The relation between food shelf-life and environmental impact of different plastic packaging alternatives

In collaboration with Orkla Foods

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MASTER THESIS

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Abstract

The attention to the environmental impact of plastics materials used in food packaging has produced several studies in the last decade and consumers have started wondering about the utility and the functions of food packaging. In fact, the use and the production of plastic polymers cause pollution due to the disposal and to the CO_2 emission. Besides that, even if new polymers from organic and biological sources are deeply studied, plastics remain the most widely used food packaging materials. With this background, it is clear how much important is to investigate both the environmental impact and the performances of the food plastic packaging. Hence, the aim of this Master Thesis is, using a simplified LCA, to compare the environmental impact of the plastic packaging production of a set of 23 products with their barrier properties. Comparing these two packaging characteristics, it is also possible to evaluate the length of the shelf-life of the food products categorizing the sample depending on different types of materials and storage temperature. The results show that can be a dependence between barrier properties parameters, type of materials and type of products but, it emerged also, that to have a complete evaluation of the environmental impact of a packaging solution it is necessary to include and to consider the entire supply chain and the requirements of both packaging materials and the food products. This study has been considered useful by the company collaborating, Orkla Foods. It contributes to screen an heterogenous sample of products and to highlight the best performant packaging solutions in comparison with the environmental impact. It has been demonstrated that the methodology and the parameters chosen for the analysis are suitable and which application could be interesting both in the academia and in industry fields.

Keywords: barrier properties, evaluation of environmental impact, food packaging, plastics materials, simplified LCA.

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List of Abbreviation

APET Polyethylene terephthalate Amorphous

CO_2 Carbon-di-oxide

EN European Norm

EU European Union

EVOH ethylene-vinyl alcohol

GHG Greenhouse Gase

GTR Gas Transmission Rate

GWP Global Warming Potential

HIPS High Impact Polystyrene

ISO International Organization for Standardization

KP Coefficient of Permeability

LCA Life Cycle Assessment

LCI Life Cycle Inventory

LCIA Life Cycle Inventory Assessment

N_2O Nitrous Oxide

OPS Oriented polystyrene

OTR Oxygen Transmission Rate

P Permeance

PA Polyamide

PA6 Polyamide 6

PE Polyethylene

PET Polyethylene terephthalate

PP Polypropylene

PS Polystyrene

PVOH Polyvinyl alcohol

SDGs Sustainable Development Goals

STEPS Sustainable Plastic and Transition Pathways

UN United Nations

UNI Ente Italiano di Normazione

WP3 Work Package 3

WVTR Water Vapour Transmission Rate

1 Introduction

The introduction presents the background, the purpose and the scope of this project. A brief description of the company is given. Finally, the outline of this project is presented.

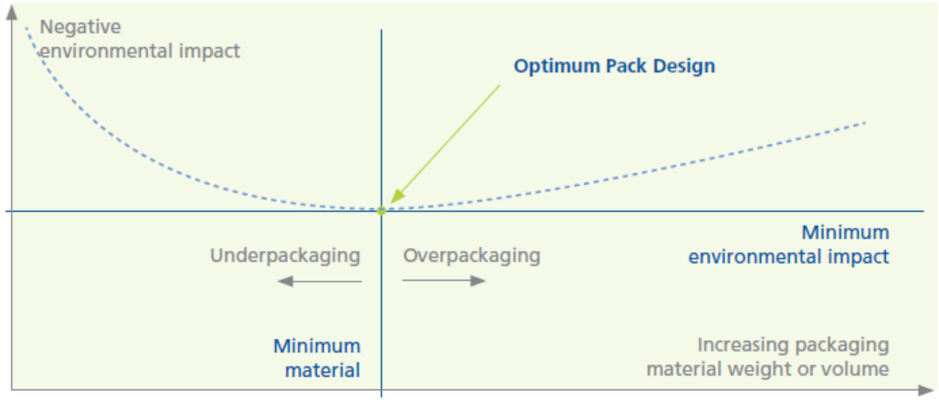
Since 1963 when Giulio Natta and Karl Zieger won the Chemistry Nobel Prize due to the plastic invention, this category of polymers become ubiquitous due to their extraordinary properties: they are inexpensive, lightweight, durable and adaptable materials. Thanks to these characteristics, in 2018 plastic production reached 359 million tons of which 61 million tons produced in Europe where packaging segment demands almost the 40% of plastic. (PlasticEurope, 2019).

But, the use of plastic has never been so controversial as during the last decades.
In fact, from a food safety point of view, plastic packaging (above all multi-layer materials) offers also barrier properties and performances that guarantee a long shelf life and food protection with a low use of material (Barlow and Morgan, 2013).

On the other side, plastics represent one of the biggest environmental problems of the 21th Century due to the pollution caused by plastic waste and the non-renewable origin of these polymers. And the recyclability, is not always a possible solution.
In fact, as stated in the Facts 2019 of Plastic Europe, in 2018 only 32.5% of the 30 million of tons of collected plastic post-consumer waste was recycled in the European Union. This is due to multiple reasons like the lack of recycling infrastructure, food or chemicals contamination and the use of multi-layer materials that enhance barrier properties but complicates recyclability.

Another important challenge is that, in food packaging, an under-packaging solution (low-performing features) can cause a higher environmental impact than an over-packaging solution.
Packaging, in fact, plays a major role in the protection of food products and thus increases the shelf life reducing food waste. The Innventia AB model (see Figure 1) shows that an extreme packaging reduction produces a negative environmental impact much greater than the one caused by an over-packaging solution (A Global Language for Packaging & Sustainability for the Consumer Goods Forum, 2011).

Figure 1: Innventia AB model – A Global Language for Packaging & Sustainability for the Consumer Goods Forum.



In order to understand this model, it is good to take into account that the food waste can easily contribute to 50% of the Greenhouse Gas (GHG) emissions in a food packaging life-cycle analysis regardless if the packaging solution is biodegradable or not (Dilkes-Hoffman et al., 2018). For this reason, talking only about the advantages of biodegradable materials, without considering the drawback, could be dangerous.

This study analyzes, in the field of the petrol-based plastic, the potential trade-offs between the production environmental impact and the barrier properties of the packaging solutions.

1.1 Background and motivation

This Master Thesis is a part of the research project STEPS (Sustainable Plastics and Transition Pathways). The Division of Packaging Logistics (Department of Design Sciences) is involved in Work Package number 3 (WP3) that focuses on accomplishing the transition towards a sustainable plastic system. In this phase of the project, Packaging Logistics is the leader of task 3.3 called "Smart and efficient use of biobased plastics in food packaging". The objectives of task 3.3 are to develop a model for environmental evaluation of biopolymers for food packaging applications and to examine the trade-off between food protection and environmental impact of different plastics packaging solutions.

The Directive 2018/852 of the European Union tries to decrease the production of packaging waste and "*promotes the reuse, recycling and [...] the transition towards a circular economy"* as written in the document summary of EU Directive 2018/852 "Packaging and packaging waste" (European Law, 2020)

To be specific, to minimize the environmental impact and the production of packaging waste, the European Union tries to use programs and schemes which have the producer and companies' responsibility as aim.

Inside the STEPS project there are some collaborations with companies and stakeholders in the plastics value chain. As an example, this master thesis project has been developed in collaboration with Orkla Foods to explore the relation between barrier properties and environmental impact of plastic packaging.

This collaboration was developed because, for packaging developers in the food industry, it might be useful to evaluate barrier properties and environmental indicators of different packaging solutions in parallel.

Currently, the protection function of packaging materials and the environmental impact of packaging materials are considered separately.

The case of Orkla Foods is just an example about how packaging consumers could evaluate the right packaging solutions with the objective to minimize their environmental impact.

1.2 Project Aim and Objectives

The aim of this Master Thesis is to explore possibilities for an integration of packaging material performance data (barrier properties or provided shelf life) and environmental indicators to support the selection of different plastic materials in the food industry.

Considering the aim and the field of research, this Master Thesis contributes to the goals of the UN 2030 Agenda for Sustainable Development (SDGs). In particular, it connected with SDG number 9, 12 and 17 respectively "Industry, Innovation and Infrastructure", "Responsible Consumption and Production" and "Partnerships for the Goals".

The research objectives of this Master Thesis work are:

- To compare a set of different food packaging solutions from the environmental and barrier performances points of view.
- To evaluate the efficiency of food packaging solutions using as the parameter the shelf-life length.
- To find methodology and parameters that can be used by food industries to lead the green packaging development comparing the environmental impact of the production of plastic packaging materials with their barrier properties.

1.3 Orkla Foods and its sustainable strategy

Orkla is a supplier of branded consumer goods to the grocery, out-of home, specialised retail, pharmacy and bakery sectors. The Nordic and Baltic regions remain the main market region of Orkla but it is widespread also in some Central Europe Countries and in India.

Orkla is divided into different business areas like: Orkla Foods, Orkla Confectionary & Snacks, Orkla Care and Orkla Food Ingredients. Orkla Foods is the biggest business area with a wide range of food products like sauces and flavourings, ready-to-eat dishes, topping, dehydrated casseroles, soups, fish and seafood. The Food business area is widespread in different European Country including Sweden where the company appears in the Swedish food industry as Orkla Foods Sverige AB.

Orkla Foods Sverige's commercial strategy is to collaborate with consumers, suppliers and partners paying attention to sustainability and innovation.

In fact, in the Sustainability Report of 2020 Orkla states that one of the major goals of the company is to create a sustainable growth taking part in the United Nations Sustainable Development achieving in particular to the Sustainable Development Goal number 12 – Sustainable production and consumption. Orkla in 2020 promoted sustainable growth identifying four targets to reach by 2025: decrease the greenhouse using renewable energy and sustainable raw materials, promote a healthier lifestyle and improve safe products trust.

From the packaging sustainability point of view, in the 2020 a lot of improvements have been done: 95 per cent of Orkla's packaging was recyclable, for 47 per cent based on recycled materials. In addition, talking about plastic: 9 per cent of plastic came from both recycled or renewable materials. The 2025 aim is to reach the 75 and 50 per cent of recycled or renewable materials respectively of total packaging and plastic packaging. That will help to reduce the use of the virgin plastic through the supply chain and, as a consequence of the higher demand of recycled plastic, "*accelerate the development of recycling systems"* that, generally speaking, is not advanced enough (Orkla Sustainability Report, 2020).

