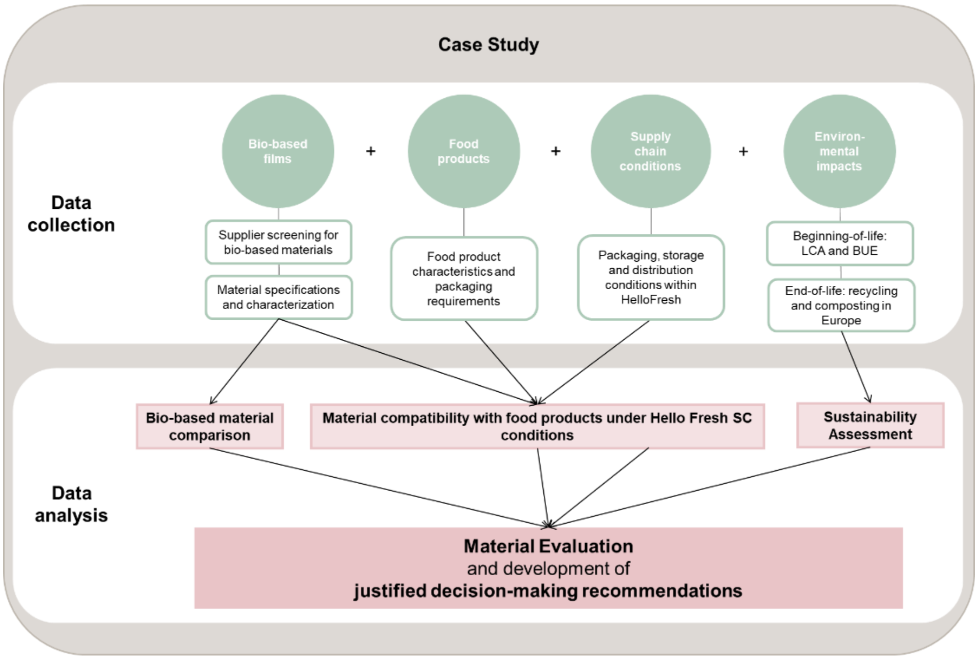

Figure 16. Case study approach split into data collection and data analysis

3.2 Data collection

3.2.1 **Primary data collection**

3.2.1.1 Data collected from bio-based material suppliers

Initially, the European market was screened through web and literature research for exemplary suppliers currently offering commercialized bio-based packaging materials. The search for bio-based material suppliers was limited to the following criteria:

- European supplier (mentioned as a requirement by HelloFresh)
- *Film* supplier (as opposed to *rigid* plastic)
- Food grade material
- Biodegradable and/or compostable and/or recyclable material
- Already available for industrial production/will be available in the near future

The screening and supplier selection were conducted for the mere purpose of gaining an overview of what is available on the market, how the available material performs in terms of barrier properties, appearance, disposal options and bio-based content and to get exemplary references for the environmental impact assessment. Factors such as value for money, reliability, service and communication etc. were not considered as relevant supplier selection criteria at this stage.

Once appropriate suppliers had been identified, the suppliers were contacted by the researcher on behalf of HelloFresh via phone and email to complete relevant material specifications and performance properties (as listed below), which could not be drawn from existing literature or website content. Informal talks with suppliers also aided in deriving expert knowledge and opinions regarding applicability of the individual material for the studied product categories and case conditions.

The following material specifications were collected:

- Bio-based content
- Biodegradability
- Recyclability
- Transparency
- Thickness
- OTR
- WVTR
- Resistance to lipids
- Intended EoL

3.2.1.2 Data collected from HelloFresh

HelloFresh meal kits include products of various categories. Fresh produce, meat products, dairy, grains, bread, spices etc. - hardly any product is missing in the product portfolio.

For the purpose of investigating the material compatibility with food products, it was decided to focus on three product categories. In consultation with HelloFresh, the following three criteria were set for the choice of the product categories to be considered:

- A category in which multi-layer packaging material is currently applied, which aggravates the recycling process
- A category which requires a lot of material due to its small apportionment

- A category, which, based on the previously acquired knowledge from the conducted literature review on bio-based packaging materials, is expected to exhibit good product-material compatibility

Within the entire product portfolio, the most perishable products and similarly those with the highest environmental impact at production stage are animal protein (meat and fish) and dairy products. The packaging material choice should therefore provide sufficient product protection to ensure a safe and sound product condition at the point of arrival at the final consumer. In such cases, it has been proven by researchers, that slight overpacking (for extended shelf life, hence lower risk for food loss) is more environmentally friendly than reducing packaging material merely for the sake of reducing material waste (Pereira et al., 2015).

Based on previously acquired knowledge it was assumed that the barrier properties provided by bio-based packaging materials will not be sufficient for adequate product protection of animal protein and dairy products. Thus, these categories were ruled out from the beginning.

Instead, the following three product categories were chosen to be focused on in accordance with the prioritized interests of HelloFresh:

- **Bakery products (BAK)** (considering only bread, buns, pita etc.) (chosen because: currently packed in non-recycling-friendly, multi-layer plastic laminate)
- **Fresh herbs (HERB)** (chosen because: short shelf life, promising product characteristics for bio-based material compatibility)
- **Spices (SPI)** (chosen because: packed in very small quantities, thus require large amounts of packaging in terms of product-to-packaging ratio)

3.2.1.2.1 Currently applied packaging materials

Information concerning the currently used packaging materials for the above listed product categories were gathered through email and personal contact with the internal procurement team as well as the product suppliers, who are also responsible for adequate packaging solutions.

Obtained information included:

- Type of packaging material
- Barrier properties
- Thickness
- Package dimensions
- Applied packaging technology

3.2.1.2.2 Supply chain conditions

The meal-kit industry follows a delivery-based and just-in-time business model, making it subject to excellent supply chain management skills, but also providing it with the competitive edge towards common grocery stores. Especially storage and distribution conditions can differ greatly from those of conventional grocery store supply chains (SC).

SC duration, storage and distribution conditions crucially affect packaging requirements and are hence essential to know to be able to evaluate material applicability with given products. Informal interviews were conducted with internal stakeholders of HelloFresh, to obtain information concerning:

- Storage conditions (temperature)
- Supply chain steps and duration
- Procurements strategies affecting required shelf life of considered products

A list of all people who have provided information through personal communication is provided in 3.2.2.3, Table 5.

3.2.2 **Secondary data collection**

3.2.2.1 Shelf life determining factors of food products and identification of packaging requirements

To develop effective packaging with the power to delay deterioration and maintain product quality as long as possible, individual product properties and resulting shelf life determining factors are of indispensable knowledge. (Peter, 2006)

For each of the chosen product categories, the most relevant factors that influence the shelf life were identified from literature. Later, these factors will be used to determine packaging requirements and to identify potential bio-based material candidates as will be described in 3.3.2.

3.2.2.2 Environmental impact data

Bio-based materials are not per se environmentally ideal. As mentioned in 2.1.3 a life cycle perspective is required to evaluate the environmental impacts of a product, process or service. To evaluate in how far applying bio-based materials can contribute to a more sustainable packaging approach, the environmental impacts of the BoL phase and the EoL phases of the materials were assessed by different means. The use-phase is not included in this assessment, because the identified material candidates are assumed to perform equally well to currently applied materials in terms of product protection, hence not leading to increased food waste. It is thus expected that the use-phase is not going to affect the environmental impact.

For the BoL evaluation, existing cradle-to-gate life LCA data and biomass utilization efficiency (BUE) data were collected from literature.

As was stated in 2.3.3 the effective EoL stage can significantly affect the resulting environmental impact. For the EoL evaluation, it was thus intended to identify how realistic it is that the considered bio-based packaging materials are disposed according to their intended EoL options. To do so, recycling rates, biowaste collection rates and information about the effective handling of biodegradable materials in composting facilities were collected for four European countries.

3.2.2.2.1 Life cycle assessment data

LCA can be conducted for a number of environmental indicators, including cumulative energy required, eutrophication potential, acidification potential and global warming potential amongst others. For the purpose of this thesis LCA data was collected for the assessed bio-based materials and for a number of conventional plastics for direct comparison. The examined indicators were limited to the global warming potential (GWP) and the cumulative energy demand (CED). The GWP represents the measured emissions of greenhouse gases, which are converted into CO_2 equivalents for simplification reasons. Therefore, it is more commonly known as the “carbon footprint” (kg of CO_2 equivalent emissions/per kg material). The cumulative energy demand is given in MJ. (Fantozzi & Bartocci, 2016) The values were gathered from cradle-to-gate LCAs from literature or from published data from a material supplying company.

3.2.2.2.2 Biomass Utilization Efficiency

The term “Biomass Utilization Efficiency” has recently been introduced as a simple method to facilitate comparison and evaluation of bio-based chemicals and materials with regard to the sustainable utilization of biomass. Rather than substituting LCA studies, it is meant to support them by contributing knowledge about the amount of biomass required for certain bio-based products. A BUE analysis essentially reveals 1.) how efficiently biomass is utilized and 2.) how much of the input biomass ends up in the final product. The BUE value considers the input-biomass (type and amount), the conversion process and the final product. The aim of BUE studies is to create more awareness of the linkage between the initial chemical molecule, the chosen biochemical manufacturing process and the final product application. It intends to emphasize the importance of alternative production methods depending on the biomass feedstock and the intended final product. (Iffland et al., 2015)

For the purpose of this thesis, BUE values were collected from existing studies (Iffland et al., 2015) for the considered bio-based materials, enabling a more holistic comparison and evaluation of bio-based materials.

3.2.2.2.3 Waste management information

To obtain a deeper insight into the effective EoL stages of packaging materials, data on post-consumer plastic packaging waste recycling and biowaste composting as well as biowaste management infrastructure in Europe was collected from literature.

In the context of biodegradable and compostable plastics the EoL option of composting is crucial to investigate.

According to EN13432 a material is compostable if it has disintegrated to an extent that no more than 10% of the original dry-weight is remaining after 3 months and 90% of the organic material has metabolized into CO_2 within 6 months under industrial composting conditions. (DIN CERTCO, 2017) Whether or not the feature of compostability can contribute to a reduced environmental impact of the product, depends heavily on the extent to which the intended compostability can be realized with the existing bio-waste management infrastructure, the capacities and operational conditions of industrial composting facilities as well as home composting habits of households.

While there is hardly any data revealing substantial information on home composting activity in Europe, the data collection is focused on the amount of collected biodegradable bio-waste for industrial composting as well as insight into the acceptance of biodegradable packaging materials in composting plants. This part of the research focused on the situation in four European countries, which HelloFresh is active in: Germany, the Netherlands, France and the UK. Country specific data was obtained from literature and from personal communication through phone or email contact with composting facilities and waste management associations.

3.2.2.3 Contacted people

A list of people who provided information through personal communication is provided in Table 5 below.

Table 5. List of contacted people within from different companies

Company	*Position/Name*	*Obtained information*
HelloFresh Internal		
HelloFresh Global	Head of Packaging	• General packaging development approaches • Product categories of interest • Applied packaging technologies
HelloFresh Global	Senior Global Procurement Manager	• Progresses and approaches in new dry product packaging in UK
HelloFresh Global	Operational Excellence	• Warehousing conditions
HelloFresh DACH	Warehouse & Fulfillment	• Warehousing conditions
HelloFresh Global	International Procurement & Sustainability Manager	• Sustainability initiatives • Packaging and product priorities • Supply chain, storage and distribution conditions BAK
HelloFresh DACH	Senior Project Manager	• Progress in consumer NPS project • Packaging vision and policy in Germany
HelloFresh NL	Business Development	• Packaging vision and policy in the Netherlands
HelloFresh DACH	Procurement BAK	• Packaging specifications Bakery • Supply chain, storage and distribution conditions BAK
HelloFresh DACH	Procurement HERB	• Packaging specifications HERB • Supply chain, storage and distribution conditions Herbs
HelloFresh DACH	Procurement SPI	• Packaging specifications SPI • Supply chain, storage and distribution conditions Spices
Material Suppliers		
Biome Bioplastics	M. Moeyersons	• Material specifications • Current applications • Potential use for considered products • Sample acquisition
Direct Packaging	A. Markey	
Futamura	J. Janz	
Repaq	S. Seevers	
Taghleef Industries	B. Dragun	
Floreon	A. Gill R. Staines	
Braksem	B. Hill M. Clemesha	
Amerplast	M. Schaller	
Papier Mettler	M. Bernard M. Lengert	

PTTMCC	F. Pieper		
	Waste Management in Europe		
Company	**Contact person**	**Provided information on**	**For x country**
Der Grüne Punkt	A. Kappel	• Waste management • Infrastructure of composting plants • Acceptance of bio-polymer materials in composting plants • Recyclability of bio-based polymers	Germany, Netherlands
FKuR	C. Michels		France, Netherlands
Biotec	R. Jongboom		France, Netherlands, Germany
AD bioresources	C. Noyce		UK
Biome Bioplastics	D. Newman		
Biotec	M. Moeyersons		
Renewable Energy Association	E. Nichols		
WRAP	Maria*		

*surname unknown

3.3 Data analysis

The data analysis will be split into three major parts:

I. **Bio-based material comparison**: based on general material characteristics and barrier properties

II. **Material compatibility with food products under HelloFresh SC conditions:** based on product packaging requirements, material barrier properties and product specific SC conditions at HelloFresh

III. **Environmental impact assessment analysis**
   a. BoL: based on LCA and BUE data
   b. EoL: based on recycling, composting and waste management data

3.3.1 Bio-based material comparison

The considered bio-based materials were compared amongst each other based on general characteristics. A grading system was used as a comparison tool. Each material was graded on the following performance indicating properties according to the below described grading scheme (Table 6).

- Bio-based content
- Level of biodegradability

- Recyclability
- Industrial availability of film
- Transparency

Transparency was included in this analysis as it can be considered as an indirect indicator of a light barrier. Besides, it was mentioned by HelloFresh to be a considered criterion for packaging material choices, related to customer perception. The level of transparency was judged by the author from received samples or from photos and information received from suppliers. The grading analysis was used to identify which of the materials reveals the best overall performance, regardless of the product-contact or exposed supply chain conditions.

Table 6. Grading scheme for bio-based material comparison

Grade	*Bio-based content*	*Bio-degradability*	*Recyclability*	*Industrial availability of film*	*Transparency*
1	0-20%	not at all	no	not yet	not at all
2	21-40%	-	-	-	strong opaque
3	41-60%	industrial compostable	only in special streams	in near future/not for intended purpose	slightly opaque
4	61-80%	industrial & home compostable	-	-	transparent
5	81-100%	industrial & home compostable & marine biodegradable	yes	yes	transparent and glossy

Another key performance indicator of packaging materials are its barrier properties, i.e. how well a package can resist gas and water vapor permeation. The materials' barrier properties in terms of OTR and WVTR were categorized according to the following categorization scheme (Table 7) as defined by Khalifa (2016) and visualized in comparison to currently applied materials by HelloFresh and other commonly used conventional plastics.

Table 7. Barrier classification according to (Khalifa, 2016)

Barrier classification	***OTR [cm3/m2/day] at 23°C, 0% RH***	***WVTR [g/m2/day] at 38°C, 90%RH***	***applied for***
low	>100	>100	frozen foods, fruit, vegetables, sugar
medium	6-100	6-100	chilled foods (e.g. dairy)
high	1-5	1-5	dry foods, high aroma content, oxidation sensitive (e.g. peanuts, coffee, spices)
very high	<1	<1	high sensitivity products (e.g. infant nutrition)

3.3.2 **Material compatibility with food products under HelloFresh SC conditions**

Required barrier properties in individual scenarios is strongly dependent on the product to be packaged. Besides, the effective permeation behavior of a package and the subsequent product shelf life also depend on external factors, such as packaging surface area and climatic conditions that a product is exposed to along the supply chain.

To assess the packaging materials' compatibility with the observed food product categories, previously identified (in 3.2.2.1) product specific shelf life affecting factors were used to determine barrier requirements to match the HelloFresh required shelf life conditions. Barrier requirements were determined in terms of

- Oxygen
- Water vapor
- Lipids
- Light

and were defined as *low, medium, high* or *very high* in accordance with literature, in which barrier requirements were defined for other product categories (Khalifa, 2016). The identified product requirements were subsequently aligned with the categorized materials to identify potential material candidates.