1.4 Delimitations

To analyse the environmental impacts of different packaging solutions from the portfolio of Orkla Foods, the Carbon Footprint (based on LCA methodology) is the indicator calculated. The approach used builds on LCA methodology but does not involve a complete LCA analysis but it will be developed in a simplified way.

Orkla Foods supplies packaging specifications for a part of its product portfolio and the environmental impact of the packaging materials is analysed in relation to the shelf life of the packed products. The food packaging solutions considered are plastics materials or multi-layers packaging where plastics provide key barriers properties.
Other secondary data are collected using the LCA databases EcoInvent.

Due to COVID-19 global pandemic, the project is conducted entirely on a remote basis and meeting have been organised weekly to ensure the right coordination between other STEPS Thesis Workers.

1.5 Outline of the Thesis

This project is organized in five chapters and presented as:

Chapter 1: Introduction presents the background, the aim and the objective of the project, the company strategy and the delimitations.

Chapter 2: Theoretical Framework describes the more important concepts useful to understand the results.

Chapter 3: Methodology describes how the data have been collected and how the study has been performed.

Chapter 4: Results and Discussion presents the data collected and analyzed following the methodology described in chapter 3 and discusses the results shown.

Chapter 5: Conclusions, Limitations and Recommendations for Future Research interpretate the results, explain the limitations of the project and how to improve future research.

2 Theoretical framework

This chapter presents the theoretical topics useful to understand the study. Firstly, the protection role of the packaging and its barrier properties are presented. Secondly, the evaluation of new packaging solutions considering the LCA methodology are exposed and finally, the performances of plastic materials are evaluated.

2.1 Packaging functions

The word "packaging" means in general the act of covering or wrapping different kind of goods to transport them (Cambridge Dictionary, 2021).
Although, speaking about the Food Packaging needs to be more specific. The functions of food packaging are various and well known:

- Protection: it saves food from biological, physical, chemical and sometimes also climatic impacts;
- Utility: packaging makes the products easier to use, to contain, to handle, to store and to transport;
- Communication: it gives information to the consumers and provides also some legal and commercial demands;

At the same time, the food packaging industry has an important role for the reduction of the food waste (Quested et al., 2011). There are food losses in the entire food chain, from agriculture to consumer (Kader, 2005), but, as shown in the FUSION EU report (Stenmarck et al.,2016), in the 2012 about 53% of the food waste is generated by the consumer.
A cause of this loss could be a non-efficient shape of the pack that could be difficult to empty and can generate around 3-10% of product left in the packaging (Johansson, 2002). Williams et al., in 2012 through a Swedish household study found that the amount of food waste is around 20 or 25% just because the packaging solutions are both too large or their shape makes the package difficult to empty.
Another cause of the food waste related to the pack could be a non-efficient packaging solution in terms of both type and quantity of material chosen (Barlow and Morgan, 2013).

Accordingly, as the thesis focuses on the protection function, in the following paragraph a description of the protection role that packaging has as well as a presentation of barrier properties are given.

2.2 Food protection and barrier properties

The protection that packaging gives to the food is the key to shelf life: the enhancement of the protection properties of the food packaging materials causes an extension of the shelf life and guarantees that the product maintains the best quality conditions (aroma, texture, appearance and taste) as long as possible (Stolberg, 2019).
This means also to reduce or minimize the food waste and, as consequence, also the environmental impact of the packaging (Varžinskas et al., 2020).

2.2.1 Permeation Theory

In general, a packed processed food is mostly isolated by all types of physical and biological contaminants present in the ambience but the requirement for most of food products is to avoid the mass transfer of solutes and gas between packaging materials (Han and Scanlon, 2013). This phenomenon is called permeation and does not affect glass or metal but involves plastic and it is strictly correlated to the barrier properties of the material.

The mechanism of gas or vapour permeation through a plastic film can be described with three phenomena: the adsorption, the desorption of the permeates molecules and their diffusion through the package thickness. The permeation phenomenon starts when gases or water vapour molecules dissolve in the film from the side with the higher concentration of the permeates (adsorption), they dissolve though the film matrix and they move to the side with a lower permeate concentration (adsorption).
As in the permeation phenomenon there are a lot of aspects involved it is possible to say that it is influenced by many factors both related to the film (like its structure, the film permeability and the thickness) and to the environment inside and outside the package (like the temperature, the pressure and the concentration gradient across the film) (Siracusa, 2012).

2.2.2 Barrier Properties

Focusing on the film permeability, it is described as the quantification of the amount of permeate molecules that pass through a film (Gaidoš et al., 2000; Pauly, 1999).

For this reason, the permeance is used to evaluate the plastic material barrier properties (Siracusa, 2012).
Barrier properties depend on the chemical structure and the composition of the material and as a consequence, the transfer of molecules ranges from high to low.
Due to the possible negative changes that oxygen and water could bring to the product, in plastic packaging applications, barrier properties regarding these two molecules are calculated in order to predict the shelf-life of the product.
The permeability is expressed like the amount of permeant (volume for gases or mass for Water Vapour) which passes through the plastic matrix, per unit area and time and, in most cases, it needs to be as lowest as possible. It can be also called Oxygen Transmission Rate (cm^3 m^{-2} $24h^{-1}$) or Water Vapour Transmission Rate (g m^{-2} $24h^{-1}$) (Siracusa 2012). It is to be noted that the Transmission Rate parameters need always to be shown with the thickness of the materials they refer to and specifying the pressure between the two sides of the layer. Usually, the GTR (Gas Transmission Rate, OTR if it is specific for the oxygen) is commonly shown in the technical sheets of the packaging suppliers.
Sometimes, to specify the barrier properties, other parameters can be used. If it needs to be considered the amount of the permeant which pass through a unit area of unit thickness, during a unit time caused for a specific temperature and a specific difference of pressure it is called Coefficient of Permeability or KP. Another parameter could be the Permeance or P and it is used when the thickness is not related to a unit dimension but needs to be specified with the results. All the three parameters are connected as the Equation 1.1 shows where $p1$ and $p2$ are the sides partial pressure and l is the thickness of the layer. (Piergiovanni and Limbo, 2010).

$$GTR = P\ (p1 - p2) = \frac{KP}{l} * (p1 - p2) \qquad \text{Equation 1.1}$$

It is clear how the evaluation of the barrier properties of a packaging solution is important to predict the shelf-life of the product (Siracusa, 2012).

2.3 How to develop a packaging solution

Packaging science is a complex universe where, obviously, food is the main character. In fact, starting from the nature of the food and its requirements, the packaging development team tries to design the packaging solution with the best characteristics for that product. Behind the food necessities there are also other important peculiarities to take into account like, for example, the production efficiency, the cost and the environmental impacts of the new packaging solution (Verghese, 2008). In fact, reaching the right balance between the food protection and the material used can increase the system efficiency while decreasing the environmental impact (Wikström et al., 2018).

Regarding the shelf life and the food requirements, the most important phenomenon to predict is the permeation to gas and water vapor of the material chosen. This because water and O_2 are the most relevant elements for the shelf life. To predict which material and which shape should be chosen for the new solution, models and mathematical equations can be used (Piergiovanni and Limbo, 2010).

From the environmental point of view, the packaging development team has also to consider the environmental impact that the new pack has from production until the end-of-life. Examples of negative environmental impacts that a packaging can have at each stage of the packaging chain (James et al., 2005) are:

- Use and consumption of resources (materials and energy) non-renewable
- Air pollution caused by the production and the transport
- Generation of solid waste

Sometimes, as stated before, packaging is also responsible for food waste at the later stages of the food supply chain, both in storage and retail as well as at home. Two aspects dominate the household's food waste related to packaging: too big packages and difficult to empty (Williams et al., 2012).

Despite of this, it is important to remember that food packaging can also have a positive environmental effect (Williams et al., 2012). In fact, due to its ability to protect food from spoilage, microbial contaminations, oxygen and humidity, it helps to reduce food waste (Gutierrez et al., 2017; Conte et al., 2015).

Accordingly, the food packaging industry has to consider a lot of aspects during the designing phase of a new package: from the food safety point of view up to the reduction of the environmental impact in the food chain (Williams and Wikström, 2011). That is to say that there are three main aspects to achieve the sustainability of food packaging: reducing CO_2 emission using recycled materials or renewable resources, choosing energy-efficient processes and improving the waste management level keeping the attention on the food quality and the shelf-life extension (Peelman et al., 2013).

2.4 Evaluation of the emission

The type of environmental impact considered in this project is the greenhouse gas emissions (GHG) due to the production of the polymers. The air pollution due to carbon dioxide (CO_2) and other greenhouse gases (like N_2O emission) is the main responsible for the Global Warming known also as greenhouse effect due to the warming of both Earth's surface and the lower atmosphere layer. The mayor index to estimate the impact of the greenhouse gases is the Global Warming Potential (GWP) used to quantify how the greenhouse gas heats the atmosphere (Amoo and Flagbenle, 2020).

Based on this context, the food packaging industry needs tools to develop packaging solutions that reduce the total environmental impact (Molina and Pålsson, 2018) always looking at the requirements of the food packaged (Barlow and Morgan, 2013).

Having a total view of the End-of-Life both of the food and the package product, helps to create a more efficient solution in terms of food waste, package waste, GHG emissions and energy demand during production and logistic phases.
It is easy to understand that sometimes, the aim is to find a new packaging solution that helps to reduce the environmental impact and the food losses. Although, in other cases, it could be necessary to increase the environmental impact of the packaging to reduce food losses. This balance has to be calculated to reduce the total environmental impact of the food packaging system (Wikström and Williams, 2010).

In particular, the environmental impact of food packaging can be direct or indirect. The direct impact of food packaging considers the production and the End-of-Life of the packaging materials used in the product's life cycle, whereas the indirect environmental impact of packaging refers to how the packaging influences the life of the food products (Molina-Besch et al., 2018).

To conduct an in-depth environmental analysis of a product, Life Cycle Assessment (LCA) is the methodology most accepted and most used in many fields to calculate the impact of that product in its life cycle (Ingarao et al., 2017).

2.4.1 Life Cycle Assessment

Life cycle assessment (LCA) is a methodological tool used worldwide to calculate the environmental impacts of all the steps of a product's life-cycle. It includes acquisition, production, distribution, use and disposal of a product and its raw materials (UNI EN ISO 14040, 2006).

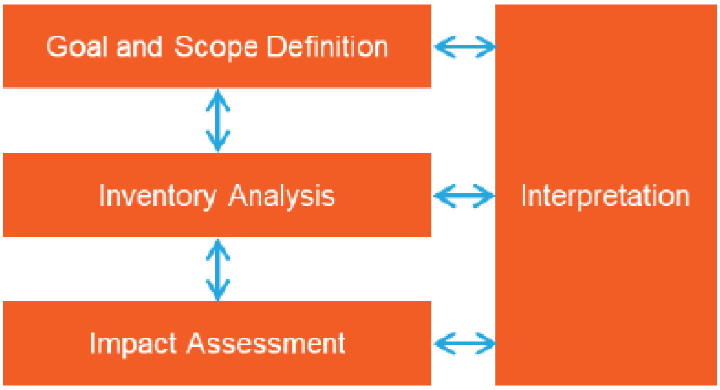
It is internationally standardized by UNI EN ISO 14040:2006 that contextualizes the principles and UNI EN ISO 14044:2006 which presents requirements and a guideline for the method.

The LCA methodology has a flexible framework that can be linear or not and it is composed by four phases (ISO 14040, 2006):

- The goal and the scope definition phase
- The Life Cycle Inventory analysis phase (LCI)
- The Life Cycle Impact Assessment phase (LCIA)
- The interpretation phase

Here a figure took from Eunomia Report (Simon Hann et al., 2020) which presents the main phases and the flexible framework of them.

Figure 2: LCA phases adapted from 14040:2006 (Eunomia Report, 2020)



While determining the Goal, during the first stage, it is necessary to define the system boundary and the level of detail of the study.

The second phase is the Life Cycle Inventory analysis phase (LCI) in which input and output data are studied. It means that, during this phase, the data useful to the LCA's goal are collected.

The aim of third phase, Life Cycle Impact Assessment phase (LCIA), is to understand the environmental impact associating inventory data with the environmental impact categories and their indicators.

The interpretation phase, as a final phase, summarizes and discusses the results creating conclusions and recommendation for the decision-making (ISO 14040, 2006).

2.4.2 Packaging Life Cycle Assessment

As the food packaging is a wide field with multiple environmental aspects to consider, conducting an LCA is the best way to calculate the overall environmental impact of a food product (Molina-Besch et al., 2018).

In the last decades, LCA methodology has been largely applied on food production (Heller et al., 2013) and on food packaging (Guinee et al., 2011) with many papers of Wikström and Williams in which the balance between the environmental impacts of the production, the disposal of the packaging and its utility to reduce food waste is evaluated (Williams et al. 2008; Wikström and Williams, 2010; Williams and Wikström, 2011; Williams et al., 2012; Wikström et al., 2014; Wikström et al., 2016).

As stated before, there are the indirect and the direct environmental impact of food packaging and it is highlighted that packaging can influence food waste and logistics (Pagani et al., 2015; Silvenius et al.,) both in a positive or in a negative way. For these reasons the general recommendation for packaging LCAs is to consider also the food waste and the indirect environmental impact of food packaging (Verghese et al., 2015; Williams and Wikström, 2010).

2.5 Plastic packaging

As the packaging material mostly used by Orkla Foods Sverige is plastic, the data analyzed refer to plastic materials and their environmental impact. For these reasons in the following paragraph, a definition and a characterization of plastics are given.

Plastic is the category of packaging material mostly used due to its multiple desirable characteristics: versatility, low weight, high or low barrier properties, easy and cheap production.
The word "plastic" is often used as a synonym of the word "polymer" even if this latter means a macromolecule composed only by repeated subunits called monomers. Most of polymers used in food packaging could contain also a minor part (3-1%) of other components such as plasticizers, antioxidants, pigments, antistatic, fillers and many others that provide the packaging material with different functionalities. For this reason, they are called "plastic" in general.

There are a lot of plastic materials used in food packaging and due to their versatility, they could be extruded as film, thermoformed or moulded as containers, trays and closures. Usually, different plastic materials are combined also to create multi-layer films and containers with the best properties. (Piergiovanni and Limbo, 2016).

2.5.1 Types of plastics

This is a list of the most common polymers used for food packaging and they are divided into five main groups (Siracusa, 2012):

- Polyolefins with different density or orientation: Polyethylene (PE), Polypropylene (PP);
- Copolymers of ethylene: most used is the ethylene-vinyl alcohol (EVOH)
- Substituted olefins like polystyrene (PS), oriented polystyrene (OPS) or polyvinyl alcohol (PVOH)

- Polyesters like polyethylene terephthalate (PET)
- Polyamide (PA)

The chemical structure and the morphology of the monomers (semi-crystalline or amorphous) gives the materials different characteristics. For example, the higher the crystallinity of the polymer, the lower is the permeability to gasses. In fact, as we can see in the Table 1 (Siracusa, 2012), polymers with the lowest value of permeabilities (good or moderate gas barrier performances) are those with a semi-crystalline molecular orientation (Piergiovanni and Limbo, 2016).

Table 1: Relative value of permeabilities for the most commercial polymers (no dimensional value) (Siracusa, 2012).

Polymer	N_2	O_2	CO_2
Polystyrene sheet	1	2.6	10.4
LLDPE	1	3.1	11.1
LDPE	1	3.1	10.7
HDPE film	1	3.2	11.9
PP film	1	4.3	13.6
Nylon 6 film	1	3.4	18.4
PET film	1	3.6	17.8

2.5.2 Type of packaging

As explained before, plastic is a material widely used thanks to its properties and versatility. For this reason, there are different types of packaging materials sold depending on the flexibility and on the components of the packaging. In the first group it is possible to divide between rigid and the flexible packaging, whereas depending on the packaging components there are two groups of packaging, monolayer and multilayer (Irzalinda and Ardi, 2020).

In the rigid packaging category, it is possible to find the type of packaging whose shape is not easily changeable after its production; the flexible packaging instead can be easily formed and shaped. In addition, by monolayer packaging a single layer between 20 and 200 micrometers (typically polypropylene, polyethylene and polyethylene terephthalate) is considered; whereas the multilayer packaging consists of a package with different layers made by different plastic or non-plastic materials (like aluminum foil or paper). The layers are adhered together by using adhesives or bonding between the polymers and the process to product multilayer packaging can be coextrusion or lamination. Multilayer packaging is, in general, flexible, lighter and versatile and for these reasons the multilayer packaging is a very popular packaging solution. Despite that, the different layers of these packaging solutions are difficult to separate and thereby difficult to recycle (Irzalinda and Ardi, 2020; Niaounakis, 2020).

In general, flexible packaging is widely used for several reason like better barrier properties, less material and energy needed for the production and less weight during the transportation that means less CO_2 emitted.

To achieve the best packaging performances, flexible packaging requires several different layers: the combination of LLDPE and HDPE enhances mechanical properties while using ethylene-vinyl alcohol (EVOH) or polyamide 6 (PA6) provide increased barrier properties of the packaging solution hence increases the shelf-life of the product (Morris, 2017).

2.5.3 Plastic packaging production

The evaluation of the environmental impact of plastics starts with the manufacturing process All the plastic materials originate from crude oil or natural gas extraction during the fuel production process, the monomer is processed into a plastic resin and then into the polymer material for the packaging use (Irzalinda and Ardi, 2020).

The emission during the production of the packaging material can be different depending on the different types of plastic packaging that are produced. For example, the production of flexible packaging uses 50% less energy than the rigid one (Packaging Digest, 2014).

There are two different ways to produce film packages: lamination and coextrusion. The lamination uses adhesives to bond the different layers whereas in the coextrusion process the layers are produced using different extruders and then, through the die they are combinate (Niaounakis, 2020).

2.5.4 Why plastic: Advantages and Disadvantages

Conventional plastic packaging materials are used worldwide because some characteristics common to all plastic polymers (light weight, flexibility and durability) combine well with specific peculiarities of food packaging materials. Barrier properties, resistance and heat sealability of some of them (like Polyethylene) are examples of the best properties of plastic materials that guarantee long shelf life and protection to food.

But using plastic does not only offer advantages. On the other hand, the process to produce plastic packaging and the material itself present one of the biggest environmental problems as the manufacturing of plastics releases GHG emissions

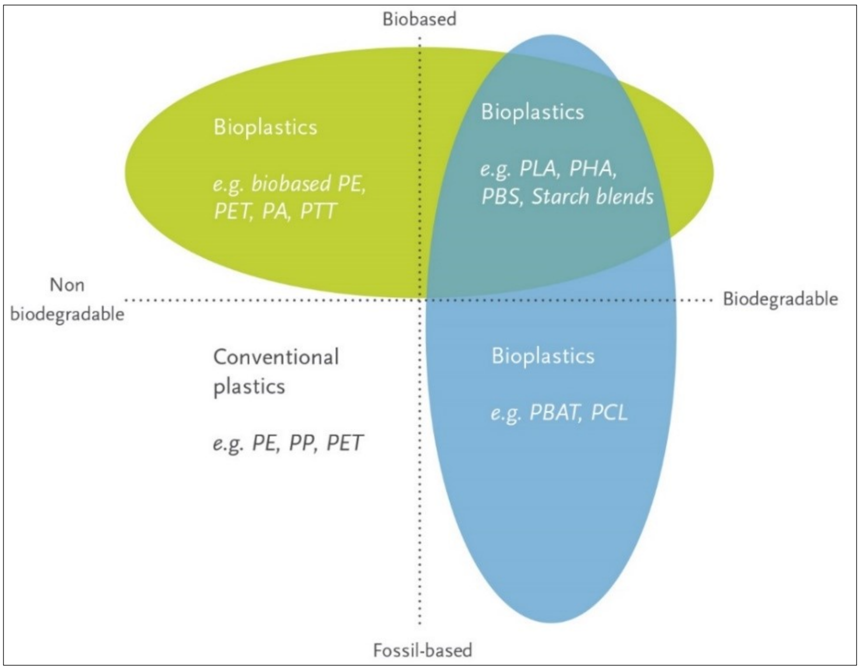
and toxic substances while plastic waste contributes to macro and micro plastics in the environment with a risk of entering food chains.
Plastic products, at the end of their life could be disposed in landfills, burnt in incinerators or, in the worst case, littered. (Acquavia et al., 2021)

Unfortunately, the disadvantages of using plastics are not only related to the environment. In general, plastic is inert but sometimes, even if the material is approved for food contact applications, migration of substances from the package to the food can happen such as micro composites like additives or NIAS (Non-Intentional Added Substances). This phenomenon can be the result of material modifications caused by the nature of the food, extreme storage conditions or improper manufacturing processes (Arvanitoyannis and Kotsanopoulos, 2015).