To further proof material compatibility, the *Norner barrier calculator* tool was used to simulate the oxygen and water vapour permeation behavior of the considered materials over time under specific conditions. The simulation was based on HelloFresh supply chain conditions and required shelf life durations, with respect to product specific packaging dimensions. The simulation was done for all product categories and all considered materials. Materials were simulated with the specific transmission rates and thicknesses as specified by the suppliers (see Appendix A.4). Materials that are currently applied by HelloFresh were simulated for direct comparison and were used as *reference* materials with which compatibility is guaranteed. Moreover, *standards* were determined to be used as thresholds. The standards were determined by means of the previously defined allowed barrier properties (Table 12) and the accordingly allowed maximum permeation rates according to Table 7. A thickness of 25 µm was determined for the standards. However, for SPI, the permeation rates of Cellulose NatureFlex NK were used standard values. Basically, materials exerting these maximum barrier properties were equally simulated in *Norner* under the defined conditions, and the resulting total permeation was then taken as a threshold value.

Input parameters concerning relative humidity inside the packages were determined based product intrinsic moisture contents derived from literature, with the mere aim to define consistent conditions for all materials, yet not to reflect realistic permeation quantities. Furthermore, respiration rates of the products were not considered. Thus, the analysis does not provide reliable quantitative results as to how much water vapor or oxygen will effectively permeate through the films. Instead, the analysis was used to prove that the materials, which were previously identified as compatible, perform within the threshold values. Moreover, the analysis gives an indication towards how comparable the considered materials perform in relation to currently applied materials and to visualize the extent to which the performances can differ between the materials. It was thus more important that the input parameters are identical for each scenario and approximately correspond to those of the product, rather than them being entirely compliant to the given conditions.

The *Norner* tool was fed with the following parameters:

- Package dimensions (product specific according to HelloFresh packages)
- OTR and WVTR values (material specific)
- Thickness (material specific)
- Storage temperature along the supply chain (HelloFresh specific)
- Assumed relative humidity along the supply chain
- Atmospheric oxygen level along the supply chain
- Relative humidity within the package (product specific)
- Storage duration (HelloFresh specific)

3.3.3 Environmental impact assessment analysis

The environmental impact assessment analysis will be split into the BoL stage and the EoL stage. For the BoL assessment LCA data will be used to compare bio-based polymers amongst each other and to fossil-based counterparts based on their GWP and CED. Furthermore, BUE data will be used as a further sustainability indicator to compare merely the bio-based polymers amongst each other.

Concerning the EoL stage, the obtained data on recycling and composting rates as well as waste management in Europe will be interpreted and discussed to eventually identify the likelihood to which the materials will follow their intended EoL scenario and hence which intended EoL scenario should be preferred.

Based on both BoL and EoL analyses a material prioritization scheme will be determined.

4 Results and discussion

This chapter presents the results in 3 parts, structured according to the 3 conducted analyses. The first part shows the results of the market screening for bio-based packaging film suppliers and compares them amongst each other. The second part elaborates the compatibility of the considered materials with three food product categories under HelloFresh specific SC conditions. Finally, the third part assesses the environmental impacts of bio-based materials based on BoL and EoL sustainability indicators. Results will be discussed to conclude with a final material preference recommendation.

4.1 Bio-based Material Comparison

4.1.1 **Supplier overview**

Table 8 gives an overview of identified supplier matching the pre-selection criteria mentioned in 3.2.1.1. All companies listed below were contacted by the researcher. Moreover, other suppliers were contacted, which were not considered for in further investigation because they did either not fit the selection criteria or were not willing to provide sufficient information.

In the case of BioPE, all suppliers turned out to be working with the same material, where Braskem is the actual producer and Amerplast and Papier Mettler are Europe-based suppliers. Yield10 Bioscience was included as the only non-European supplier, as very little information was obtained through European producers.

Table 8. Overview of identified material suppliers in Europe, contacted by the researcher

Material Type	*Position*	*Material Name*	*Supplier Location*
Starch	BIOTEC	Bioplast 160/02	Germany
Cellulose	FUTAMURA	NatureFlex NVS/NK	UK
	rePAQ	Repaq 19/45	Germany
PLA	Taghleef Industries	Nativia NTSS	Germany
	Floreon	Floreon 400	UK
PHA	Yield10 Bioscience	Mirel PHA	US
	bio-on	Minerv PHA	Italy
BioPE	Braskem		Germany
	Amerplast	I'm Green Polyethylene	Finland
	PAPIER-METTLER		Germany
BioPBS	ptt MCC Biochem	BioPBS PTTMCC FD92	Germany (Thailand)

4.1.2 Material characterization and comparison

Materials were characterized based on information obtained from discussion with the suppliers directly or from provided datasheets. Further information was obtained from website content and other publications. A table with detailed material characterization can be found in A.1. To compare the materials amongst each other, they were scored on five features according to the grading scheme below.

Table 9. Grading scheme for bio-based material comparison (repetition of Table 6)

Grade	*Bio-based content*	*Bio-degradability*	*Recyclability*	*Industrial availability of film*	*Transparency*
1	0-20%	not at all	no	not yet	not at all
2	21-40%	-	-	-	strong opaque
3	41-60%	industrial compostable	only in special streams	in near future/not for intended purpose	slightly opaque
4	61-80%	industrial & home compostable	-	-	transparent
5	81-100%	industrial & home compostable & marine biodegradable	yes	yes	transparent and glossy

Due to lacking information for Bio-On PHA, this material was discarded from the analysis.

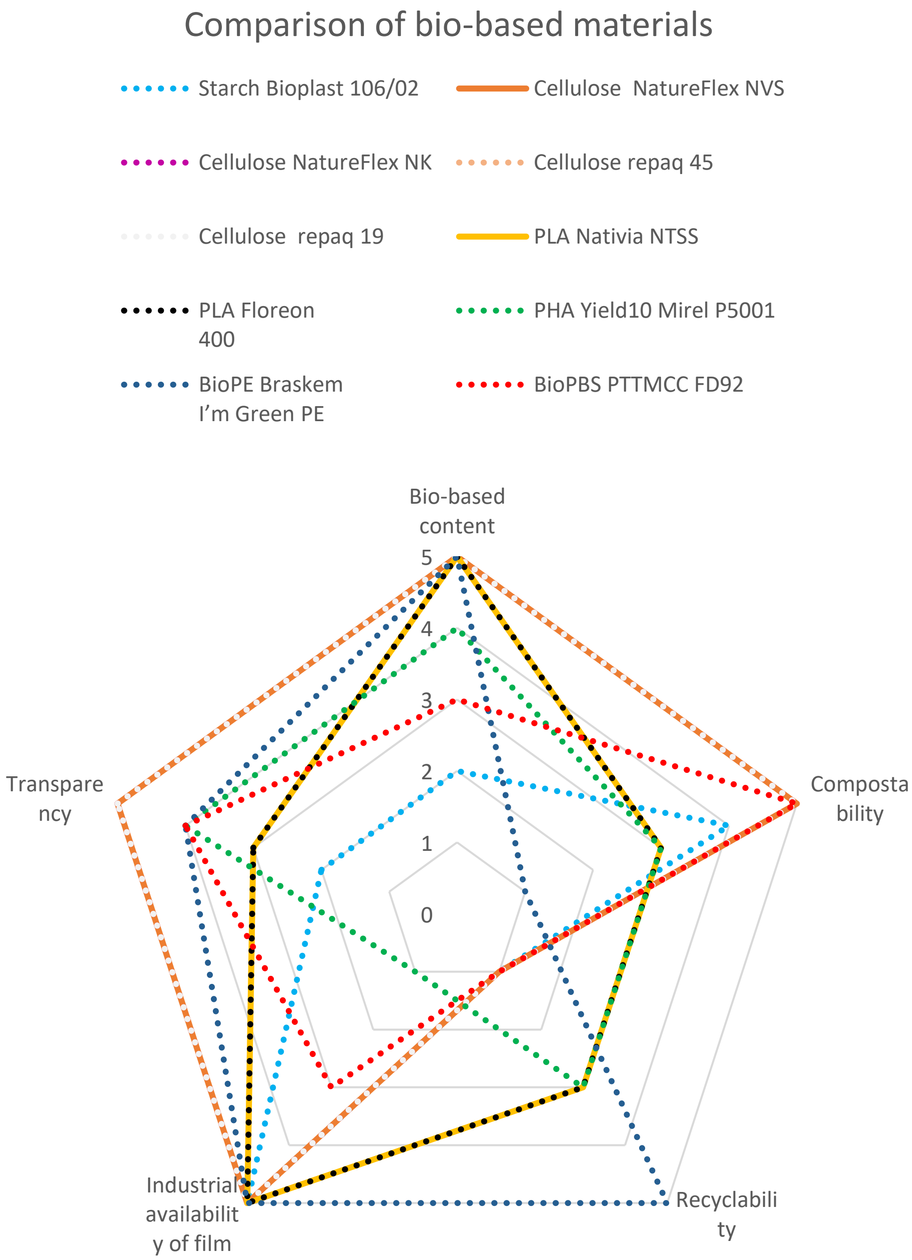

Figure 17. Overall bio-based material evaluation

Spider diagrams for every individual material can be found in Appendix A.3.

As was set as a prerequisite, all considered materials are food grade and are thus allowed to be in food contact without risking migration of contaminants from packaging into the product.

The general material characterization revealed the following key insights:

- PHA is only applicable as a blend with PLA, however not as a film alone
- no technical information with regards to barrier properties could be retrieved for PHA, as these depend on the laminate ratio with PLA
- Similarly for BioPBS, which is available as a film material, however not for the intended packaging purpose, but rather for agricultural applications (e.g. mulching film) or as a coating layer
- Cellulose and PLA films can be produced with the highest bio-based content (up to 99% and 90% respectively), followed by BioPE with up to 85%
- Cellulose also claims to have the quickest rate of biodegradation according to repaq: 42 days in undefined conditions)
- Starch films can only be produced with a very low bio-based content (ca. 30%)
- All polymers except for BioPE are compostable to a certain extent: cellulose-based, and BioPBS are industrially, home and marine compostable, starch-based is industrially and home compostable and PLA and PHA are only compostable under industrial composting conditions
- PLA, PHA and BioPE can be recycled, however only BioPE can be recycled in conventional recycling streams, as opposed to specially construed streams for PLA and PHA
- PLA and PHA are the only materials that are both compostable *and* recyclable to the previously mentioned extent
- Transparent films can be obtained from all polymers, except for starch
- Cellulose-based materials exhibit the highest degree of transparency, BioPE is slightly milky

Judging from the observed criteria, both cellulose-based materials and BioPE obtained the highest scores. Besides a slightly weaker level of transparency of BioPE, the major difference lies in the potential EoL option: cellulose is compostable and BioPE is recyclable. PLA performs comparatively well, except its EoL option being limited to industrial composting and specially construed recycling streams. However, according to a Floreon speaker, they are currently in the development stage for a home compostable PLA grade, which would however only contain 50% bio-based content.

Starch-based materials revealed the weakest performance in terms of the observed features. While being well compostable in industrial and home conditions, its main drawbacks are the low bio-based content and opaque or white appearance, making it less desirable for packaging purposes within HelloFresh.

However, a high score does not necessarily indicate that it is the *best fit* for *every* purpose. Required material characteristics depend entirely on the individual application purposes and must thus be evaluated for individual cases.

4.1.3 **Barrier property comparison**

Oxygen transmission rates and water vapor transmission rates of the investigated bio-based materials, of currently applied materials by HelloFresh and for a list of commonly applied conventional plastics, were collected. They were extracted from data sheets provided by the material suppliers and literature. For PHA, no explicit numerical information on barrier could be obtained, which is most probably due to the fact that PHA is most commonly applied in combination with PLA. However, vague barrier characteristics of PHA films were described by (Koller, 2014): the hydrophobic nature of PHA provides high water vapor barriers, and the homopolyester PHB has a high oxygen barrier. Yet, due to lacking numerical data, both PHA materials were not included in the following comparison.

A categorization defined by Khalifa (2016) (Table 7) was used to categorize the materials according to the barrier performance.

The identified barrier properties are illustrated in Figure 18. Note that the axes increase on a logarithmic scale. The larger the value, the higher is the transmission rate, thus the lower the barrier performance.

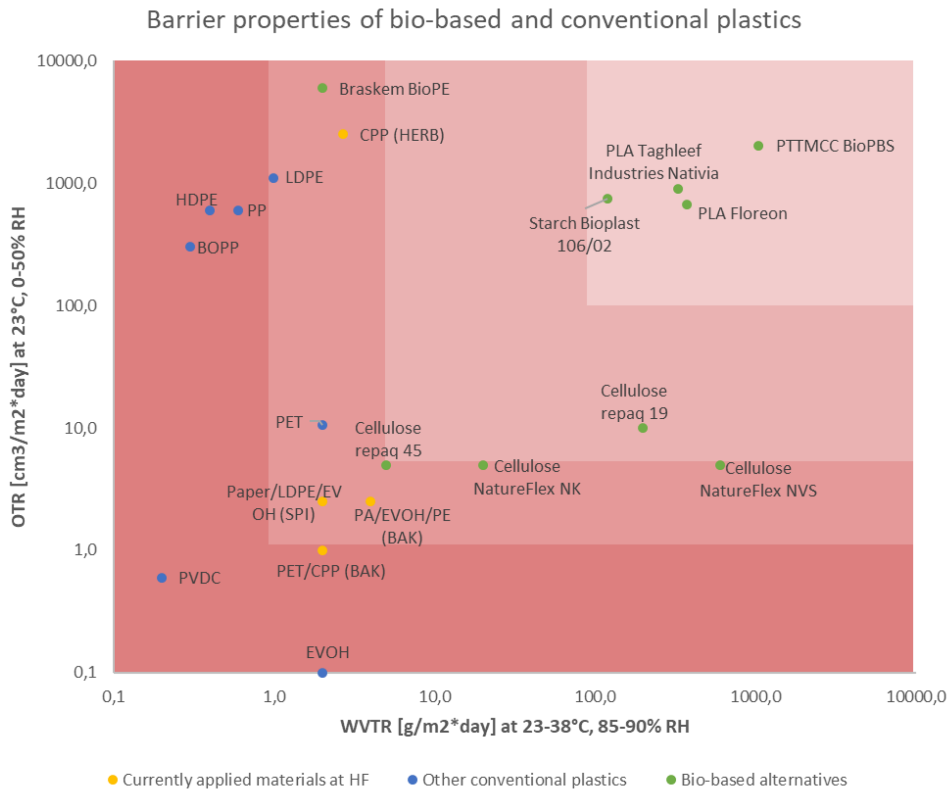

Figure 18. Barrier properties of conventional plastics and bio-based polymers (partially adapted from Schmid et al., (2012), bio-based polymers' and HelloFresh current material values are supplier specific)

A table with the detailed transmission values for all materials is provided in Appendix A.4. A further table with the categorized provided barriers, also including light barrier and oil resistance of bio-based materials is provided in Appendix C.1.

Results showed the following:

Currently applied materials at HelloFresh

- The SPI and one of the BAK (PA/EVOH/PE) packaging materials are high barriers for both oxygen (O_2) and water vapor (WV)
- The other BAK packaging (PET/CPP) is categorized as a very high O_2 barrier
- The HERB packaging (CPP) has a high WV barrier but only a low O_2 barrier

Bio-based materials

- The strongest barriers in terms of both O_2 and WV is provided by Cellulose repaq 45 (both high), making it perform similar to the currently applied BAK and SPI packaging
- The remaining observed cellulose films provide equally high O_2 barriers (except repaq 19 is medium), however they vary from high to low regarding the WV barrier
- BioPE on the other hand has a low O_2 barrier and a high WV barrier, thus featuring similar properties to CPP (currently used for HERB), conventional PP and OPP (oriented polypropylene), and both LDPE and HDPE (high-density polyethylene) which are the fossil-based counterparts of BioPE
- The starch film, both PLA films and BioPBS are all characterized by both low O_2 and low WV barrier

Conventional plastics

- PVDC exhibits both very high O_2 and WV barriers
- EVOH has a very high O_2 barrier, and a high WV barrier
- PET has a high WV barrier, and medium O_2 barrier
- Both PE materials are both within low O_2 barrier and differ slightly in their WV resistance: HDPE very high, LDP high
- Both PP materials (PP and BOPP (biaxial-oriented polypropylene) have similar WV barrier properties: both very high; the difference in O_2 barrier is negligible

Overall, Figure 18 immediately indicates weaker barrier performances compared to conventional plastics, including those currently applied by HelloFresh. Especially substantially lower WV barrier properties of bio-based materials (except BioPE and Cellulose repaq 45) compared to conventional plastics are undeniable. In terms of O_2 they range from high to low, none however can provide a very high O_2 barrier. It can be said that cellulose materials appear to be more applicable for oxygen sensitive products, whereas BioPE and Cellulose repaq 45 are more suitable for water vapor sensitive products. PLA, starch-based and BioPBS films on the other hand proved to have weak barrier performances and should thus rather be considered for packaging applications where low barriers are sufficient.