2.5.5 Biopolymer and their use in food packaging

Biopolymers are plastics that can be produced totally or in part from renewable materials (e.g. corn and sugar cane), for this reason they can be also called bio-plastics (Hottle et al., 2017). The name bioplastics refers to a whole family of plastic material that can be both biobased or biodegradable. With the term "biobased" a material totally or partly derived from biomass is consider. Whereas "biodegradable" refers to the biodegradation process in which microorganisms of the environment bring the material to natural molecules like water, carbo dioxide and compost. Depending on the chemical structure, a material can be biodegradable or not (European Bioplastic, 2020). In the Figure 2.1 the different types of bioplastics are presented.

Figure 2.1: Material coordinate system of bioplastics (European bioplastics, 2020)



Considering the environmental impact of the petroleum-based plastics use, it is clear why the new biopolymers and, more specifically, bioplastics research has been developing in the last decades. Biological origin materials represent, in fact, a possible solution to reduce the environmental impact of the food packaging as their overall environmental footprint is lower than the one of the fossil fuel materials (Varžinskas and Markevičiūtė, 2020). Moreover, as the increase of the demand for sustainable packaging materials, efficiency and sustainability of biopolymer need to be investigated (Colwill, 2013).

The use of bioplastics has a lot of advantages like reducing the environmental impact of products and materials and saving fossil resources (European bioplastic, 2020). The use of biopolymers, in fact, helps to reduce up to 20 per cent of carbon dioxide to the warming potential of 1.5°C (Intergovernmental Panel on Climate Change, 2018). However, biopolymers also present drawbacks from different point of view. Firstly, the cost for their production is higher referring to the fossil-based plastics and, in addition, the increasing use of the soil for the natural sources production (corn, starch, sugarcane) influences negatively the general sustainability of these new materials (Kabir et al., 2020). Moreover, most of the biopolymers lacks technical and mechanical performances. In fact, the application of biopolymers in food packaging needs depth evaluations in terms of barrier properties, strength, flexibility and chemical resistance (Porta et al., 2020).

3 Methodology

This chapter presents the development of the study. The environmental impact analysis of Orkla Foods' materials can be considered as a case study divided into two parts: data collection part followed by the data analysis part.

3.1 Study approach

This Master thesis project applies a well-known method, the LCA methodology, into a case study to investigate the unknown connection between food waste and packaging waste through environmental parameters and material barrier properties. The aim of this work is to apply a simplified LCA to a set of 23 Orkla Foods' products to clarify the trade-off between the use of plastic in the packaging and the protection that this material gives to food.

Simplified LCA means that it will be shorter than the standard methodology because it will be applied only to primary packaging and the system boundaries are very limited as it has been evaluated only the production process of the packaging without considering either transport nor recyclability of the materials and neither the food.

However, the backbone of the LCA methodology is fully followed and, for this reason, the steps of this work are compared to the four phases of the LCA methodology.

In this way, the first LCA's phase is the definition of the goal and the scope of the analysis. In literature, there are a lot of applications of LCA methodology to food packaging but the protection function of packaging materials and the environmental impact of packaging are considered separately. From this, the need to find out a model or an indicator that can satisfy this requirement.

Once the scope of the work has been identified, the second step concerns to collect data useful to the scope and, if needed, to supply additional information to support the data collected. These two main steps can be grouped in the phase of "Data Collection".

The following step of the LCA methodology is the assessment phase that, in this work, will be called "Data Analysis". This part consists in comparing, through graphs, the Carbon Footprint to barrier properties (permeability of the materials) first, and then, to the shelf life of the products. In this way it will be clear the trade-off between the importance of barrier properties of packaging solutions and the environmental impact of them.

The last step of the LCA methodology is the interpretation phase where the results are discussed and interpretated. In this project, this last part coincides with the "Results Chapter".

3.2 Data collection

To achieve the goal of the project, the first step is to find the data that are really important and they have to be useful for the goal of the project. For an LCA analysis, data can be measured, calculated or estimated and they are used to quantify the inputs and the outputs of process (ISO 14040:2006).

As the project arises as a collaboration with Orkla Foods, the data collected will be related to their product portfolio and the food products chosen will be the most interesting to study from the perspective of the company.

The case study is focusing on long shelf-life products that can be stored in ambient, chilled and frozen temperature and Orkla Foods has collected products to make the sample as heterogenous as possible.

The packaging or the product data collected can be both primary or secondary data and the major difference between them will be better explained in the following paragraphs.

3.2.1. Primary data collection

Usually, primary data originate directly from the parties involved and they are collected for the specific research problem. The advantages of using the primary data are that the collection strategy is shaped on the case study and the information is collected directly from the source whereas the disadvantages of using primary data are that the data collecting is cost and time-consuming (Hox and Boeije, 2004).

In this project, the primary data collected are from Orkla Foods and its packaging material suppliers.

3.2.1.1. From Orkla Foods

The information collected from Orkla Foods, are related both to the food product and to packaging requirements.

For the food point of view, the important information is the type of product packaged, its storage conditions and its shelf life.

The food packaging information that the company involved gave were the type of the material used, the weight and the thickness of the package or of the layers, the dimensions (and the volume) of the packs in question and the surface exposed to permeation of water vapor or gasses.

From this information, knowing the density of the materials, it was possible to calculate the amount of each material present in the packaging solutions.

3.2.1.2. From the packaging suppliers

The information collected from packaging suppliers are related to performance and technical properties of the film and the materials used for Orkla Foods' products. Specifically, the details obtained from materials technical sheets are the thickness of the layers, the Oxygen Transmission Rate (OTR) and the Water Vapor Transmission Rate (WVTR). From the Transmission Rates the Permeability Coefficient (KP) was calculated as described in the theory chapter, and from this latter the total Permeance (P) of the pack to the oxygen and to the water vapor. The permeance parameter was used to compare the barrier properties of the packages, while the Transmission Rates were used to compare the barrier properties of the materials.

It is necessary to specify that, to collect the materials information about the barrier properties (Water Vapour and Oxygen Trasmission Rate), both the technical sheets from the packaging suppliers and the Norner Calculator software (Orkla Foods' database; Norner AS) have been used. The latter has been useful to calculate the WVTR and the OTR of the materials in different condition of humidity.

3.2.2. Secondary data collection

Secondary data include any data that are originally collected to answer the same research question but collected from literature, reports and other available sources.

Due to the disadvantages stated before about using primary data, collecting data directly is not always the most economic or most feasible way to get the information required. In addition, using large secondary data sets allows the researcher to have more information than using primary data sets (T.P. Vartanian, 2011).
However, to make the data collection phase more complete, sometimes, it is useful to obtain information both through the direct way (using primary data sets) and the indirect way (using secondary data sets). This is the methodology that has been used in this case study.

Secondary data, besides in literature, books or reports, can be also set in databases specific for each field of research. The one that is used for this work is called EcoInvent.

3.3.1.1. EcoInvent Database

EcoInvent is a software database used to collect data for a complete LCA. It provides around 18.000 LCI datasets in many areas like energy supply, agriculture, transport, materials and chemicals chains and waste treatment (EcoInvent, 2021).

The data collected for this project through EcoInvent are about the Carbon Footprint for the production of polymer packaging materials. For what this study concerns, EcoInvent can supply information about both the "production" and the "market" of the materials. By the key word "production" it is possible to select the data that regard only GHG emitted during the production of the polymers without considering the logistic of the final products. These latter data can be collected using "market" as a key word. To make the research even more accurate, in the software it is possible to select the geographical area which the data refer to.

For this work it has been chosen only the impact of the production of the materials and not the "market environmental impact" because it has not been possible to know the origin and the destination of the polymers used. For the same reason it has been chosen the "World Production".

The data found using EcoInvent refer to the carbon footprint of the specific materials and they are then multiplied with the amount of each material in every single packaging solution. Afterwards, the data gained are analyzed in different graphs in which the amount of packaging material and its environmental impacts are compared to packaging characteristics.

3.3 Data Analysis

Once that all the data are collected, they need to be analyzed and interpreted. In this phase it is important to choose the correct analysis methodology to achieve the goal and the scope of the LCA study.

The environmental impact data, that are collected as Carbon Footprint indicator, are analyzed in three different types of graphs to highlight three different analyses. In every analysis the relationship between barrier properties (OTR and WVTR) and the other aspects will be investigated. The first comparison will be between barrier properties and packaging materials; the second one analyses OTR and WVTR in relation to Carbon Footprint of each single packaging solution; the third one will be a correlation between Carbon Footprint and the shelf life.

3.3.1. Material analysis

In this part the aim is to evaluate the Carbon Footprint compared to the performances, the characteristics of the different types of plastics used in the packages in the sample. To obtain this information, all the materials used in the packaging solutions were firstly collected in a list and their kilograms of CO_2 equivalent had been gained from the EcoInvent Database.

Then, the Carbon Footprint has been calculated and presented as kilograms of CO_2 per surface (kg CO_2/m^2). In fact, considering one kilogram of materials and using the density of each material and the thickness of 1 micrometer, it has been possible to calculate the Carbon Footprint of the material related to surface.

3.3.2. Packaging Analysis

In this part of the analysis, the Carbon Footprint is evaluated considering each different type of packaging solution and its characteristics. As seen for the material analysis, the first information that was collected is the CO_2 equivalent related to different materials. This information has been multiplied per the amount of the single materials present in one pack (found using the technical information gained from the company). The data of the materials obtained for a single pack have been multiplied per thousand packs and expressed in kilograms (kg CO_2 eq./1000 packs in kg). Whereas, speaking about the comparison between barrier properties and the data of Carbon Footprint, the kilograms of CO_2 equivalent will be considered for a single pack.

As the set of the products considered is very heterogenous in terms of flexibility of the materials, length of shelf-life and storage conditions, the products and the types of packaging are sorted into different categories to better present the results analysis. Considering the flexibility of the packaging solution, the sample has been separated into two groups: flexible and rigid packaging. While, speaking about the number of the days of shelf-life, all the products are long shelf-life but they have been split into two groups: “medium-long shelf-life” and “long shelf-life” respectively from 49 up to 250 days and from 251 until 730.
Whereas, to distinguish between the product based on the temperature of storage, by the company classification, three groups have been chosen: room temperature, chilled temperature and frozen storage.

3.3.2.1. Barrier properties

In this part the same analysis of the previous paragraph will be applied but, as stated before, the permeability performances are evaluated using the permeance (P) of the materials to oxygen and water vapor because the entire packaging solutions are analyzed.