Which of the barrier performance combinations is considered as the overall best cannot at all be generalized, as it depends entirely on the product to be packed and the storage conditions. It is for example possible, that a very high WV barrier is beneficial to reduce moisture uptake and is yet detrimental, as it equally prevents moisture escape, causing e.g. respiration moisture to accumulate internally.

Material choices must therefore be done in alignment with product requirements and supply chain conditions.

4.2 Material compatibility with food products under HelloFresh SC conditions

4.2.1 **Shelf life affecting factors of food products**

As mentioned previously, required barrier properties are product dependent. The food product properties and stability in turn are closely related to the products components, e.g. carbohydrates, proteins, lipids and water. Depending on the composition, a product is accordingly sensitive to environmental and processing factors, such as exposure to humidity and oxygen, changes in temperature or light, all of which are likely to cause biochemical changes within the product eventually leading to product deterioration. For certain highly sensitive food products categories Schmid et al. (2012) has defined barrier requirements. These however do not cover the three considered product categories.

To be able to pinpoint essential packaging requirements for the considered products, one must first understand the related spoilage factors.

4.2.1.1 Bakery products

Staling

A major contributing mode to bread deterioration is staling, affecting especially the quality appearance of bakery products. Bread is characterized by a gluten network and its hydrated starch molecules provide the springiness of most bread types. In the process of mixing and baking, the previously ordered (crystalline) starch molecules transform into a non-ordered state: when mixing bread ingredients, the starch molecules in the flour absorb water, which causes the molecules to swell. When exposed to heat (during baking), they continue to swell until they burst. Once the water migrates out of the starch granules into the gluten network, recrystallisation of the starch molecules occurs. This is called staling. The result is a firm, crisp and dry texture. The degree of crystallization is entirely time and temperature dependent. According to Cauvain and Young (2010) the rate of starch recrystallisation is at its highest at temperatures of 4°C. Bread storage temperatures are thus recommended to be either below -5°C or above 21°C. While moisture loss equally results in a drier product, the process of staling is more temperature dependent, thus also occurs independently of moisture loss. (Cauvain & Young, 2010; Robertson, 2012) The best way to prevent staling is thus to freeze the product as soon as possible after baking.

Moisture gain/loss

Adequate moisture content is a key quality indicator for the freshness of the product. Consumers often tend to squeeze bakery product to test the softness and crust texture, by which they indirectly test the remaining moisture content. Little resistance and quick recovery of original shape will be perceived as "fresh" by the consumers. The moisture content of bakery products differs depending on the type of product but can be as high as e.g. 36% in white bread, for which the a_w value is around 0.96 in the crumb, while the crust is often a bit drier (Kilcast & Subramaniam, 2011) Since the rate of moisture migration into or out of the product is mainly driven by the difference between the products a_w value and the relative humidity (RH) in the surrounding atmosphere, packaging plays a significant role in delaying moisture loss. (Robertson, 2012)

Besides affecting the products texture, water content is also strongly related to the potential of bacterial growth, which is considered a major spoilage factor of bakery products. The higher the moisture content, the higher is the risk for bacterial growth. (Cauvain & Young, 2010)

Moisture gain can quickly lead to increased a_w values, hence making the conditions more conducive to mold growth, especially on the product's surface. Besides time moisture gain will cause unwanted loss of crust crispness. Moisture gain should thus be equally avoided as moisture loss.

At the same time bread has a respiratory activity, in which moisture is "emitted" from the product. To minimize the risk for mold growth, moisture accumulation within the package must also be avoided. To reduce both excessive moisture loss and gain, a semi-permeable material is favorable. Alternatively, a perforated material can be applied to allow the moisture to escape. (Robertson, 2012)

Rancidity

Rancidity refers to the development of off flavors as a result of chemical or enzymatic breakdown of lipids (lipid oxidation or lipolysis). Bread products have a low lipid content, compared to other bakery products, such as cakes or cookies in which lipid-based flavoring components are often used. Bread products are thus comparatively stable in terms of rancidity. (Cauvain & Young, 2010) Nevertheless, oxidative rancidity does occur. It is more likely to occur within the crumb (internal bread part) than on the crust. To delay rancidity, antioxidants are suggested to be used. (Robertson, 2012)

As stated by Robertson, (2012) shelf life can be increased by creating less mold growth favored conditions through modified atmosphere packaging (MAP). For example, a 50% CO_2 concentration resulted in a doubled mold-free shelf life of bread, which was stored at mold favorable conditions. In that case, a high gas barrier would be required to keep the gas concentration constant. (Robertson, 2012)

4.2.1.2 Fresh herbs

Senescence

Herbs belong to the category of leafy greens. These are especially sensitive to senescence. Senescence, which is essentially cell deterioration, leads to loss of membrane integrity, wilting and increased susceptibility to potentially pathogenic bacteria, which in turn can accelerate decay. Factors causing senescence are primarily water loss, but also too high storage temperatures and wounds caused by physical damage or stress. Prevention of excessive water loss is thus key to maintain product quality. (Cantwell & Reid, 1993) Herbs commonly have a high water content (78-92%) (Chakraborty & Dey, 2016). Studies conducted by Cantwell and Reid (1993) proved that the maximum amount of acceptable water loss prior to rendering them unsaleable is strongly dependent on the type of herb: thyme and chives for example turned out to still be saleable after a loss of 25-40%, while mint and dill were not considered unacceptable at this level of water loss. Lopresti et al. (1997) are considering 10% as reasonable maximum water loss, to avoid rapid deterioration. (Bartz & Brecht, 2002; Lopresti et al., 1997) As with bread, moisture migration is dependent on the product's a_w value and surrounding RH, thus for herbs high RH in the storage environment is favorable. Similarly, water impermeable packaging can delay moisture loss. (Robertson, 2012)

Respiration

On the other hand, herbs produce condensation moisture due to their respiratory activity, which – once accumulated in a package – becomes conducive to undesired microbial growth. The respiratory activity is measured in µl CO_2/g*h. The average rate for herbs at a storage temperature of 10°C is 24-83 µl CO_2/g*h, while Basil and chives have considerably higher rate (37 µl CO_2/g*h and 58 µl CO_2/g*h respectively). (Lopresti et al., 1997) The condensation moisture is released once herbs are moved from an ambient to a chilled storage environment, or once warmer outer air comes in contact with a cooler inner surface of the packaging. Lopresti et al. (1997) also found a clear increase of respiratory activity with increasing storage temperature. (Lopresti et al., 1997)

While one wants to reduce water loss as much as possible to prevent senescence, one must equally prevent moisture accumulation. This can either be achieved by utilizing a semi-permeable film, allowing breathability or by applying an anti-mist coating, which is effective through a mechanism of lowering the surface tension to avoid drop formation (MacVarish, 2017).

Ethylene production

A further factor driving deterioration of herbs, is the production of ethylene, more commonly known as the ripening hormone in plants. The extent of ethylene production varies according to different fruits and vegetables and is dependent on storage temperature and humidity. Amongst fresh herbs, the ethylene production is generally higher than that of other green vegetables. On average, herbs produce 0.10-0.57 µl/kg*h ethylene at a storage temperature of 10°C. (Ethylene Control.com, n.d.) Effects caused by ethylene include loss of green color, abscission of leaves, epinasty (bending of stems) and change in texture. (Lopresti et al., 1997)

Ethylene production and undesired consequences of the presence of ethylene can be minimized by keeping low storage temperature and low oxygen concentrations within the package. (Ethylene Control.com, n.d.)

4.2.1.3 Spices

Moisture sensitivity

Dried and powdered spices have an a_w value between 0.5-0.6 and a moisture content ranging from 8-23%, with an average between 10-12% (containerhandbuch.de, n.d.). Spices are characterized as highly hygroscopic, making them absorb moisture from the surrounding atmosphere. Moisture uptake will result in the formation of sticky lumps, by which the powders lose their free-flowing properties. Much more trouble-some however, is the fact that moisture uptake induces microbial growth and can cause fermentation, both of which would cause irreversible product spoilage in terms of aroma, flavor and development of mycotoxins creating a risk for food-borne illnesses. (containerhandbuch.de, n.d.; ICPE, 2000)

Loss of aroma

Spices (and herbs) are loaded with aroma compounds such as flavonoids and phenolic acids, to which they owe their characteristic flavors and odors. The compounds are mostly present in form of essential oils. On the one hand, the volatiles of these compounds provide antioxidant and antimicrobial activity, which are beneficial in terms of protection against microbial growth. (Robertson, 2012) On the other hand, their volatility quickly leads to undesired loss of aroma, which can be largely prevented through air-tight packaging. (ICPE, 2000)

Light sensitivity

Furthermore, essential oils are strongly light sensitive. Light can induce lipid oxidation, hence development of off flavors and discoloration. Light and oxygen exposure is especially fatal for highly pigmented spices and ground spices, as they have a greater surface area exposed to the elements. Light induces deterioration can be delayed through lightproof packaging. (ICPE, 2000)

Table 10 summarizes the previously described shelf life determining factor and recommended storage conditions.

Table 10. Shelf life affecting factor and recommended storage conditions of products

Product	***Factors determining shelf life***	***Storage recommendations***	***Reference***
BAK	➢ Respiration ➢ Staling ➢ Water gain/loss ➢ Microbial growth	➢ Ambient or frozen storage (<-18°C) ➢ Dry ➢ MAP with >50% CO_2 or O_2 concentration below 10% can delay mold growth and prolong shelf life	(Cauvain & Young 2012, Robertson 2012, Petersen 1999) (Upasen 2018)
HERB	➢ Respiration ➢ Ethylene production ➢ Water loss (senescence) ➢ Physical damage	➢ Refrigerated temperatures (5-10°C), except Basil & Mint (>10°C preferred, to prevent tissue damage) ➢ low O_2 concentration (below 10% to control ethylene production and respiration rate, but excessively low O_2 rates risk the growth of anaerobic bacteria (toxigenic) ➢ Optimal RH: 95-98% ➢ Semi-permeable or anti-mist coating	(Bartz & Brecht, 2002; Cantwell & Reid, 1993; Ethylene Control.com, n.d.; Lopresti et al., 1997; Petersen et al., 1999)
SPI	➢ High moisture sensitivity ➢ Microbial growth ➢ Aroma loss ➢ High light and oxidation sensitivity (lipid oxidation)	➢ Cool-ambient storage ➢ Dry ➢ Dark ➢ Mold growth RH threshold: max. 75% RH ➢ Grease and oil resistance required	(containerhandbuch.de, n.d.; ICPE, 2000; Peter, 2006; Robertson, 2012)

4.2.2 **Currently applied packaging materials in HelloFresh**

Table 11 provides an overview of the packaging materials, that are currently applied for the considered product categories in the HelloFresh Germany branch. The indicated dimensions are of exemplary products from the category, of which comparatively large volumes are sold. Within the BAK category, different materials are applied depending on product supplier.

Table 11. Details on the currently applied packaging materials (HelloFresh DACH, 2019b, 2019d, 2019e)

Product category	*Packaging Material*	*Dimensions [cm] (exemplary)*	*Thickness [µm]*	*OTR [cm3/m2*day]*	*WVTR [g/m2*day]*
BAK	Multilayer PA/EVOH/PE	22x18x7	80	2,5	4,0
	PET/CPP		50	1,0	2,0
HERB	Anti-mist coated CPP	32x12	30	2500	2,7
SPI	Co-extruded Paper/LDPE/ EVOH laminate	10x2,5	40	<2,5	<2,0

BAK products are either packaged in a co-extruded high-barrier multilayer film made up of a PA (polyamide), EVOH (ethylene vinyl alcohol) and PE layers or another multilayer film consisting of PET and oriented PP. The PA/EVOH/PE is used for thermoforming packaging process, while PET/CPP (cast-extruded polypropylene) is processed through a vertical form fill seal (VFFS) machine. They are packed in modified atmosphere conditions with a controlled carbon dioxide concentration. (HelloFresh DACH, 2019b) Both are multilayer laminates, which exhibit very poor recyclability because specific delamination processing steps are required. Although processing techniques enabling recycling of multilayer materials do exist, they often require e.g. high energy input. Therefore, the effective EoL destination of multilayer materials is usually landfill or incineration (according to German waste systems). (Kaiser et al., 2018)

HERB are packed in CPP film through a horizontal form fill seal (HFFS) process. (HelloFresh DACH, 2019d) The film is one side corona-treated, which increases the material's surface energy, providing an inherent anti-mist effect (Doi & Steinbüchel, 2002). According to the packaging material supplier, the material is fully recyclable.

The packaging material used for SPI is a co-extruded LDPE coated paper material, with an additional EVOH layer providing high-barrier properties. SPI are packed through a VFFS process. It provides excellent barriers to water vapor, gases, aroma, light and lipids. The material is not recyclable. (HelloFresh DACH, 2019e)

4.2.3 HelloFresh supply chain conditions and required shelf life

HelloFresh receives end customer orders on a weekly basis. Based on customer orders precise demands are calculated and requested from the suppliers to be delivered to the HelloFresh distribution center (DC) on a just-in-time (JIT) basis. The product specific required shelf life has been identified based on the following SC conditions identified within HelloFresh:

SC conditions:

- 1 day is considered for production and packaging at supplier
- 0.5 day is considered for transport from supplier to HelloFresh DC
- 1-2 days are considered for transport from DC to consumer
- Every product must exhibit a minimum of 5 days shelf life once received by the consumer
- Transport from DC to consumer is either carried out in refrigerated trucks or non-refrigerated trucks depending on destination (for this purpose, non-refrigerated trucks are considered)
- Perishable products (Dairy, protein, fresh produce etc.) are usually not kept for more than 1-2 days in production (box packing) at HelloFresh
- Occasionally, products are ordered to be delivered a day in advance to provide buffer time to avoid consequences of potentially occurring supply issues (buffer time is included in above-mentioned 1-2 days)
- Non-perishable products (Processed foods (e.g. sauces), dry products (e.g. pasta, grains, spices) are usually kept for a longer period, as they are not ordered on a just-in-time basis

(HelloFresh DACH, 2019b, 2019d, 2019e)

Figure 19 illustrates the SC conditions as they are currently executed for the three product categories at HelloFresh. For each product category, the HelloFresh specific storage temperatures in the different SC stages are indicated as well as the resulting required shelf life for each product category.