The parameter of the package Permeance (P) takes into account the surface of the product. Therefore, it is necessary to consider the dimension and the shape of the package and to do that it has been chosen the surface-volume (S/V) ratio to compare properties of different sized packages. In fact, the bigger the package, the smaller is the surface-volume (S/V) ratio and the smaller is the amount of material used in proportion to the volume.

3.3.2.2. Shelf-life

For this last analysis, the length of the shelf-life has been considered and used as a parameter to evaluate the quality of the packaging solution in terms of good barrier properties. The higher the quality of the barrier properties, the longer the shelf-life will be, the first correlation studied is that one between these two characteristics.

Afterwards, it was analysed how the amount of material in the pack (and so the Carbon Footprint) is linked to the shelf-life of the products.

4 Results and discussion

This chapter presents and analyses the data collected. Also, comments to the results will be given. Finally, in the last paragraph the results are discussed. The same structure of the methodology chapter will be followed.

4.1 Results presentation

The results in this chapter will be presented using different tools.

The tables will be used to present all the data collected both primary and secondary sources whereas graphs and comments to graphs will be used for the data analysis part.

As presented in the methodology chapter, the data collected was used to examine the environmental impact (expressed in kg CO_2 eq.) of different packaging solutions and materials. The barrier properties of them are analyzed in parallel to highlight the different performances of the materials.

4.2 Data presentation

4.2.1. Products characteristics

The packaging data collected are referred to 23 products selected from Orkla Foods' portfolio. The choice of the products has been led by the company using the criteria of creating an heterogenous sample. That means that the products chosen have different requirements, size, shelf life and storage temperature.

In the Table 2 there are the descriptions of the products considered in this project.

Table 2: Products considered in this project.

Code	Name of the product	Type of container	Shelf life (day)
1	Rice pudding with jam	Plastic container	50
2	Ketchup 1 kg	Bottle	545
3	Ketchup 500g	Bottle	545
4	Cured flavoured herring	Flexible pouch	210
5	Lingonberry jam, refill	Flexible pouch	270
6	Rice pudding, rullpack	Flexible pouch	49
7	Strawberry jam, squeeze bottle	Bottle	180
8	Strawberry jam XL, squeeze bottle	Bottle	240
9	Dressing	Bottle	270
10	Sauce	Bottle	455
11	Potato powder	Flexible pouch	455
12	Frozen fries	Flexible pouch	545
13	Frozen meat balls	Flexible pouch	365
14	Minced vegan meat	Flexible pouch	605
15	Cured herring bucket	Bucket	244
16	Blueberry powder	Flexible pouch	545
17	Rosehip powder	Flexible pouch	730
18	Jam minipack	Film formed	240
19	Frozen ready meal	Rigid bowl	365
20	Chilled soup	Rigid bowl	60
21	Herring flavoured ready-to-eat	Film formed	244
22	Tortilla wrap	Flexible pouch	180
23	Tortilla crisp chips	Flexible pouch	240

With the different colours in table 2 the different characteristics of the products like the type of packaging, storage temperature and length of the shelf life are been highlighted (table 2.1).

Table 2.1: Key for table 2

(green)	=flexible packaging
(orange)	=Rigid packaging
(yellow)	=room temperature
(light blue)	=chilled
(blue)	=Frozen
49-250	=medium-long shelf life
251-730	=long shelf life

From Table 2, the first comment that can be done is the difference shelf-life length of products 7 and 8. These two packaging solutions, in fact, are used for the same food product but the shelf-life shown is different. The dimensions and the mass of products are the only characteristics that change. That means that S/V ratio influences also the food conservation: the higher the ratio the smaller is the volume (respectively to the surface) and the packaging solutions. As a consequence, in the smaller packaging, the possibly permeant surface has a bigger impact on the food (represented by the volume) and this explains why the shelf-life is longer for the bigger products.

Most of the packaging solutions are composed by multiple parts, usually two: the lid and the container. These two parts are made with different materials which have different properties. Table 3 provides the information about the components of the products.

The last column of the table 3 presents the name of material selected from the EcoInvent database. Further, the same data are used to calculate the CO_2 equivalent in the next tables.

Table 3: Packaging specification

Product name/description	Package type	Type of material	Name of the material in EcoInvent
Rice pudding with jam	plastic chamber	PS Extruded	HIPS
Ketchup 1 kg	Bottle Capsule	PET PP or PE	Bot grade PET PP
Ketchup 500g	Bottle Capsule	PET PP or PE	Bot grade PET PP
Cured flavoured herring	flexible pouch	PET 12 micron OPA PP	APET nylon 6 or 6-6 PP
Lingonberry jam, refill	flexible pouch	PE OPA PE	LDPE nylon 6 or 6-6 LDPE
Rice pudding, rullpack	flexible pouch	PE OPA PE	LDPE nylon 6 or 6-6 LDPE
Strawberry jam, squeeze bottle	bottle capsule	PET PP	Bot grade PET PP
Strawberry jam XL, squeeze bottle	bottle capsule	PET PP	Bot grade PET PP

Dressing	bottle capsule	PP PP	PP PP
Sauce	bottle capsule	PP PP copolymer (Adh) EVOH PP Copolymer (Adh) Gloss polypropylene PP or PE	PP PP Ethylene vinyl acetate PP PP PP
Potato powder	flexible pouch	PET mLDPE	APET LDPE
Frozen fries	flexible pouch	PE	LDPE
Frozen meat balls	flexible pouch	PE	LDPE
Minced vegan meat	flexible pouch	PET PE "green"	APET PE
Cured herring bucket	bucket lid	PP PP	PP PP
Blueberry powder	flexible pouch	PET mLDPE	APET LDPE
Rosehip powder	flexible pouch	BOPP LLDPE white	PP LLDPE
Jam minipack	bottom film formed top film	PET PET PE EVOH PE	APET APET LDPE Ethylene vinyl acetate LDPE
Frozen ready meal	rigid bowl top film	PP PET	PP APET
Chilled soup	rigid bowl lidding film	PP PET	PP APET

Herring flavoured ready-to-eat	bottom film formed	APET	APET
		PE	LDPE
		EVOH	EVOH
		PE	LDPE
	top film	PET 12 micron	APET
		MPET	APET
		PE	LDPE
Tortilla wrap	flexible pouch	PE	LDPE
		PE EVOH	Ethylene vinyl acetate
Tortilla crisp chips	flexible pouch	PE	LDPE
		PE EVOH	Ethylene vinyl acetate

4.3 Data Analysis

In the following paragraphs the results are presented in graphs and, whenever necessary, tables to analyse the relationship between the environmental impact of the packages and their barrier properties and shelf-life of the products.

Firstly, the environmental impact is analysed in relation to the barrier properties of the plastic materials used in the packaging solutions (section 4.3.1).

Secondly, the barrier properties and Carbon Footprint of the different packaging solutions are presented (section 4.3.2.1).

Finally, the parameters of both barrier properties and environmental impact of the packaging solutions are analysed in relation to the length of the shelf-life (section 4.3.2.2).

4.3.1. Materials Analysis

The table 4 shows the list of materials presented in the packages considered.

In the Figure 3 and 4, the barrier properties for both oxygen and water vapour are presented and compared to the Carbon Footprint of each material (Table 5).

Finally, in the last graph (Figure 5) both the permeability characteristics and Carbon Footprint of the materials are shown. The environmental impacts are presented per surface (m^2) of layer of 1 micron thickness and, for the calculation, the density presented in the table 4 has been considered (Omnexus database).

Table 4: Packaging materials

Material	**Density (kg/m³)**
HIPS	1040
Bot grade PET	1500
PP	900
APET	1350
nylon 6	1120
LDPE	930
EVOH	1150
LLDPE	930

Figure 3: barrier properties and Carbon Footprint, focus on O_2

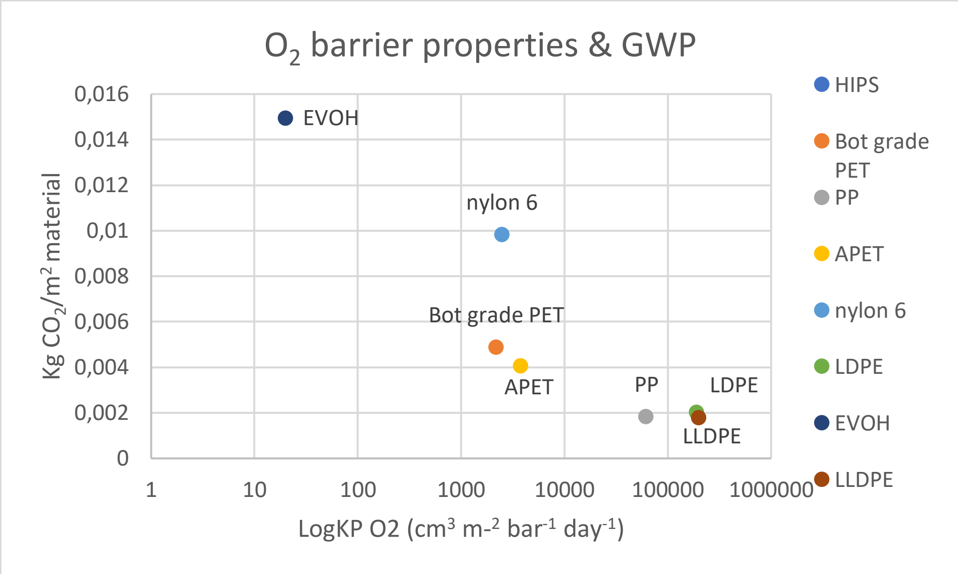
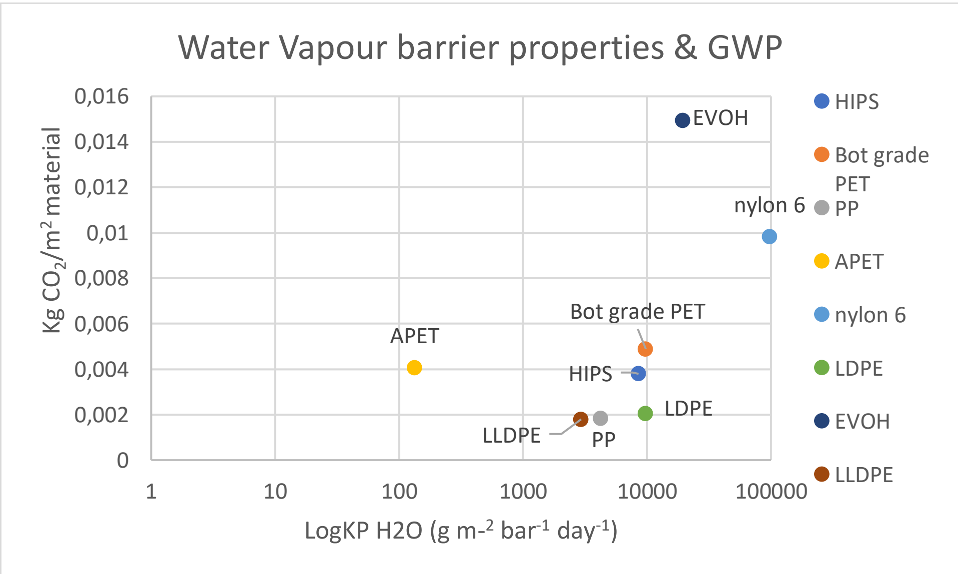


Figure 4: barrier properties and Carbon Footprint, focus on Water Vapour



In the graphs in the Figure 3 and 4 the two barrier properties respectively the oxygen and the water vapour permeance are presented and compared with the Carbon Footprint. It should be noted that the environmental impact is expressed in kilograms per surface and the Coefficient of permeance in the x axis in logarithmic scale.