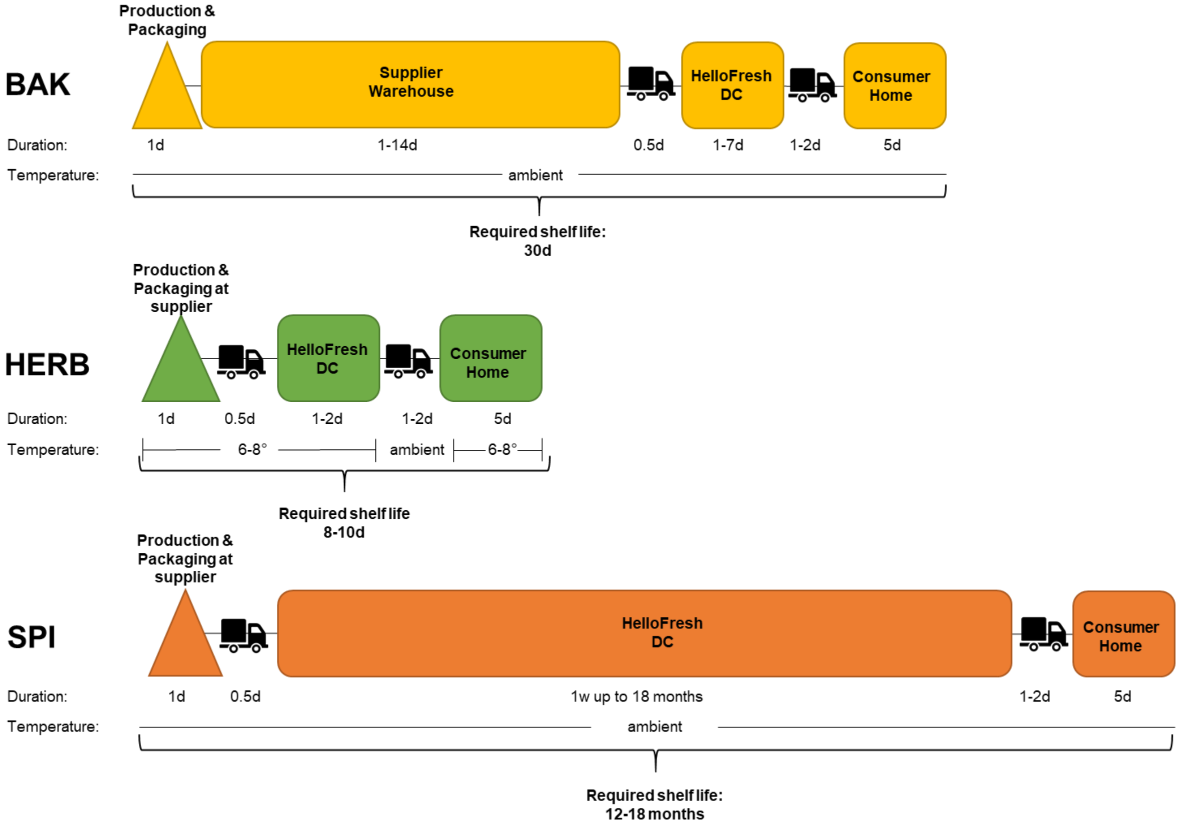

Figure 19. Mapped supply chain at HelloFresh for considered product categories (BAK, HERB and SPI) (HelloFresh DACH, 2019b, 2019d, 2019e, 2019c)

4.2.3.1 BAK

HelloFresh sources BAK products from two different suppliers. BAK product orders are placed by HelloFresh every three months with a predicted outlook indicating when which products will be needed. The suppliers then produce on a continuous basis to be able to provide the predicted weekly demands. Packaging is done by the suppliers. Once packed, the products are temporarily stored at the supplier's warehouse until HelloFresh requests precise weekly demands according to consumer recipe orders. This period can be up to approximately 14 days. The products will then be transported to the HelloFresh DC where they are stored for up 5 days until they are packed into meal kit boxes and picked up to be delivered to the consumers' homes All bakery products are stored and transported at ambient temperatures (~19°C), except when in the production area in the HelloFresh DC, where the prevailing temperature is between 6-8°C. Upon arrival at the consumer, the product must have a minimum remaining shelf life of 5 days. (HelloFresh DACH, 2019b)

Due to the procurement strategy of placing product orders well ahead, the BAK products require a shelf life of 30 days.

4.2.3.2 HERB

Most herbs are produced outside Germany but provided to HelloFresh by a German supplier. The supplier receives the herbs in bulk and packages the herbs according to HelloFresh demands. HelloFresh sends orders on a weekly basis, according to received customer recipe orders. However, since meal kit distribution is split over several days of the week, herbs are delivered to the HelloFresh DC fresh each morning of a distribution day. Delivery to HelloFresh takes place over night. Once received by HelloFresh they are moved directly to the production area, packed into the meal kit boxes and usually leave the DC the same day. Occasionally, herbs are ordered to be delivered a day in advance to provide buffer time to avoid consequences of potentially occurring supply issues. All storage and distribution steps take place at temperatures between 6-8°C, until they are sent out to the consumers' homes. During delivery they are kept in the non-chilled compartment. At the consumers' home they are most likely stored in the fridge with other chilled goods. The herbs are not marked with an expiry date. However, they are expected to remain fresh for a minimum of 5 days once received by the consumer. (HelloFresh DACH, 2019d)

Following the HelloFresh supply chain for herbs, they should ideally exhibit a shelf life of 8-10 days.

4.2.3.3 SPI

SPI are ordered on an irregular basis depending on demand and existing storage. SPI are packaged for HelloFresh into consumer size sachets by the supplying company. Once packaged, they are delivered to the HelloFresh DC, where they are kept in cardboard boxes in ambient and dry conditions. Storage in the DC may be for up to 12-18 months. Once they are required for the meal kit, they are moved to the production area, packed into the boxes and further sent out for delivery. SPI must exhibit a minimum remaining shelf life of 5 days upon arrival at the consumer. (HelloFresh DACH, 2019e)

Due to long storage time at the HelloFresh DC, a shelf life of 12-18 months is required.

From the SC insights, it can be concluded that the expected JIT procurement is only executed on HERB. Procurement strategies, logistical challenges, warehousing and production processes do not allow JIT delivery for BAK and SPI.

4.2.4 **Product packaging requirements**

Based on previously identified shelf life affecting factors of the products as well as HelloFresh specific supply chain conditions and shelf life requirements, the following barrier requirements for each product have been determined (Table 12).

Table 12. Product specific barrier requirements to achieve common product shelf life

Product category	*Storage conditions and required shelf life at HelloFresh*	*Barrier requirements for common shelf life*			
		O_2	*WV*	*Lipids*	*Light*
BAK	➢ Ambient temperature ➢ Dry ➢ Required shelf life: 30 days	**High-very high**	**Medium-high** (semi-permeable)	**Low-very high**	**Low-very high**
HERB	➢ Refrigerated and non-refrigerated ➢ Required shelf-life: 8-10 days	**Low-high**	**Low-high** (semi-permeable)	**Low-very high**	**Low-very high**
SPI	➢ Cool and ambient storage ➢ Dry ➢ Dark intermediate storage (within secondary box) ➢ Required shelf life: 12-18 months	**High-very high**	**High-very high**	**Medium-very high**	**Medium-very-high**

4.2.5 **Expected material-product compatibility**

Following the defined barrier requirements in accordance with previously identified barrier ranges from literature (see Table 7), and with respect to identified lipid and light resistances (transparency) (see Appendix C.1) the product-material compatibility for the identified supply chain conditions was determined.

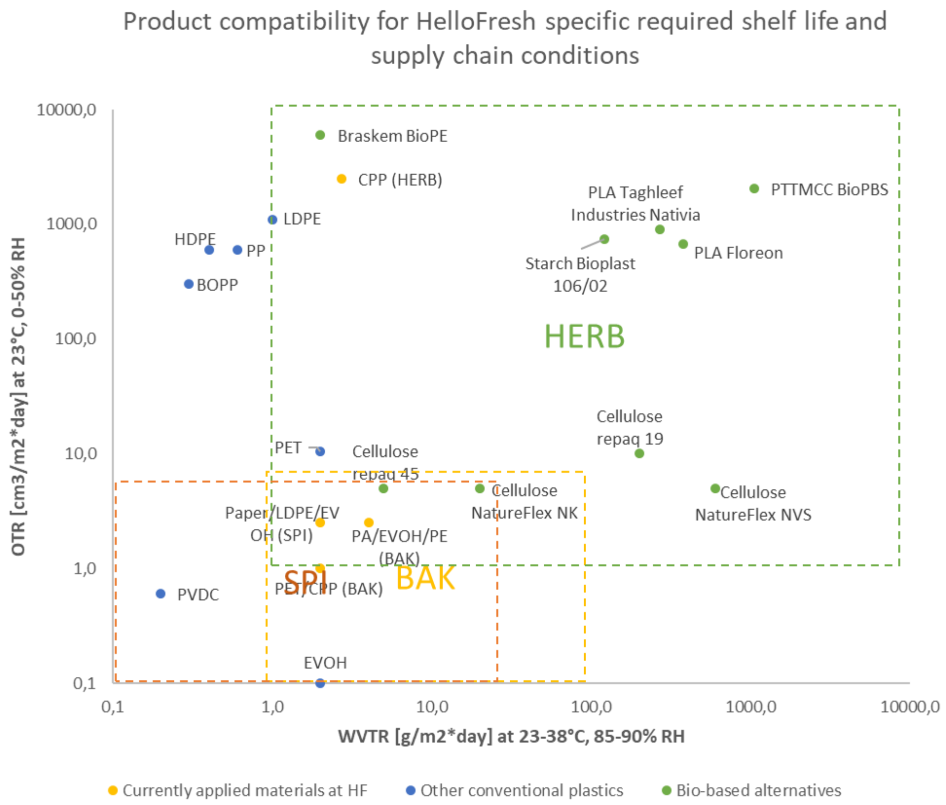

Figure 20. Material-product compatibility resulting from product specific barrier requirements

A tabular listing of the above visualized results is provided in Appendix C.2.

As can be seen in Figure 20 the product-material compatibility varies for the three product categories.

The previously conducted research on product specific shelf life affecting factors initially revealed that both BAK and HERB products generally favor a semi-permeable water vapor barrier to allow the respiration moisture to escape. In theory the high water vapor permeability of most bio-based materials is thus a beneficial characteristic as it essentially provides a natural anti-mist coating effect. On the other hand, excessive moisture loss must be prevented.

Furthermore, neither BAK nor HERB products contain high amounts of oxidation sensitive components, hence would not require high oxygen barriers. Yet for HERB the oxygen level should not be excessively low to prevent growth of anaerobic bacteria, hence a very high oxygen barrier is disadvantageous.

At HelloFresh, HERB require a shelf life of 8-10 days, partially stored at refrigerated conditions. Considering these conditions, a broad compatibility with all considered bio-based materials is expected. Apart from the barrier properties matching with product requirements, the compatibility has also been predicted by several material specialists and suppliers that were contacted (Bernard, 2019; Dragun, 2019; Seevers, 2019).

For the BAK category on the other hand, the required shelf life of 30 days, limits the compatibility significantly. While a weak oxygen barrier is considered unproblematic for a short storage time for BAK products, it certainly raises an issue concerning potential mold growth when the product is stored for up to 30 days. To prevent mold growth within the package the oxygen concentration within the package must be controlled, hence a high or very high oxygen barrier is required. Equally the moisture permeation must be reduced to prevent quick drying out of the product. Subsequently the only potential material candidates for BAK are Cellulose repaq 45 and Cellulose NatureFlex NK.

These are however, the mere candidate predictions for the current supply chain conditions. That is to say that adjusting storage conditions or procurements strategies which would lead to shorter required shelf life could broaden the compatibility considerably. For example, according to technicians from contacted packaging companies (Bernard, 2019; Clemesha, 2019) (M. Bernard, M. Clemesha), a shelf life of 8-10 days is realistically expected for BAK products when packed in Braskem BioPE. Their statement is based on experiences from the Scandinavian bakery Polarbröd, that has successfully implemented BioPE for a large selection of their product portfolio. Furthermore, the Papier Mettler interviewee indicated that the required shelf life of 30 days or even longer could easily be achieved with BioPE if the product was stored at frozen conditions for the majority of the SC. Frozen conditions however would quickly lead to increased energy demands and consequent CO_2 emissions during product transport and storage. In that case one would need to carefully evaluate the trade-offs. Alternatively, a prolonged shelf life can be achieved by controlling the internal gas concentration through MAP conditions, in which case an appropriate gas barrier is required, which is not feasible with BioPE. (Bernard, 2019)

The compatibility with the SPI category is very limited. Spices at HelloFresh are ordered in bulk and stored for up to 12-18 months, depending on the individual spice. While water vapor permeability may be beneficial for BAK and HERB, it is a detrimental material characteristic for highly moisture sensitive powdered spices. Equally disadvantageous are limited oxygen barriers, due to oxidation sensitive aroma compounds. A further negative characteristic is the transparency of most considered bio-based films, resulting in lacking light protection. The lacking light protection, however, is not considered a knock-out criterion, as the sachets are stored in a light proof secondary package (card board box) during storage and are only removed from it once needed for production. Besides, a light barrier can also be achieved otherwise, e.g. with labels or printing. Evaluating from these requirements, the barrier requirements were initially set to high – very high for both OTR and WVTR. The product-material compatibility was then restricted to Cellulose repaq 45 film, providing both suitable oxygen and water vapor barrier. Furthermore, based on discussions with material specialists, also Cellulose NatureFlex NK film is suitable for spice packaging, despite a WVTR of 20 g/m2*day, which is relatively high compared to Cellulose repaq 45 (5 g/m2*day) and the currently applied material (<2 g/m2*day). In fact, it was found that an Austrian company already successfully applies NatureFlex NK for their spice products (Sonnentor.com, n.d.). However, the supply chain and storage conditions within that company remain unknown. A direct conclusion as to whether the material is equally suitable for the HelloFresh SC cannot be drawn. However, upgrading the barrier properties of the secondary package at HelloFresh to obtain better moisture and oxygen protection during the long-time storage in the HelloFresh warehouse, could possibly enable the applicability with SPI products. Nevertheless, the extent to which aroma retention inside the primary packages can be obtained with the weak barrier properties of the potentially bio-based films.

An alternative for spices could be the application of a bio-based film as a coating layer for a paper-based material. This was also suggested by Cellulose film suppliers NatureFlex and repaq (Markey, 2019; Seevers, 2019). Besides, as was mentioned in 2.3.4, recent packaging material development has shown progresses towards the development of high-barrier bio-based films. Methods that are being investigated include metallization through e.g. $SiOx_2$ coating. Examples include CeramisPLA or EnvirometPLA from Celplast (celplast.com, n.d.).

Even though BioPBS is included in the barrier range of HERB, its effective applicability of a pure film packaging is limited due to its reduced film availability at current stage of development. Instead it is frequently applied as paper coating or sealant layer in flexible packaging (PTTMCC, 2017).

All predictions were drawn from a theoretical approach of merging product characteristics with given material properties and current supply chain conditions. Practical tests that can substantiate and confirm these predictions are highly recommended.

4.2.6 **Barrier performance simulation to currently applied packaging at HelloFresh**

The Norner barrier calculator was used to simulate each material's barrier performance for both OTR and WVTR. Materials currently applied at HelloFresh are used as reference materials (visualized with dotted light red lines). The determined threshold values are visualized as standards with solid dark red lines.

The following input parameters were used for the barrier simulation.

Table 13. ***Norner*** **input parameters**

Parameter	***BAK***	***HERB***	***SPI***
Area	0,135 m^2	0,077 m^2	0,005 m^2
Time	30 days	10 days	360 days
Temperature	19°	4 days: 7°C, 2 days: 19°C, 4 days: 7°C	19°C
RH inside	36% *	92% *	8%*
RH outside	50%	50%	50%
Oxygen level	21%	21%	21%

*: the product specific RH values are according to the individual moisture content values derived from literature during 4.2.1

The barrier performance simulation yielded the following results:

BAK

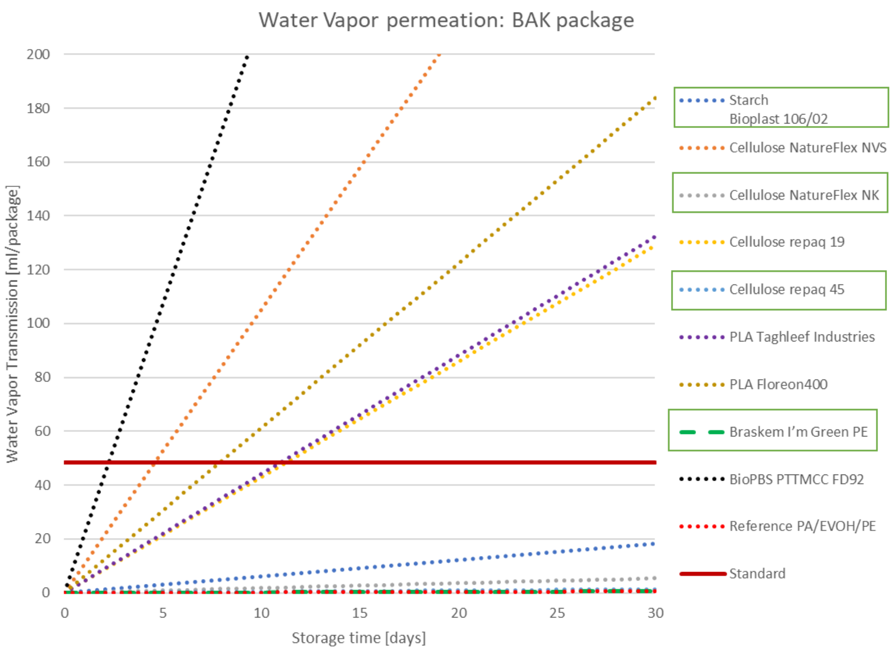

Figure 21. Water vapor permeation for BAK packaging

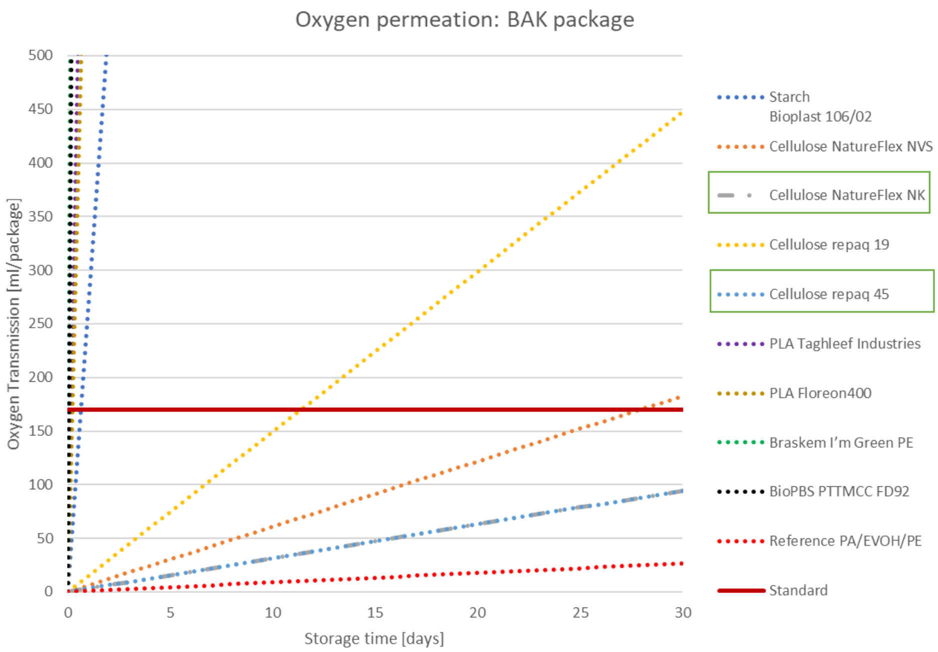

Figure 22. Oxygen permeation for BAK package

The barrier performance for BAK packaging was simulated for a storage duration of 30 days.

Figure 21 and Figure 22 prove that previously identified Cellulose NatureFlex NK and Cellulose repaq 45 stay within the acceptable limits over the required shelf life period. Additionally, Figure 21 shows that also Braskem Green PE and Starch Bioplast 106/02 stay within the limits in terms of WV transmission, yet do not perform sufficiently well in terms of oxygen transmission (Figure 22). The reason why Starch Bioplast 106/02 presents such a low EV permeation event though it has a relatively high WVTR, is due to its thickness. From the diagrams it can also be identified, which shelf lives can theoretically be achieved with other materials. For example, Cellulose repaq 19 performs sufficiently for 11 days for both oxygen and WV transmission. In terms of oxygen transmission all materials perform worse compared to the reference, while the WV permeation performance of the reference is identical to that of GreenPE.

HERB

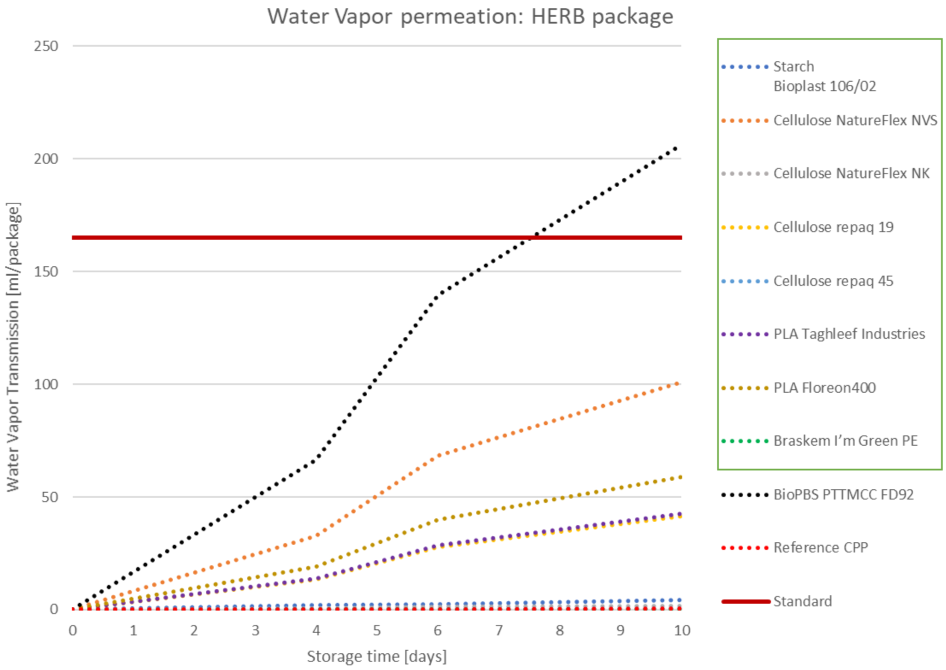

Figure 23. Water vapor permeation for HERB package

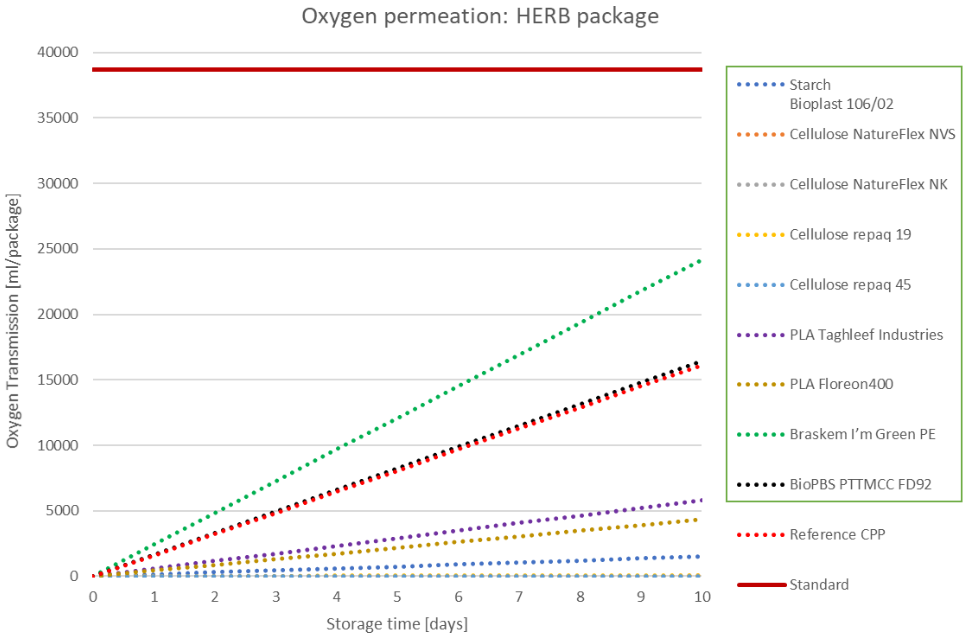

Figure 24. Oxygen permeation for HERB package

For HERBs, the simulation was conducted for 10 days. Figure 23 indicates that the lower storage temperature decelerates the water vapor permeation rate. While the qualitative performance differences amongst the individual materials do not change in comparison to the BAK package, the quantitative performance varies due to reduce packaging surface and shorter time period.

Figure 24 proves that all materials stay within the limits, whereas in Figure 23 BioPBS exceeds the threshold. In the case of HERB, it must be considered that upper transmission limits are not clearly defined as per Table 7. Instead, both OTR and WVTR are defined as >100. The upper threshold limits were therefore simulated with the highest occurring permeation rates amongst the observed materials (BioPBS for WVTR and Braskem GreenPE for OTR). (The reason why BioPBS yet exceeds the water vapor threshold already on day 7, is due to a lower material thickness as was used for the standard simulation. In turn, Braskem GreenPE does not reach the oxygen permeation limit, because the material exerts a higher thickness than the standard, as can be seen in Figure 24)).

Also consider, that even though it appears as if many of the materials could achieve a longer shelf life until the threshold is reached, this is because upper limits are not clearly defined and can thus not be taken as definite. Practical tests are required to confirm the compatibility and to determine definite shelf lives.

Figure 24 also shows that all materials, except I'm Green PE demonstrate comparable or better barrier performance compared to the reference material CPP. However, despite I'm Green PE having a much higher OTR value (6000 cm3/m2*day) compared to CPP (2500 cm3/m2*day), they are both categorized in the same barrier category (low), thus the difference of the effective barrier performance is considered marginal.

As was previously concluded in 4.2.5, all materials except BioPBS, are considered to be compatible with HERB products.

SPI

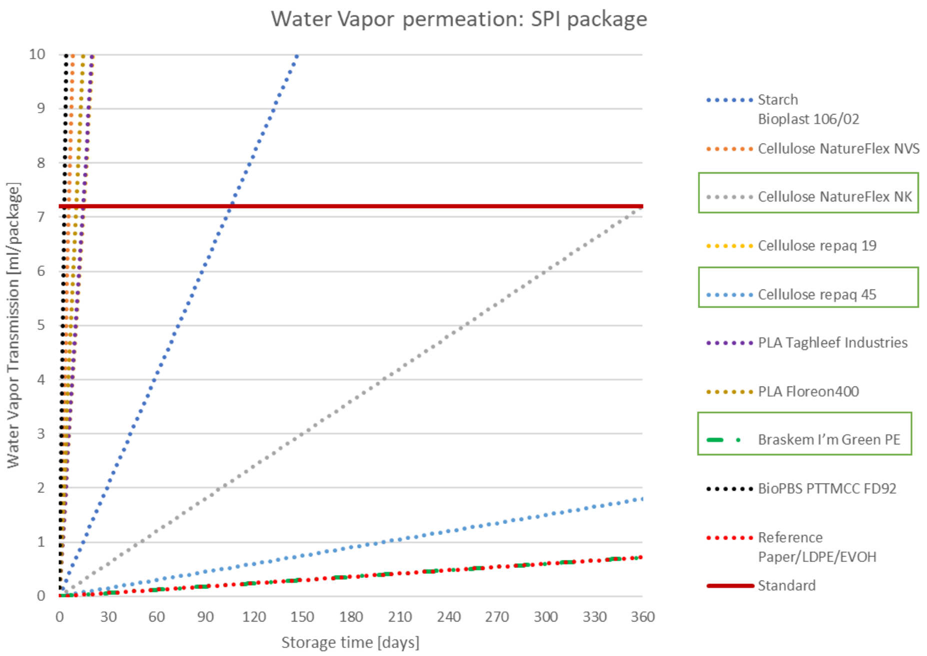

Figure 25. Water vapor permeation for SPI package

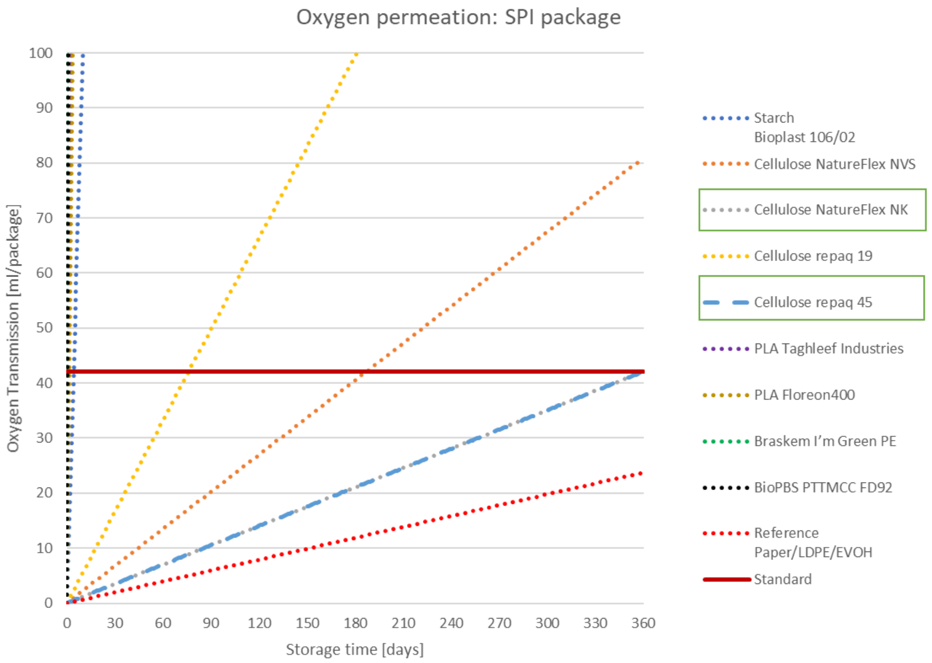

Figure 26. Oxygen permeation for SPI package

SPI packaging was simulated for 360 days. Following discussion with material supplier, who indicated material compatibility with Cellulose NatureFlex NK, the thresholds for SPI were defined based on the transmission rates of Cellulose NatureFlex NK. The spice packaging surface is 27 times smaller than the exemplary BAK packaging size. Accordingly, lower are the permeation rates.

Both Figure 25 and Figure 26 prove compatibility with Cellulose repaq 45 and Cellulose NatureFlex NK. Yet, both perform worse compared to the reference material. While, as seen in Figure 25, GreenPE still performs within the threshold in terms of WV transmission, it exceeds the oxygen limit already after the first day of storage.

Tables with precise numerical output values can be found in Appendix C.3.

4.3 Environmental impact assessment

4.3.1 **Beginning of life**

4.3.1.1 LCA data

For the purpose of this thesis, cradle-to-gate LCA data on the GWP and CED was collected for the considered bio-based materials and fossil-based PE, PET and PP for direct impact comparison with conventional plastics (Figure 27).

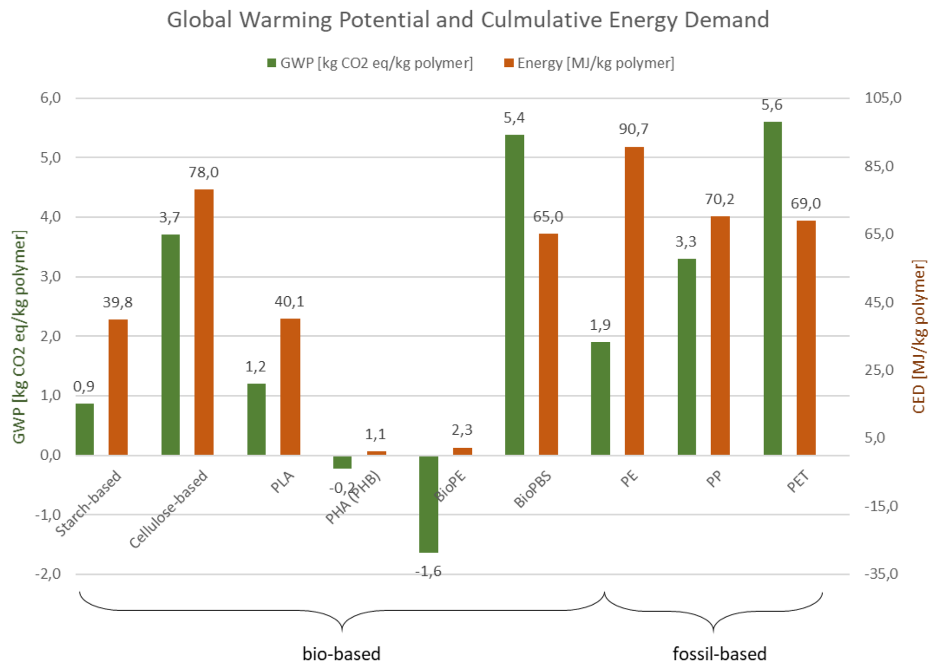

Figure 27. Cradle-to-gate LCA data on GWP and CED for bio-based and fossil-based polymers (see Appendix D1 and D.2 for various references)

Global Warming Potential

In terms of GWP results reveal that bio-based PE and bio-based PHA(PHB) perform significantly better than all other considered materials values. Their negative values, -1,6 and -0,2 kg CO_2 eq/kg polymer respectively, reflect the plants' (e.g. sugarcane, which act as the glucose sources) ability to capture CO_2 from the atmosphere during growth phase rather than emitting it, essentially yielding a net reduction of

greenhouse gases. The remaining polymers exhibit a GWP up to a maximum of 5,4 kg CO_2 eq/kg polymer for BioPBS.
In contrast, fossil-based polymers exhibit GWP values between 1,9 kg CO_2eq/kg polymer for PE and 5,6 kg CO_2 eq/kg polymer for PET, being the polymer with the highest CO_2 equivalents emissions.

Cumulative energy demand

Similarly results for cumulative energy demand reveal that bio-based PHA(PHB) and BioPE have the lowest values compared to all other materials with 1,1 MJ and 2,3 MJ respectively. Energy demand amongst bio-based polymers reach as high as 78 MJ/kg polymer for cellulose-based materials. The notably high CED for cellulose-based polymers is most likely to result from the extensive processing steps executed to extract pure cellulose from wood. Pulping, bleaching and purification steps are required to obtain lignin and hemicellulose-free cellulose derivatives. (Iffland et al., 2015)

Required energy demands for fossil-based materials on the other hand range between 69 MJ/kg polymer for PET being the least energy demanding conventional polymer, and 90,7 MJ/kg polymer for PE being the highest energy demanding polymer.