Taking into account that the surface has been calculated considering the density values in the table 4 with a thickness of 1µm, it is possible to compare the performances and the environmental impacts of layers with the same thickness.

From the environmental point of view, the best materials are the ones in the lower part of the graphs, whereas the ones with the best barrier performances are in the left part of the graph.

From these two figures it is possible to have a first overview about the relation between barrier properties and environmental impact of the materials. In the Figure 3, in fact, we can see that the plastic materials with the higher environmental impact are those ones with a higher oxygen barrier property. Even if there is not a linear relation, it is helpful to quantify the protection for the oxygen that the packaging provides in relation to the GWP. An example could be comparing the Bottle grade PET and nylon 6.

For water vapour barrier in the Figure 4 there is no correlation between the GWP and the barrier properties. That means that the packaging consumers and developers could choose the materials with the lowest environmental impact if the level of barrier protection is the same.

To have an overall view about the barrier properties and the Carbon Footprint, in Figure 5 both the O_2 and the Water Vapour per each material are presented.

Figure 5: Carbon Foot Print and barrier properties of materials

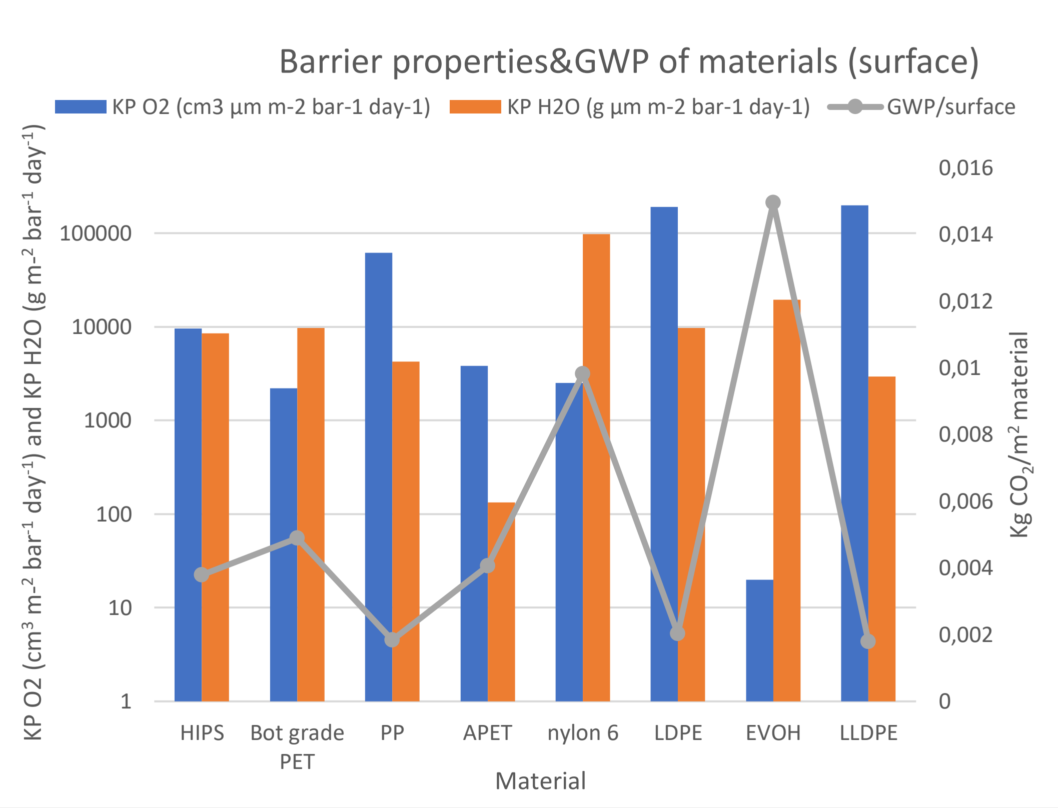


Table 5: Carbon Footprint and barrier properties, key for Figure 2

Material	KP O_2 (cm^3 µm m^{-2} bar^{-1} day^{-1})	KP H_2O (g µm m^{-2} bar^{-1} day^{-1})	CO_2 equivalent/m^2 (material thickness: 1µm)
HIPS	9568,8	8522,8	0,003796
Bot grade PET	2200	9753,8	0,00489
PP	62000	4226,6	0,001836
APET	3800	134	0,0040635
nylon 6	2500	97538,1	0,0098224
LDPE	190000	9753,8	0,0020367
EVOH	20	19507,6	0,01495
LLDPE	199378,2	2936,6	0,0017949

In the Figure 5 is highlighted the high-performance products in terms of barrier properties and in terms of Carbon Footprint equivalent per surface of material. Even if, it seems that Polypropylene (PP) and Polyethylene Terephthalate (both APET and bottle grade PET) are the highest-performance material both for environmental impact and higher barrier properties, it is very difficult to define an optimal material in general because it will depend on the type of the food product and its requirements.

4.3.2. Packaging Analysis

In the following paragraphs, from the packaging solution point of view, the relation between barrier properties and environmental impact as well as between the length of shelf-life and environmental impact are analysed.

From the EcoInvent database, the Carbon Footprint expressed as kilograms of CO_2 equivalent (kg CO_2 eq.) for these materials was taken. Then, the total amount of CO_2 equivalent for each packaging solutions has been presented (table 6) and a focus on the impacts from the different types of material is given in the Figure 6. The amount of CO_2 equivalent in this last graph is linked to thousand packs.

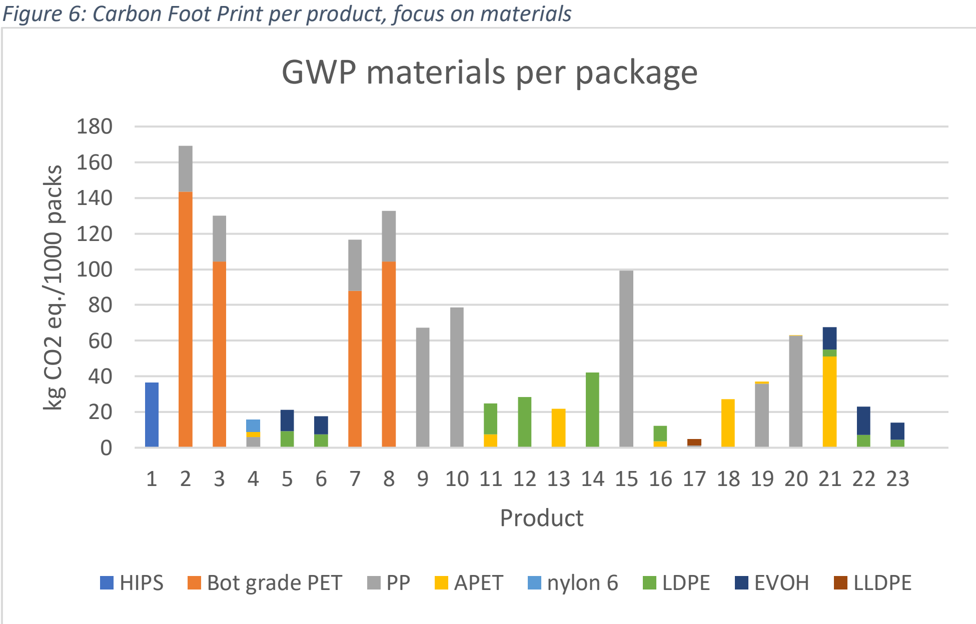
Table 6: Carbon Foot Print per package

Code	Name of the product	Type of container	kg CO_2 per product x 1000 packs (kg)
1	Rice pudding with jam	Plastic container	36,50
2	Ketchup 1 kg	Bottle	**169,14**
3	Ketchup 500g	Bottle	**130,02**
4	Cured flavoured herring	Flexible pouch	15,97
5	Lingonberry jam, refill	Flexible pouch	21,26
6	Rice pudding, rullpack	Flexible pouch	17,58
7	Strawberry jam, squeeze bottle	Bottle	**116,58**
8	Strawberry jam XL, squeeze bottle	Bottle	**132,88**
9	Dressing	Bottle	67,32
10	Sauce	Bottle	78,74
11	Potato powder	Flexible pouch	24,87
12	Frozen fries	Flexible pouch	28,47
13	Frozen meat balls	Flexible pouch	21,90
14	Minced vegan meat	Flexible pouch	42,14
15	Cured herring bucket	Bucket	**99,14**
16	Blueberry powder	Flexible pouch	12,37
17	Rosehip powder	Flexible pouch	4,74
18	Jam minipack	Film formed	27,09
19	Frozen ready meal	Rigid bowl	37,03
20	Chilled soup	Rigid bowl	63,15
21	Herring flavoured ready-to-eat	Film formed	69,91
22	Tortilla wrap	Flexible pouch	23,01
23	Tortilla chips crisp	Flexible pouch	14,11

In the Table 6 it is clear how the type of packaging solution can influence the environmental impact. The rigid packaging (orange cells) is the type of packaging with the higher environmental impact (bold type).

Even if it is not already shown the motivation of the higher environmental impact for rigid packaging (whether is for the weight or for the type of plastic used) it can be said that rigid packaging could have more plastic material because rigid packaging provides also functions as convenience, easy open solutions and formed shapes.