Bio-based PE vs fossil-based PE

Brazilian BioPE producing company Braskem conducted an LCA study for their bio-based PE. Within their assessment, they conducted an LCA of fossil-based PE under identical conditions for direct comparison. Their values can thus be compared as direct counterparts. In their study they found both GWP and CED to be evidently lower for BioPE compared to fossil-based PE. (GWP: -3,1 vs 1,9 kg CO_2 eq/kg polymer and CED: 2,3 vs 90,7 MJ/kg polymer). (Plasticoverde - Braskem, 2017)

Overall bio-based vs fossil-based

Gathering average values for an overall comparison of bio-based vs fossil-based was not considered appropriate for the analysis, due to unequal numbers of data point per polymer and the set of data being too small to obtain representative, integral average results.

Nevertheless, it is evident, that the overall best performing materials in terms of GWP and CED are BioPE, PHA(PHB), starch-based and PLA all of which are bio-based polymers. The most negatively performing in both GWP an CED are BioPBS[1] and conventional PET. While BioPE, starch-based polymers and PLA can be applied as materials as such, PHA is so far only useful as an additive to e.g. PLA, hence it is not processed into a film packaging material on its own. Hence, BioPE turns out to be the most promising film material in terms of GWP and CED, followed by starch-based and PLA.

From the LCA data it can be concluded that particularly BioPE, PHA, starch-based polymers and PLA exert reduced environmental impacts in terms of GWP and CED compared to petrochemical counterparts.

The following factors must be kept in mind when interpreting the LCA data:

- The given comparative analysis of LCA data was merely taking two indication factors into consideration, thus neglecting indicators such as eutrophication potential, acidification potential or land use. While such factors do not necessarily affect the final picture, a certain influence on the data is to be expected once more factors are considered, hence they should not be underestimated. Including further indication factors would enable a more holistic assessment and hence provide more justification for the support of certain materials.
- The LCA data considers only cradle-to-gate, thus does not encompass all product life stages.
- All considered LCA results include the biogenic carbon content of the final polymers. According to Pawelzik et al. (2013) and Spierling et al. (2018) this is especially important when comparing fossil-based to bio-based polymers in a cradle-to-gate boundary system. While both fossil- and bio-based polymers contain carbon which is released during a products EoL, only bio-based polymers have the ability to capture atmospheric CO_2 through the feedstock, which leads to a negative CO_2 emissions flow. However, depending on the type of EoL (which is unclear in a cradle-to-

[1] A project coordinated by the association de coordination technique pour l'industrie agroalimentaire (Succipack), was run to investigate the potential of bio-based PBS for the packaging industry. Within this study, cradle-to-*grave* LCA results revealed that the most crucial step is the production of SA, especially in terms of energy consumption. As was explained in 2.3.4.7, SA is required for the synthesis of both monomers BDO and PBS. Furthermore, a comparative cradle-to-*grave* lifecycle analysis of different packaging materials for food products proved that the impact of bio-based PBS materials is higher compared to those of conventional polymers or other bio-based materials, such as PLA. The negative environmental impact roots back to high-energy consuming production technologies. (European Commission, 2015)

gate system) this negative flow would be neutralized in case of CO_2 emissions during the EoL.

- Individual LCA data was collected from various references. Despite careful selection of the consulted data, uniform conditions and identical approaches of all individual LCAs cannot be guaranteed. The data set used for the purpose of this thesis is sufficient to provide a general overview, yet it does not ensure unconditional comparability.
- For some polymers several LCA studies were found, for which an average value is presented above, whereas other polymers' values might only be based on a single study. A table with all included LCA values and according references can be found in Appendix D.1 and D.2.

4.3.1.2 BUE data

As an additional beginning-of-life sustainability indicator, the biomass utilization efficiency, specifically the BUE_H, which represents the "highest realistic percentage of used biomass ending up in the desired product" was used. The BUE compares merely bio-based materials amongst each other, as opposed to the LCA analysis which also included petrochemical counterparts. (Iffland et al., 2015) Figure 28 shows the BUE for the considered bio-based materials.

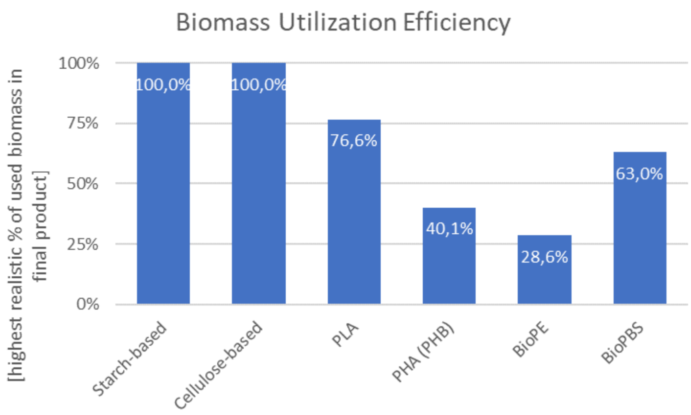

Figure 28. BUE_H values (highest realistic percentage of used biomass ending up in the desired product) for the considered bio-based polymers (Data is retrieved from Iffland (nova-Institute) et al., 2015)

The highest biomass BUE is achieved for starch and cellulose, both exhibiting 100% efficiency, followed by PLA with 76,6% efficiency. BioPE on the other hand only yield an efficiency of 28,6%. PHA(PHB) and BioPBS remain with intermediate efficiencies: 40,1% and 60,3% respectively.

Following Iffland (nova-Institute) et al. (2015), the differences in BUE can be explained by the chemical complexity of the raw materials being reflected in the final products to different extents. When comparing PLA to BioPE, the presence of oxygen in the building blocks chemical structure is an essential factor affecting the BUE. In the case of PLA, 100% of a glucose molecule can directly be converted into lactic acid (the building block of PLA), in which oxygen remains present. This means that all atoms of the glucose molecule (6 carbon, 12 hydrogen and 6 oxygen atoms) are retained. Depending on the microorganisms and fermentation conditions, a final yield of 85-97% of lactic acid can be obtained. When considering also the 98.7% of conversion rate of the polymerization process, a final 76.6% BUE_H is achieved. In the case of BioPE, ethylene is the building block. Ethylene does not contain any oxygen; hence all oxygen atoms need to be removed from the glucose molecules, which is achieved by removing CO_2 from the sugar molecule. At the end of that twostep process (via ethanol as an intermediate product) only 3 carbon atoms remain of the glucose molecule which PE can be made from. Eventually this leaves one with a 28% BUE. On a positive note, the polymerization of ethylene to Polyethylene has a 100% efficiency, resulting in a 28% efficiency rate overall. (Iffland et al., 2015)

This explains why biomass is used more efficiently for PLA than for PE. It must be mentioned at this point that the BUE is also strongly dependent on the type of processing pathway applied to produce the polymers from the resources. (Iffland et al., 2015)

The 100% efficiency revealed for starch and cellulose derivatives can be explained as follows: Starch and cellulose are both polymers made from complete glucose molecules attached to each other, creating a chain. Whereas PLA and BioPE require fermentation and polymerization steps to eventually obtain the polymers from glucose, cellulose and starch are derived as polymers themselves. The atomic structure is not touched upon, thus not risking any loss of atoms. This results in a 100% BUE. (Iffland et al., 2015)

At the same time, the BUE gives a direct link to the amount of farm land required for the growth of resources. Materials with a low BUE require more farm land compared to materials made from a resource with a higher BUE for the same output. For example, the production of PLA requires only half the amount of arable land as the production of the same amount of BioPE, both derived from sugarcane (Iffland et al., 2015).

This emphasizes the importance of including land and water consumption indicators in LCA evaluations, especially when looking into plant-based materials. Concluding from the BUE results, the initially obtained positive picture of BioPE is drastically weakened and becomes less meaningful. In that context it must also be mentioned that the growing demand for sugarcane (as a feedstock for large-scale bioethanol production, which is further needed to produce BioPE) in Brazil, has risen numerous sustainability debates. Concerns include potential damage of soils through the use of chemicals (fertilizers, pesticides, etc.), deforestation, soil decarbonization, water contamination and competition of arable land needed for food production. On the other hand, it is said that the fermentative production process of bioethanol requires hardly any external, non-renewable energy sources and the amount of agricultural area used for sugarcane production accounts for 10 million hectares, which is less than 1% of the global arable land (Goldemberg et al., 2008; Zuurbier & van de Vooren, 2008).

BioPE remains debatable. Instead a focus on starch-based materials and PLA, which performed considerably well in both assessments, should be taken into closer consideration.

4.3.2 **End-of-life**

4.3.2.1 Intended EoL scenarios for bio-based materials

Table 14 lists the intended EoL options according to the individual certifications of the considered materials. Except for BioPE all materials are meant to be composted in either home or industrial composting conditions. BioPE is the only material which can be recycled in existing recycling streams, together with commonly recycled conventional plastics. PLA and PHA materials have the potential for mechanical recycling, yet they require specifically construed recycling streams. The deviating melting temperatures and glass-transition temperatures render them incompatible with conventional PET or PE recycling processing steps, in which PLA could cause yellowing or haziness of the recyclate or result in flake agglomeration and cluster formation of pellets hindering further operations. (Alaerts et al., 2018)

Table 14. Intended EoL options for bio-based materials according to supplier information

Material type	*Supplier & Material name*	*Intended EoL*
Starch	***Biotec Bioplast 106/02***	Compost: home or industrial
Cellulose	***Futamura NatureFlex***	Compost: home or industrial
	repaq	Compost: home or industrial
PLA	***Taghleef Industries Nativia NTSS***	Compost: industrial Recycling: only is designated streams
	Floreon 400	Compost: industrial Recycling: only is designated streams
PHA	***Yield10 Mirel PHA P5001***	Compost: industrial Recycling: only is designated streams
	Bio-On Minerv PHA	Compost: home or industrial Recycling: only is designated streams
BioPE	***Braskem I'm Green PE***	Recycling is conventional streams
BioPBS	***PTTMCC BioPBS FD92***	Compost: home or industrial

As was mentioned in 2.3.3 the report by the European Commission (2019) proved that the EoL scenario of packaging films significantly affects the environmental impact of a product. Apart from BioPE, which can be recycled in conventional recycling streams, all considered bio-based materials are intended to be either home or industrially composted. To assess the likelihood of the materials ending up in their intended EoL scenario, statistics on biowaste collection and processing facilities as well as plastic packaging waste recycling rates in Europe were collected. Furthermore, the compatibility of composting plants with biodegradable/compostable materials was analyzed. This was done for four European countries: Germany, the Netherlands, France and the UK.

4.3.2.2 Recycling and composting rates in Europe

Plastics Europe has conducted a breakdown analysis of recycling rates specifically for *plastic packaging waste.* According to their results, a total of 16,7 million tons of plastic post-consumer packaging waste (this includes household, industrial and commercial packaging) was collected and processed through official systems in 2016 in the EU28 countries plus Norway and Switzerland. Following their analysis, 40,8% of this was recycled, 38,8% was processed for energy recovery and 20,4%

went to landfill. (Plastics Europe, 2018) These quotes however should be handled with care. Friege (2014) argues that such numbers mostly refer to what is *collected* for recycling, not however how much is effectively *recycled*. According to Baum, (2014) the realistic yield of eventually recyclable material is lower than 50% (in Germany), due to collected waste being contaminated with non-recyclable products, such as multilayer compound packaging or food waste.

On the other hand, the following statistics are reported about biowaste in Europe: as was stated by the European Commission between 118 and 138 million tons of bio-waste is created annually of which only approximately 25% is processed in composting plants to yield digestate (European Commission, 2010). Other analyses based on Eurostat data reveal that about 96 million tons of bio-waste are collected in form of municipal solid waste annually in Europe. Following the European Compost Network, only slightly more than 30% of this was collected as a compostable organic fraction and processed into digestate. (European Composting Network, n.d.)

4.3.2.3 Handling of biodegradable plastics in composting facilities in Europe

In order for biodegradable or compostable plastics to be effectively processed into high-quality compost, composting plants must accept such materials in the first place and must further be construed appropriately to fit the materials composting behaviors and requirements. The industrial composting facilities in Germany, the Netherlands, France and the UK have been reviewed regarding their compatibility with bio-plastics. Table 15 presents the results on the number of separate bio-waste collection sites, the usual duration of a composting cycle, the handling of biodegradable or compostable materials in a composting plant and the acceptance in anaerobic digestion plants. Furthermore, potential recycling possibilities for biodegradable/compostable materials was investigated.

Table 15. Summarized information of EoL options of biodegradable materials in four European countries (Information was retrieved from (Burgstaller et al., 2018; Kappel, 2019; M. Moeyersons, 2019; Myriam Moeyersons, 2018; Newman, 2019; Nichols, 2019; Noyce, 2019; Siebert, 2017; WRAP, 2019)

Country	***Number of composting/ bio-waste facilities***	***Average duration of industrial composting cycle:***	***Handling of biodegradable/compostable materials (BDs) in industrial composting plants:***	***Acceptance in anaerobic digestion:***	***Handling of biodegradables in recycling:***
Germany	912	3-9 weeks	**There are 2 possible processes in industrial composting facilities:** a.) With pre-sorting (65-70% of facilities): no technology in place that identifies BDs → all **non-identified plastics** will be sent to **incineration** for energy recovery b.) With post-sorting (99% of facilities): non-decomposed residues will be sorted out → and sent to incineration	Not accepted. Considered as contamination.	- No streams in place - Potential to develop with rising PLA waste volumes - BDs are sorted out and sent to incineration with energy recovery
Netherlands	135	Anaerobic digestion: 20 days + subsequent composting: 2-6 weeks	- Often anaerobic digestion takes place prior to composting **There are 2 possible processes in industrial composting facilities:** a.) With pre-sorting: **biodegradables will be sorted-out** → will be sent to **incineration** for energy recovery b.) With post-sorting: filtering of large particles → will be sent to incineration for energy recovery OR residues are sent into second composting round	Executed as part of composting cycle.	- Very rare streams exist for PLA - Potential to develop with rising PLA waste volumes - BDs hardly ever reach recycling (disposed through general waste)

France	692	3-6 months	- **BDs are accepted**, no sorting prior to composting process → majority is effectively composted, HOWEVER BDs rarely find their way into Organic waste bins - If BDs end up in mechanical-biological waste systems, BDs are sorted out and sent to incineration with energy recovery	Rarely executed.	- No streams in place - BDs are sorted out and sent to incineration with energy recovery
UK	199	- Most common: 8 weeks - Less common: 10-12 weeks	- **BDs are not distinguished** from non-biodegradable plastics by mechanical-optical sorting machinery/unpacking machinery/human sorting lines → all plastics are considered as "contaminant" and will be removed prior to composting process → **will be sent to incineration or landfill** - **Post-composting screening**: MOST undigested pieces (large and small) are removed by air-blowing add-on units - Since not ALL is removed, a batch will be considered as poor-quality and will be sent to a recovery process or disposal → contamination causes loss: low compost yield, added processing costs, disposal costs (landfill/incineration) for composters - ALL remaining plastics (BD or non-BD) is considered contaminant → composts with 0.12% w/w plastic contaminant not allowed on market in UK - According to a further source: BDs are accepted by about 25% of all composting plants (Moeyersons, 2018)	Not accepted except in one dry-AD plant	- No streams in place. - BDs are sorted out and sent to incineration with energy recovery

Insights retrieved from composting facilities, municipalities and literature reveal that in 3 out of 4 countries any type of plastic, regardless whether biodegradable/compostable or not will be identified as “contamination”. Consequently, either the entire incoming waste batch will be rejected, or unwanted products will be removed from the composting stream. In most cases this is executed during a pre-compost sorting process, meaning that potentially compostable items do not even reach the composting cycle. Furthermore, a post-compost sorting process takes place in which over-sized or non-identifiable items are removed. All removed and rejected items are usually sent to landfill or incineration for energy recovery.

Even more disillusioning is the fact that active composting cycle durations are most commonly not longer than 3-10 weeks. This is somewhat contradictory to the European standard EN13432 of industrial composting, in which 12 weeks are defined as the time period after which a maximum of 10% of the original dry weight of the product may be remaining, as was described in 2.3.2. In other words, currently, industrial composting plants do not provide adequate conditions to ensure complete decomposition. This essentially means, if - in the rare occasion - items do enter the composting cycle, the probability that they do not degrade entirely is very high, in which case residues would be removed during the post-composting process and sent to landfill or incineration. Since compostable materials claim their compostability based on the European standard, it is not to be expected that they degrade in less time than is necessary for the certification. The only material of those considered which explicitly indicates decomposition within 42 days are the two cellulose-based films from repaq.