Figure 6: Carbon Foot Print per product, focus on materials



In the Figure 1 the set of 23 products is presented. The materials are highlighted using different colours and the heights of the sticks represents the total amount of Carbon Footprint emitted for the production of 1000 packs.

At the first sight of the Figure 6, it is clear that the materials commonly used in primary packaging of the Orkla Foods products considered in this study are the Bottle Grade PET, Polypropylene and the Low-Density Polypropylene. The products with the highest environmental impact are the ones which are composed mainly of Bottle Grade PET.

4.3.2.1. Barrier properties

To analyse the relation between the environmental impact of the different packaging solutions and the barrier properties, it was necessary to calculate the Permeance (P) of each pack (P pack) both for the WVTR (table 7) and for the OTR (table 8). Using the data collected from EcoInvent it has been possible to calculate the CO_2 equivalent used for the production both of each package and of 1000 packages.

Table 7: Water Vapour Permeance of the products

	Water Vapour Permeance		
Code	**P pack (g pack^{-1} bar^{-1} day^{-1})**	**kg CO2 product x 1000packs**	**kg CO2 product x pack**
1	537,97	36,5	0,037
2	0,20	169,14	0,169
3	0,21	130,02	0,130
4	2,79	15,97	0,016
5	54,14	21,26	0,021
6	45,23	17,58	0,018
7	0,96	116,58	0,120
8	1,10	132,88	0,130
9	1,35	67,32	0,067
10	1,28	78,74	0,079
11	17,71	24,87	0,025
12	226,65	28,47	0,028
13	173,53	21,9	0,022
14	107,26	42,14	0,042
15	2,66	99,14	0,099
16	8,62	12,37	0,012
17	24,96	4,74	0,005
18	7,58	27,09	0,027
19	31,47	37,03	0,037
20	5,37	63,15	0,063
21	10,37	69,81	0,070
22	139,27	23,01	0,023
23	85,36	14,11	0,014

Table 8: Oxygen Permeance of the products

	Oxygen Permeance		
Code	**P pack (cm^3 $pack^{-1}$ bar^{-1} day^{-1})**	**kg CO2 product x 1000packs**	**kg CO2 product x pack**
1	49,25	36,50	0,037
2	<0,001	169,14	0,170
3	<0,001	130,02	0,130
4	0,006	15,97	0,016
5	0,74	21,26	0,021
6	3,30	17,58	0,018
7	0,01	116,58	0,120
8	0,01	132,88	0,130
9	<0,001	67,32	0,067
10	<0,001	78,74	0,079
11	0,03	24,87	0,025
12	576,00	28,47	0,028
13	441,00	21,90	0,022
14	22,10	42,14	0,042
15	0,54	99,14	0,099
16	0,015	12,37	0,012
17	0,01	4,74	0,005
18	0,04	27,09	0,027
19	5,28	37,03	0,037
20	0,81	63,15	0,063
21	0,10	69,91	0,070
22	<0,001	23,01	0,023
23	<0,001	14,11	0,014

These data are then used in the following graphs that show the permeance (P) to water vapour (Figure 7) and oxygen (Figure 8) of each packaging solution in relation to its Carbon Footprint. As in this case the barrier properties refer to the pack itself, the CO_2 equivalent of the single pack were used instead of 1000 packs.

Figure 7: Relation between the WVTR and the Carbon Footprint of each packaging solution

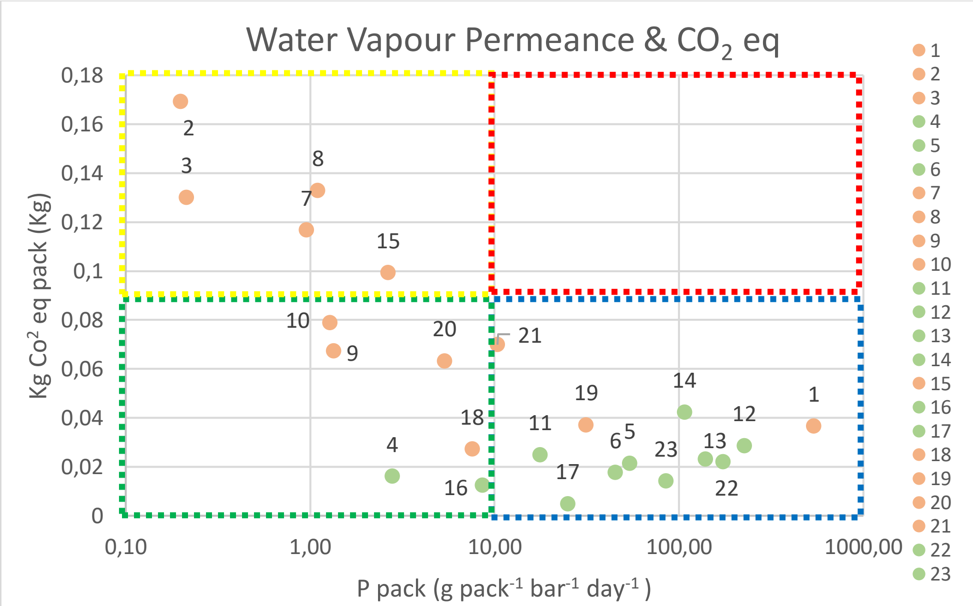
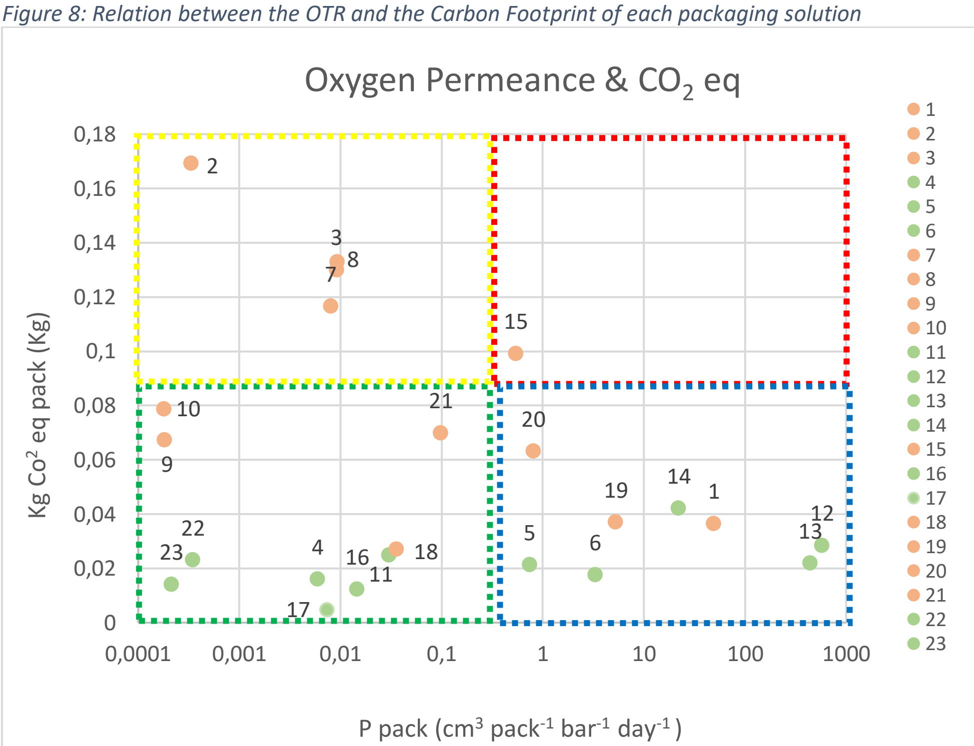


Figure 8: Relation between the OTR and the Carbon Footprint of each packaging solution



Flexible Packaging   Rigid Packaging

In both Figure 7 and 8 it is possible to divide the graph in four areas to identify classes of products with similar properties and performances: Low Permeance-Low impact (green area), Low Permeance-High impact (yellow area), High Permeance-Low impact (blue area), and the worst case High Permeance-High impact (red area). The division of the surface of the graph represents the level of efficiency of the packaging solution. The products in the red area can be considered as the less efficient from both the environmental and barrier properties point of view due to the higher CO_2 equivalent and the higher permeance; on the contrary, the ones in the green area are can be considered the more efficient products. The yellow and the blue squares highlight the middle way where, respectively, the Carbon Footprint is higher but the barrier performances are lower and vice versa.

Furthermore, using two different colours for the dots Figure 7 and 8, it is possible to see if the package considered is flexible (in green) or rigid (in red). It is possible to say that there are five packaging solutions which represents the worst cases (yellow and red areas) and they are the number 2, 3, 7, 8 and 15: to be noticed that all of them are rigid packaging.

The most important thing highlighted by the graph in the Figure 7 is that to have a high water vapour barrier, it seems to be necessary having a thick material (rigid packaging) with a higher Carbon Footprint as a consequence. For oxygen, instead (Figure 8), the package thickness impacts less on the barrier performances.

Focusing on the four categories for both the figure 7 and figure 8 graphs, we can highlight which type of products are in each category and see if there are some connections on that. In the following tables (table 9 and 10) we can see the different types of packaging solutions presented in each category. The same colours used in table 2 are used.