The mere country amongst those reviewed, which demonstrates both acceptance of compostable plastics as well as cycle durations long enough for effective decomposition, is France. However, as was mentioned by in Burgstaller et al. (2018) compostables rarely find their way into organic waste bins. Instead they are disposed of through regular waste or plastic waste, which equally minimizes the likelihood of it being composted.

Similarly devasting are the outlooks for the recycling opportunities of bioplastics: none of the observed countries have designated recycling streams for biodegradable/compostable plastics in place.

Table 16 summarizes the consequential prediction on the countries’ waste infrastructure compatibility with the intended EoL scenarios of bio-plastics.

Table 16. Country-specific EoL scenario compatibility

Country	*Composting compatibility*	*Recycling compatibility*
Germany	×	×
Netherlands	×	×
France	(✓)	×
UK	×	×

Concluding from the EoL analysis, the likelihood of effective composting of a packaging film in a composting facility appears to be very small.

Furthermore, despite the materials being certified as compostable any type of plastic is commonly considered as a risk of contamination for the compost and more often than never simply do not match the composting plants cycle times.

On top of that, researchers from Plymouth University recently published a study in which they examined the degradation behavior of biodegradable, compostable, oxo-biodegradable and conventional HDPE in different natural environments. The materials were exposed to open-air, soil or marine conditions. While compostable materials disintegrated in marine conditions within 3 months, the same bag was still entirely existent after 27 months in soil. Overall results revealed that none of the materials exhibited reliable decomposition over a period of 3 years in all observed environmental conditions (Napper and Thompson, 2019).

Equally there are no recycling possibilities for biodegradable/compostable materials. This is at least the present status of waste management and facility infrastructure, which does not rule out that the situation will change in the following years. In fact, the technological feasibility and hence the potential for the implementation of designated recycling streams has been frequently exclaimed, provided that the volumes of circulating bio-based recyclables increase to an extent that implementation of according technology and infrastructure becomes more economical. Similarly, the adaptation of composting plants to be able to handle compostable materials is technologically already feasible and certainly conceivable.

According to a recently published study by the European Commission (2019) bio-based plastics account for less than 1% of the market. Due to such little amount as well as rare knowledge amongst consumers of how to properly dispose it, bio-based products, are most likely to follow fossil-based counterparts in general waste bins.

In that context, the remaining question is, who needs to initiate such change in the first place: the waste infrastructure by starting to provide suitable composting conditions and adapted recycling streams or the industry by bringing compostable materials into circulation to pressurize the waste management to follow up. So far, industrial composting facilities have been very reluctant towards the acceptance of any type of plastic, because they are scared, that once they accept compostable plastic, they will also receive non-compostable plastics in their waste. (Kappel, 2019)

At the same time, it cannot explicitly be concluded that recycling of a recyclable material is guaranteed. Even though the claimed average European recycling rate of plastic packaging waste was discovered to be surprisingly high, and in fact higher than the average composting rate, it is not meaningful enough to conclude that a recyclable material is the perfect option. This is especially true in the context of *food* packaging and when considering *films* as opposed to rigid: food contamination and film characteristic are both factors which significantly reduce the likelihood of being recycled. (Kappel, 2019; Molenveld et al., 2015) According to recycling specifications by Der Grüne Punkt (2018), e.g. a plastic film may not contain more than 4%wt of organic waste contamination, to be eligible for recycling. Chances that food packaging is contaminated to such extent, hence becomes non-recyclable, certainly exist.

Yet, considering the low likelihood of effective composting, recycling can be concluded to be a more probable EoL to be reached, as long as the material has high chances for recyclability (not exceeding the contamination threshold). Following this, BioPE, as being the only recyclable material in existing streams, gained a preferred status compared to the others.

4.4 Development of material candidate recommendation

Overall, the results revealed that current HelloFresh SC conditions are not as beneficial to the applicability of bio-based polymers packaging as was initially expected. Despite BAK and HERB exerting product characteristics that could theoretically benefit especially lower water vapor barriers, logistical and procurement strategies at HelloFresh require prolonged shelf lives that are only achievable with the considered bio-based materials to a certain extent.

The question whether or not the applicability of bio-based polymers is a realistic solution towards more sustainable packaging, remains questionable. Judging from the conducted BoL scenario, bio-based polymers outperform conventional plastics, yet the effective impact depends heavily on the development of the waste infrastructure and the possible EoL scenarios. According to European Commission (2019) "[…]*The influence is especially significant for climate change impact: with the intended EoL, the bio-based products on average could offer more than 65% of the GHG emissions savings, instead of 14% in the baseline, compared to their petrochemical counterparts. This indicates the great potential of low carbon bio-based products if the EoL waste management are implemented appropriately"* Yet, the disposal compatibility of bio-based materials with the current waste management situation seems unpromising. While the intentions and the required technology for both adequate composting and recycling of compostables does exist, sufficient amount of certified compostable materials in the waste streams is missing to ensure economic sustainability. Similarly, clear communication with consumers, indicating which "plastics" are allowed in organic wastes bins and which not, is crucial to assure composting plant operators that they receive uncontaminated organic waste on an unconditional basis.

Considering the unlikely scenario of bio-based packaging waste being either composted or recycled in designated streams, one needs to work with the options that are currently available. In that sense, recyclability in existing recycling streams appears to be the preferred material characteristic. On the contrary one has the arguments, that packaging film, which is most likely contaminated with food residues, is rarely effectively recycled, in which case compostability can be seen as a preferred characteristic, as it will at least enable faster decomposition in landfill compared to conventional. However, in landfill, compostable material is exposed to anaerobic digestion resulting in emissions of methane, which is a more potent greenhouse gas compared to CO_2.

Table 17 gives a summarizing overview over the material evaluation.

Following all arguments, the following material preference recommendation has been developed for HelloFresh, which indicates how far the considered materials are applicable for the company and which is considered to be the most sustainable choice at the current stage (Figure 29). The preference development also took into consideration the results from the general material comparison (4.1).

Table 17. Summarizing material evaluation

Material type and name		*Product protection*	*BoL*		*EoL*
		Product-material compatibility	*GWP and CED*	*BUE*	*Likelihood for intended EoL scenario*
Starch	***Biotec Bioplast 106/02***	HERB	+ +	+ + +	-
Cellulose	***Futamura NatureFlex NVS***	HERB	+	+ + +	+
	Futamura NatureFlex NK	BAK HERB SPI			
	Repaq 45	BAK HERB SPI			
	Repaq 19	HERB			
PLA	***Taghleef Industries Nativia NTSS***	HERB	+ +	+ +	-
	Floreon 400	HERB			
PHA	***Yield10 Mirel PHA P5001***	-	+ + +	-	-
	Bio-On Minerv PHA	-			
BioPE	***Braskem I'm Green PE***	HERB (BAK)	+ + +	-	+ +
BioPBS	***PTTMCC BioPBS FD92***	(HERB)	-	+ +	-

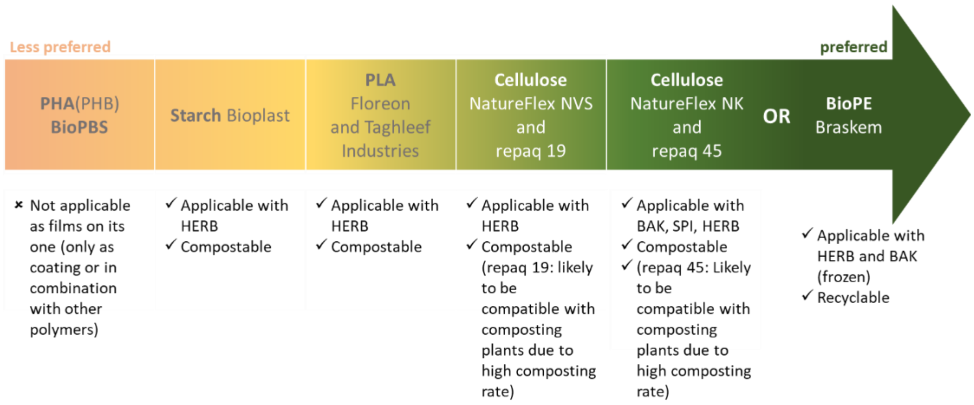

Figure 29. Material candidate recommendation scheme

Changes in the supply chain as well as developments towards improved material properties can considerably broaden the material applicability in the future.

Along the process of this thesis it was also realized that primary packaging should not be the only focal point of interest when trying to achieve sustainability goals within HelloFresh. A side study was conducted which revealed that all primary packaging accounts for only 13wt% of the total packaging amount of one meal-kit box. Primary packaging carries high responsibility in product protection, thus require high performance materials to avoid food loss and subsequently raise the overall environmental impacts. Instead of tackling the sustainability issue from that angle, it is advised to investigate into other areas of packaging and logistics, such as optimization of secondary packaging, storage efficiency or the possibilities of a return system. Regardless of what is being done, it is crucial to communicate the changes and resulting consequences with consumers in order to reduce consumer discontent.

5 Conclusions and recommendations for future research

In this chapter, the research questions are answered to conclude the study. Furthermore, recommendations for future research opportunities are elaborated.

The study was conducted to answer the following two research questions:

1. *In how far are bio-based packaging films applicable for food packaging in the meal kit industry context?*
2. *In how far does the application of bio-based materials in the meal kit context contribute to a more sustainable packaging approach?*

Regarding research question 1:

The study identified a variety of food-grade, bio-based packaging films available on the European market. It proved that bio-based films exert overall weaker barrier properties compared to conventional plastics.

Contrary to expectations, the study revealed that SC conditions at HelloFresh do not allow just-in-time delivery for every product category. The required shelf lives for the considered categories were found to be 30 days for BAK, 8-10 days for HERB and 12-18 months for SPI.

The following product-material compatibility was concluded: HERB category is predicted to be compatible with all considered materials, except BioPBS and PHA(PHB), while the selection of potential material candidates for BAK and SPI is limited to Cellulose repaq 45 and Cellulose NK. Additionally, Braskem BioPE is expected to be applicable for BAK, provided that BAK products are stored at frozen conditions for the majority of the supply chain duration. Practical shelf life tests need to be conducted to verify the predictions.

Regarding research question 2:

The BoL analysis has shown that BioPE, PHA(PHB), starch-based polymers and PLA outperform fossil-based counterparts in terms of GWP and CED. In terms of

BUE however, starch and cellulose perform best amongst their bio-based competitors.

Concerning the EoL perspective, industrial composting proved to be an unlikely scenario in Germany, the Netherlands, France and the UK. Similarly, no recycling streams designated for biodegradable/compostable materials exist. Furthermore, average composting rate of biowaste is 10-15% lower than the claimed recycling rates of post-consumer plastic packaging waste.

Concluding from that, *recyclability* in existing recycling streams is suggested to be a more favored material feature as opposed to *compostability*. Nevertheless, considering the product being a packaging *film* which is likely to be *contaminated with food*, the likelihood of recyclability is also reduced in this case.

Overall, it has been concluded that a bio-based material which exhibits both a considerably lower BoL environmental impact and a realistic intended EoL option has the highest potential to contribute to a more sustainable packaging approach.

Considering all aspects, Cellulose repaq 45 or NatureFlex NK are recommended as a compostable option and Braskem GreenPE as a recyclable packaging material.

Future research recommendations

The developed recommendations during the study were derived from a mere theoretical approach. Practical shelf life test and sensory evaluation of products after storage are highly recommended to confirm the predictions. This should include frozen storage of BAK products. Besides, the was restricted by some delimitations. To extend the study, the following research recommendations are worth investigating:

- Material applicability with **other food products**
- Bio-based **rigid** packaging options, paper **coatings** and **metallized** or **$SiOx_2$** coated films, which are worth investigating.
- Comparison to **paper** packaging
- Material **compatibility** with the **packaging and production processes/technologies**
- A **price comparison** of the materials could add further value to the given recommendations and are most likely of interest for any kind of industry

In terms of bio-based material development, more research ought to be put into **how** to make the **materials** more **compatible**/identifiable in **mechanical-optical sorting technology**, e.g. visual marking or labelling of compostable plastics.

Apart from further investigating the bio-based material applicability for primary packaging, it is also recommended to explore other ways of approaching a more sustainable packaging future. For example, it is advised to study potential optimization of the secondary packaging, e.g. improving volume and weight efficiency or optimizing the use of cooling elements in the insulation pouch. Further, opportunities for recyclable and/or recycled materials should be investigated. Another thought which should also be thoroughly considered is the potential implementation of a return system, at least for certain packaging elements such as the cool pouch or cooling elements.

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Appendix A Bio-based Polymers

A.1 General bio-based material characterization

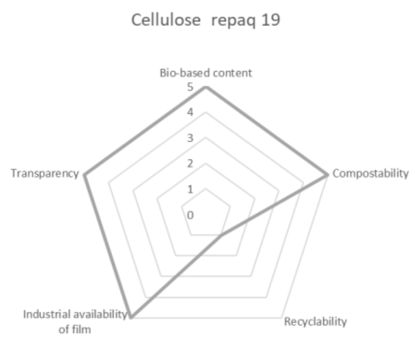
Material type	***Supplier & Material name***	***Film available***	***Biobased content of film***	***Biodegradability***	***Recyclability***	***Transparency***	***Applicable for***	***Other properties***	***References***
Starch	***Biotec Bioplast 106/02***	✓	~30%	✓H+I	×	Opaque or white	Grocery bags	resistant to oil/grease (Khwaldia 2010)	(Biotec, 2019; Khwaldia et al., 2010; M. Moeyersons, 2019)
Cellulose	***Futamura NatureFlex NVS***	✓	96%	✓H+I+M	×	Transparent and glossy	Fresh produce, bakery	Cellulose has quickest biodegradation rate Semi-permeable (moisture), good anti-mist, exc. Gas and aroma barrier, resistant to oil/grease	(Futamura, 2019b, 2019a; Markey, 2019)
	Futamura NatureFlex NK	✓	90%	✓H+I+M	×	Transparent and glossy		Incorporated PVdC layer for high-barrier properties, excellent aroma barrier, resistant to oil/grease	

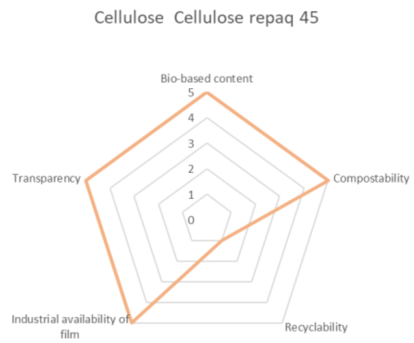
	Repaq 45	✓	99%	✓H+I	✗	Transparent and glossy	Dry, less respiring products	Compostable within 42 days, good moisture barrier, resistant to oil/grease	(Repaq, n.d.; Seevers, 2019)
	Repaq 19	✓	99%	✓H+I	✗	Transparent and glossy	Fresh produce, bakery	Compostable within 42 days, resistant to oil/grease	
PLA	***Taghleef Industries Nativia NTSS***	✓	Up to 100%	✓I	✓ in special streams	Transparent	-	High stiffness, brittle, thermally instable, good O2 barrier, excellent moisture transmission, resistant to oil/fat	(Dragun, 2019; Taghleef Industries, 2019)
	Floreon 400	✓	(50-)90%	✓ (H+)I	✓ in special streams	Transparent	Fresh produce, meat, bread	Home compostable grade is still at very early dev. Stage, more flexible than other PLAs, processable at higher temperatures, resistant to oil/fat	(Floreon, 2019; Staines & Gill, 2019)
PHA	***Yield10 Mirel P5001***	(✓)	77%	✓H+I	✓ in special streams	Transparent	So far **only applicable as performance additive for PLA or PVC**, then for cereals, Bakery, Fresh produce, frozen	Similar to PP, good moisture and aroma barrier, highly brittle, potentially marine degradable, improves mechanical properties of PLA, low oil/fat resistance	(Haftka, 2012; Koller, 2014)
	Bio-On Minerv PHA	(✓)	-	✓H+I+M	✓ in special streams	Transparent	So far **only applicable as performance additive for PLA**		(Bio-on.it, 2019)
BioPE	***Braskem I'm Green PE***	✓	79-85%	✗	✓	Transparent	Same applicability as conventional PE	identical properties to conventional PE, slightly opaque, resistant to oil/fat	(Clemesha, 2019; Plasticoverde - Braskem, n.d.)
BioPBS	***PTTMCC FD92***	✓	35-51%	✓H+I+M	✗	Transparent	Mulching film, bag liners, coating	Far from industrial scale, more flexible and more heat resistant compared to PLA	(PTTMCC, 2017, 2019)

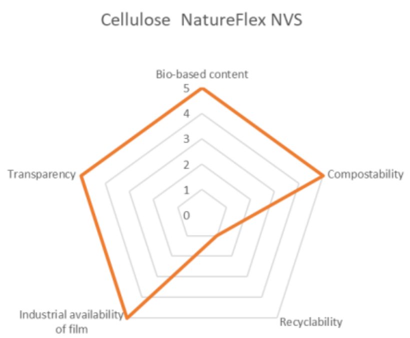
A.2 Scoring results of material characterization

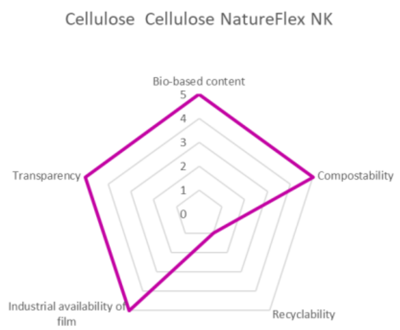
Material type	*Material*	*bio-based content*	*compostability*	*recyclability*	*industrial availability of film*	*transparency*
Starch	***Biotec Bioplast 106/02***	2	5	1	5	2
Cellulose	***Futamura NatureFlex NVS***	5	5	1	5	5
	Futamura NatureFlex NK	5	5	1	5	5
	Repaq 45	5	5	1	5	5
	Repaq 19	5	5	1	5	5
PLA	***Taghleef Industries Nativia***	5	3	3	5	3
	Floreon 400	5	5	3	5	3
PHA	***Yield10 Mirel P5001***	4	3	3	1	4
BioPE	***Braskem I'm Green PE***	5	1	5	5	4
BioPBS	***PTTMCC FD92***	3	5	1	1	4

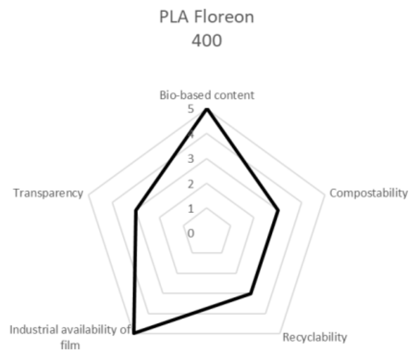
A.3 Individual spider diagrams

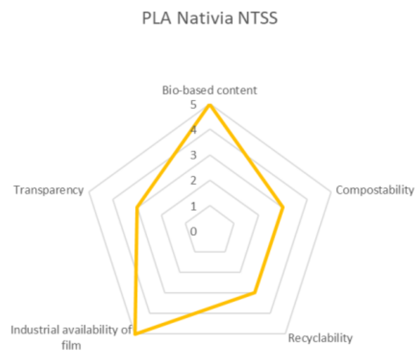


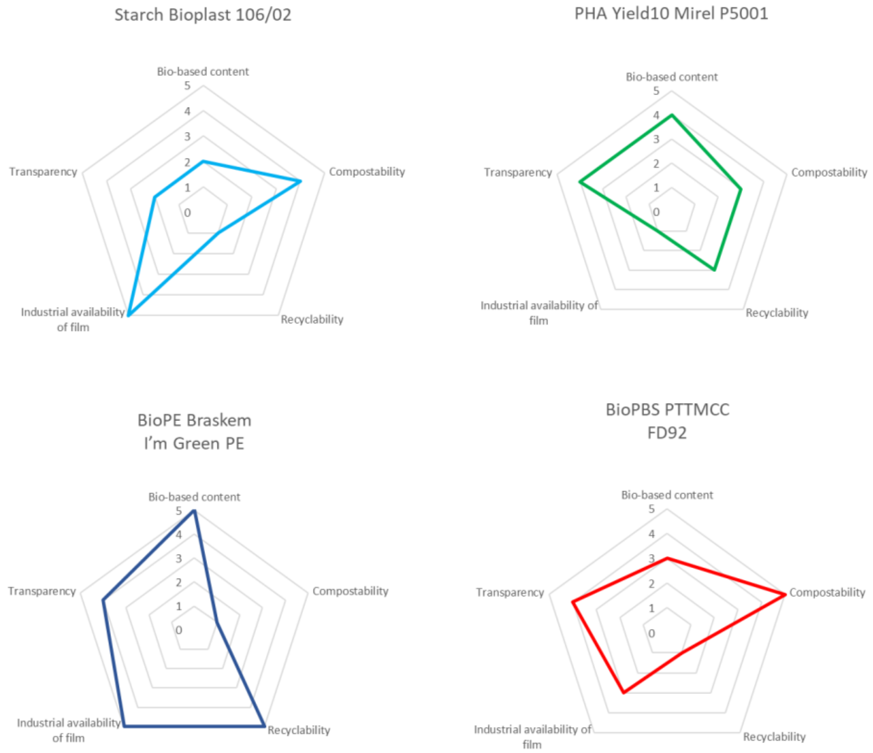











Starch Bioplast 106/02
Bio-based content
Compostability
Recyclability
Industrial availability of film
Transparency
0
1
2
3
4
5
PHA Yield10 Mirel P5001
Bio-based content
Compostability
Recyclability
Industrial availability of film
Transparency
0
1
2
3
4
5
BioPE Braskem I'm Green PE
Bio-based content
Compostability
Recyclability
Industrial availability of film
Transparency
0
1
2
3
4
5
BioPBS PTTMCC FD92
Bio-based content
Compostability
Recyclability
Industrial availability of film
Transparency
0
1
2
3
4
5

A.4 Technical characteristics

Material type	***Supplier & Material name***	***Thickness [µm]***	***OTR [cm3/m2*day]***	***WVTR [g/m2*day]***	***Heat-sealability***	***Printability***
Starch	***Biotec Bioplast 160/02***	80,0	750 23°C, 0% RH	120 38°C, 90% RH	✓	✓
Cellulose	***Futamura NatureFlex NVS***	23,3	5,0 23°C, 50% RH	600,0 38°C, 90% RH	✓	✓
	Futamura NatureFlex NK	45,0	5,0 23°C, 50% RH	20,0 38°C, 90% RH	✓	✓
	Repaq 45	45,0	5,0 23°C, 50% RH	5,0 23°C, 85% RH	✓	✓
	Repaq 19	19,0	10,0 23°C, 50% RH	200,0 23°C, 85% RH	✓	✓
PLA	***Taghleef Industries Nativia NTSS***	25,0	900,0 23°C, 0% RH	270,0 38°C, 90% RH	✓	✓
	Floreon 400	25,0	675,0 n.a.	375,0 n.a.	✓	✓
PHA	***Yield10 Mirel P5001***	n.a.	n.a.	n.a.	n.a.	n.a.
	Bio-On Minerv PHA	n.a.	n.a.	n.a.	n.a.	n.a.
BioPE	***Braskem I'm Green PE***	40,0	6000,0 23°C, 0-50% RH	2,0 23°C, 85% RH	✓	✓
BioPBS	***PTTMCC FD92***	20,0	2040,0 23°C, 0% RH	1050,0 38°C, 90% RH	✓	n.a.

Appendix B Conventional polymers

B.1 Barrier properties of fossil-based polymers

All values were derived from Schmid et al. (2012).

Fossil-based Polymer	***Thickness [µm]***	***OTR [cm3/m2*day]*** 23°C, 0-50% RH	***WVTR [g/m2*day]*** 23°C, 85% RH
HDPE	100	600,0	0,4
PP	100	600,0	0,6
BOPP	100	300,0	0,3
LDPE	100	1100,0	1,0
EVOH	100	0,1	2,0
PET	100	10,5	2,0
PVDC	100	0,6	0,2

Appendix C Product – Material Compatibility

C.1 Categorized barrier properties including light and oil barrier

Material type	*Supplier & Material name*	*Oxygen barrier*	*Water vapor barrier*	*Light barrier*	*Oil barrier*
Starch	***Biotec Bioplast 160/02***	Low	Low	Medium	yes
Cellulose	***Futamura NatureFlex NVS***	high	low	Low	yes
	Futamura NatureFlex NK	High	Medium	Low	yes
	Repaq 45	High	High	Low	yes
	Repaq 19	Medium	Low	Low	yes
PLA	***Taghleef Industries Nativia NTSS***	Low	Low	Low	yes
	Floreon 400	Low	Low	Low	yes
BioPE	***Braskem I'm Green PE***	Low	High	Medium	yes
BioPBS	***PTTMCC FD92***	Low	Low	Low	yes

C.2 Tabularized compatibility of product-material system with HF supply chain

Material type	*Supplier & Material name*	*Supply chain Compatibility*
Starch	***Biotec Bioplast 160/02***	BAK HERB SPI
Cellulose	***Futamura NatureFlex NVS***	BAK HERB SPI
	Futamura NatureFlex NK	BAK HERB SPI
	Repaq 45	BAK HERB SPI
	Repaq 19	BAK HERB SPI
PLA	***Taghleef Industries Nativia NTSS***	BAK HERB SPI
	Floreon 400	BAK HERB SPI
BioPE	***Braskem I'm Green PE***	(BAK) HERB SPI
BioPBS	***PTTMCC FD92***	(BAK) (HERB) (SPI)

C.3 Norner output values

BAK package

Material	Thickness µm	WVTR [g/m2*day)]	TR/day [ml/(package*day)]	WV transmission after 30 days [ml/package]	OTR [cm3/m2*day]	TR/day [ml/(package*day)]	Oxygen transmission after 30 days [ml/package]
Starch Bioplast 106/02	80,0	120,0	0,612	18,36	750,0	265,781	7973,438
Cellulose NatureFlex NVS	23,3	600,0	10,514	315,42	5,0	6,084	182,52
Cellulose NatureFlex NK	45,0	20,0	0,181	5,43	5,0	3,15	94,5
Cellulose repaq 19	19,0	200,0	4,298	128,94	10,0	14,921	447,63
Cellulose repaq 45	45,0	5,0	0,045	1,35	5,0	3,15	94,5
PLA Taghleef Industries	25,0	270,0	4,41	132,3	900,0	1020,6	30618
PLA Floreon400	25,0	375,0	6,124	183,72	675,0	765,45	22963,5
Braskem I'm Green PE	40,0	2,0	0,02	0,6	6000,0	4252,5	127575

BioPBS PTTMCC FD92	20,0	1050,0	21,435	643,05	2040,0	2891,7	86751
PA/EVOH/PE	80,0	4,0	0,02	0,6	2,5	0,886	26,58
-	25,0	100,0	1,633	48,995	5,0	5,67	170,1

HERB package

Material	***Thickness*** ***µm***	***WVTR*** ***[g//m2*day]***	***WVT [ml/(package] after day*** ***0***	***4***	***6***	***10***	***OTR*** ***[cm3/m2 *day]***	***TR/day*** ***[ml/(package*day)]***	***Transmission after 10 days*** ***[ml/package]***
Starch Bioplast 106/02	80,0	120,0	0	1,901	2,57	4,471	750,0	151,2	1512
Cellulose NatureFlex NVS	23,3	600,0	0	32,642	68,53	101,172	5,0	3,461	34,61
Cellulose NatureFlex NK	45,0	20,0	0	0,563	1,183	1,746	5,0	1,792	17,92
Cellulose repaq 19	19,0	200,0	0	13,343	28,013	41,356	10,0	8,488	84,88
Cellulose repaq 45	45,0	**5,0**	0	0,141	0,296	0,437	5,0	1,792	3,58
PLA Taghleef Industries	25,0	270,0	0	13,69	28,741	42,432	900,0	580,608	5806,08
PLA Floreon400	25,0	375,0	0	19,014	39,919	58,933	675,0	435,456	4354,56

Braskem I'm Green PE	40,0	**2,0**	0	0,063	0,133	0,196	6000,0	2419,2	24192
BioPBS PTTMCC FD92	20,0	1050,0	0	66,549	139,715	206,265	2040,0	1645,056	16450,56
Reference CPP	25,0	2,7	0	0,137	0,287	0,424	2500,0	1612,8	16128
Standard	25,0	1050	165,012	165,012	165,012	165,012	6000	3870	38700

SPI package

	Thickness	***WVTR***	***WVTR/day***	***WV Transmission after 360 days***	***OTR***	***OTR/day***	***Oxygen Transmission after 360 days***
Material	***µm***	***[g/m2*day]***	***[ml/(package*day)]***	***[ml/package]***	***[cm3/m2*day]***	***[ml/(package*day)]***	***[ml/package]***
Starch Bioplast 106/02	80,0	120,0	0,068	24,48	750,0	9,844	3543,84
Cellulose NatureFlex NVS	23,3	600,0	1,168	420,48	5,0	0,225	81
Cellulose NatureFlex NK	45,0	20,0	0,02	7,2	5,0	0,117	42,12
Cellulose repaq 19	19,0	200,0	0,478	172,08	10,0	0,553	199,08
Cellulose repaq 45	45,0	5,0	0,005	1,8	5,0	0,117	42,12
PLA Taghleef Industries	25,0	270,0	0,49	176,4	900,0	37,8	13608
PLA Floreon400	25,0	375,0	0,68	244,8	675,0	28,35	10206
Braskem I'm Green PE	40,0	2,0	0,002	0,72	6000,0	157,5	56700

BioPBS PTTMCC FD92	20,0	1050,0	2,382	857,52	2040,0	107,1	38556
Reference Paper/LDPE/EVOH	40,0	2,0	0,002	0,72	2,5	0,066	23,76
Standard	45,0	20,0	0,02	7,2	5	0,117	42,12

Appendix D LCA data

D.1 GWP

			bio-based						***fossil-based***		
Reference	***Resource***	***Incl. biogenic carbon***	***Starch-based***	***Cellulose-based***	***PLA***	***PHA (PHB)***	***BioPE***	***BioPBS***	***PE***	***PP***	***PET***
Kurdikar et al. (2000)	Corn stover	yes				-3,2					
Vink et al. (2003)	Corn stover	yes			-0,3						
Vink et al. (2003)	Corn stover	yes			-1,7						
Akiyama et al. (2003)	Corn	yes				0,3					
Yokosuka et al. (2004)	Corn	yes			5,0						
Bohlmann (2004)	Corn	yes			0,7						
Kim and Dale (2005)	Corn	yes				1,7					
Kim and Dale (2005)	Corn	yes				-1,2					
Vink et al. (2007)	Corn	yes			2,0						
Vidal et al. (2007)	Corn	yes			1,8						

Harding et al. (2007)	Sugarcane	yes				2,6					
Kim and Dale (2008)	Corn	yes				-2,3					
Yu and Chen (2008)	Corn-Glucose	yes				0,5					
Vink et al. (2010)	Corn	yes			0,8						
Vink et al. (2010)	Corn	yes			1,3						
Petchprayul et al. (2012)	Cassava	yes			1,8						
Petchprayul et al. (2012)	Sugarcane	yes						5,4			
Chen and Patel (2012)	Sugarcane	yes					-2,1				
Novamont (2012)	Corn	yes	0,9								
Ziem et al. (2013)	Sugarcane	yes					-2,2				
Tsiropoulos et al. (2015)	Sugarcane	yes					0,8				
Vink and Davies (2015)	Corn	yes			0,6						
Braskem (2017)	Sugarcane	yes					-3,1		1,9		
Futamura (2018)	Fossil	yes								3,3	5,6
Natureflex (2010)	Wood pulp	yes		3,7							
Average GWP			0,9	3,7	1,2	-0,2	-1,6	5,4	1,9	3,3	5,6

All values were retrieved from Spierling et al. (2018); Futamura, (2018); NatureFlex (2010); Plasticoverde - Braskem (2017); Tsiropoulos et al. (2014)

D.2 CED

		bio-based						fossil-based		
Reference	***Incl. biogenic carbon***	**Starch-based**	**Cellulose-based**	**PLA**	**PHA (PHB)**	**BioPE**	**BioPBS**	**PE**	**PP**	**PET**
Kim and Dale (2008)	yes				1,1					
Novamont (2012)	yes	39,8								
Chen and Patel (2012)	yes						65			
Vink and Davies (2015)	yes			40,1						
Braskem (2017)	yes					2,3		90,7		
Futamura (2018)	yes		78						70,2	69
Average CED		39,8	78	40,1	1,1	2,3	65	90,7	70,2	69

All values were retrieved from Spierling et al. (2018); Futamura, (2018); Plasticoverde - Braskem (2017).