Table 9: Packaging solutions classification based on Figure 7

Water vapour permeance		
Low Permeance-Low impact		
Code of product	*Flexibility of package*	*Storage temperature*
4 – Cured flavoured herring	Flexible	Chilled
9 - Dressing	Rigid	Room
10 - Sauce	Rigid	Room
16 - Blueberry powder	Flexible	Room

18 – Jam minipack	Flexible	Room
20 - Chilled soup	Rigid	Chilled
21 – Herring flovoured ready-to-eat	Rigid	Chilled
Low Permeance-High impact		
2 - Ketchup 1 kg	Rigid	Room
3 - Ketchup 500g	Rigid	Room
7 - Strawberry jam, squeeze bottle	Rigid	Room
8 - Strawberry jam XL, squeeze bottle	Rigid	Room
15 – Cured herring bucket	Rigid	Chilled
High Permeance-Low impact		
1 – Rice pudding with jam	Rigid	Chilled
5 - Lingonberry jam, refill	Flexible	Room
6 – Rice pudding, rullpack	Flexible	Chilled
11 - Potato powder	Flexible	Room
12 – Frozen fries	Flexible	Frozen
13 – Frozen meat balls	Flexible	Frozen
14 – Minced vegan meat	Flexible	Frozen
17 - Roseship powder	Flexible	Room
19 - Frozen ready meal	Rigid	Frozen
22 – Tortilla wrap	Flexible	Room
23 – Tortilla crisp chips	Flexible	Room
High Permeance-High impact		
-	-	-

Table 10: Packaging solutions classification based on Figure 8

Oxygen permeance		
Low Permeance-Low impact		
Code of product	*Flexibility of package*	*Storage temperature*
4 – Cured flavoured herring	Flexible	Chilled
9 - Dressing	Rigid	Room
10 - Sauce	Rigid	Room
11 - Potato powder	Flexible	Room
16 - Blueberry powder	Flexible	Room
17 - Roseship powder	Flexible	Room
18 – Jam minipack jam	Rigid	Room
21 – Herring flavoured ready-to-eat	Rigid	Chilled
22 – Tortilla wrap	Flexible	Room
23 – Tortilla chips crisp	Flexible	Room
Low Permeance-High impact		
2 - Ketchup 1 kg	Rigid	Room
3 - Ketchup 500g	Rigid	Room
7 - Strawberry jam, squeeze bottle	Rigid	Room
8 - Strawberry jam XL, squeeze bottle	Rigid	Room
High Permeance-Low impact		
1 – Rice pudding with jam	Rigid	Chilled
5 - Lingonberry jam, refill	Flexible	Room
6 – Rice pudding, rullpack	Flexible	Chilled

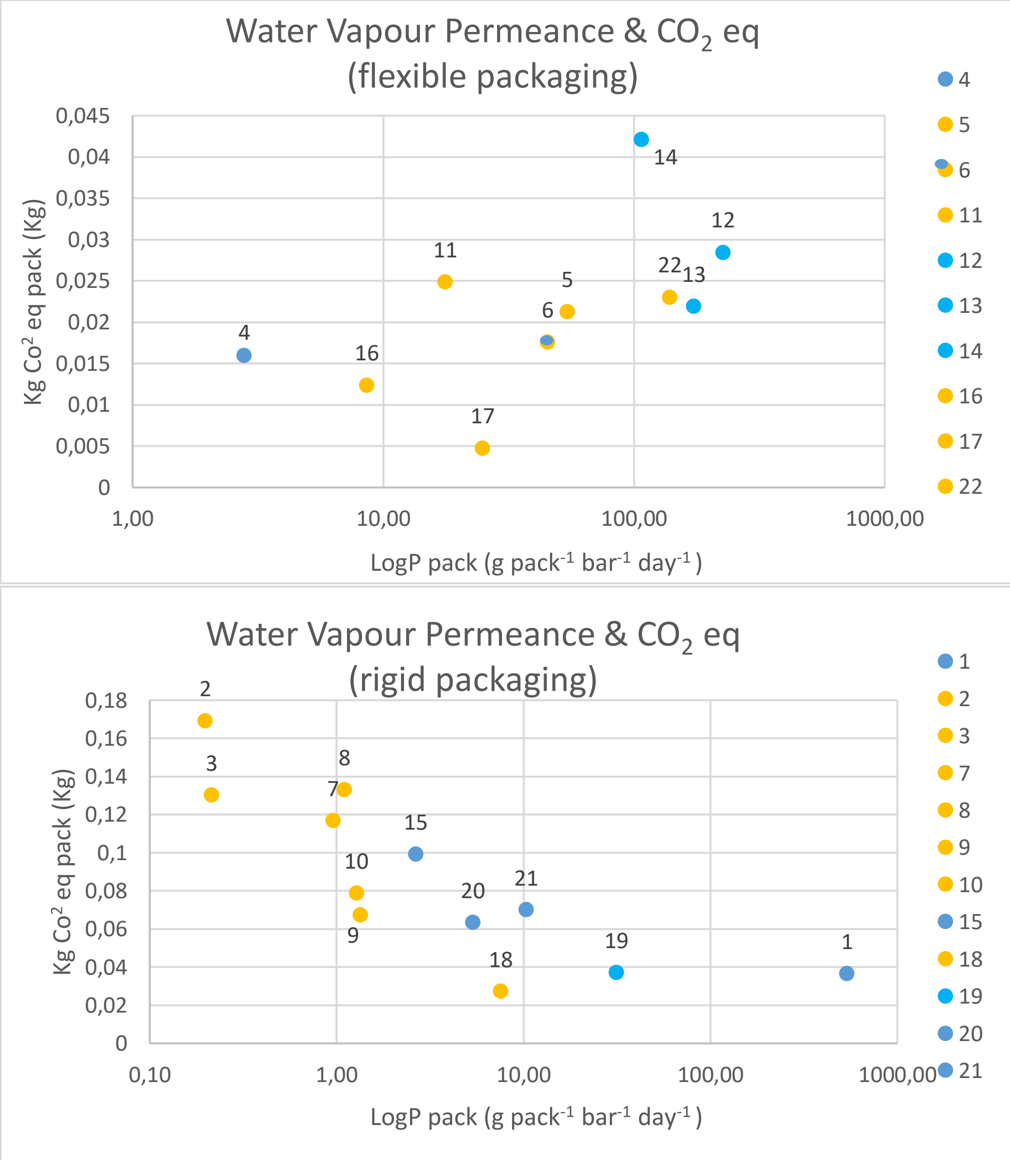
12 – Frozen fries	Flexible	Frozen
13 – Frozen meat balls	Flexible	Frozen
14 – Minced vegan meat	Flexible	Frozen
19 - Frozen ready meal	Rigid	Frozen
20 - Chilled soup	Rigid	Chilled
High Permeance-High impact		
15 – Cured herring bucket	Rigid	Chilled

In general, for both the barrier properties analysed it is evident that, the products that have a low impact material use flexible packaging material.

Since there are a lot of flexible packaging products in the green area (best performances) it is possible to achieve good barrier properties with a low Carbon Footprint. The rigid packaging, instead, despite having good barrier properties it has a higher environmental impact.

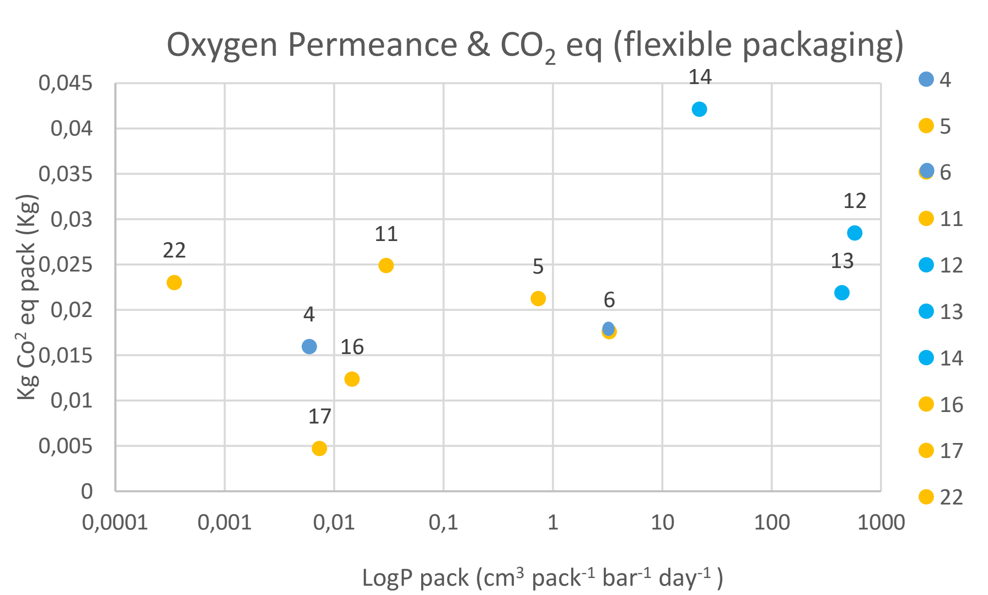
With this following four graphs it is highlighted the nature of the packaging (flexible or rigid) and the storage temperature (yellow, light blue and blue) to find out a possible correlation between the barrier performances (in the logarithmic x axis) and the Carbon Footprint (y axis) of different type of packaging solutions.

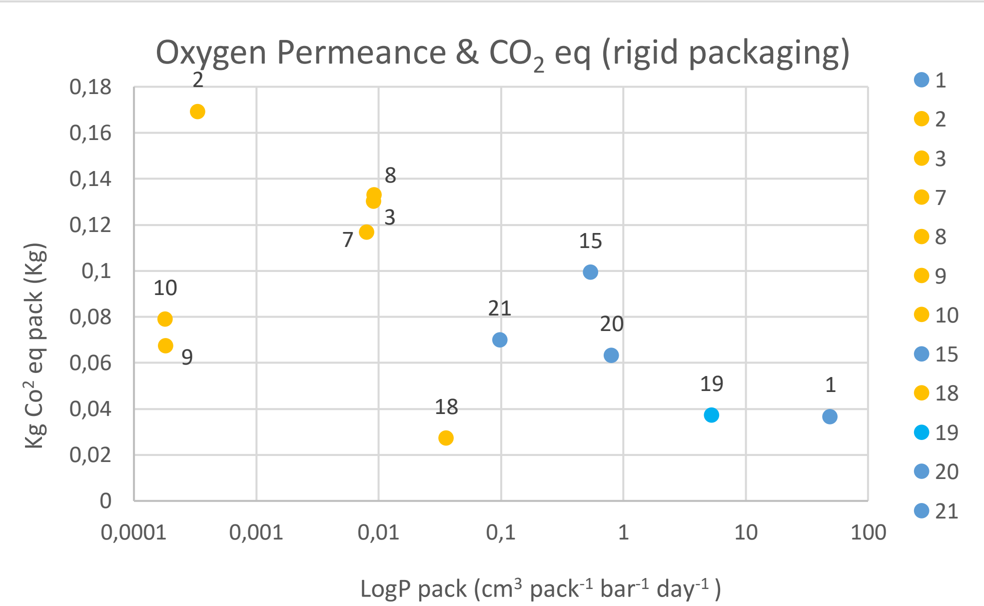
Figure 9: Environmental impact and barrier properties for flexible and rigid packaging, focus on Water Vapour



In the Figure 9 for the flexible packaging, it can be noticed that the Carbon Footprint values are very close to each other (y axis) and no correlation between the amount of material and the Water Vapour barriers properties is visible. Whereas in the second graph about the rigid packaging, it is confirmed as stated before: the thicker the package, the lower is the Water Vapour permeability (see products 2, 3, 7 and 8).

Figure 10: Environmental impact and barrier properties for flexible and rigid packaging, focus on Oxygen



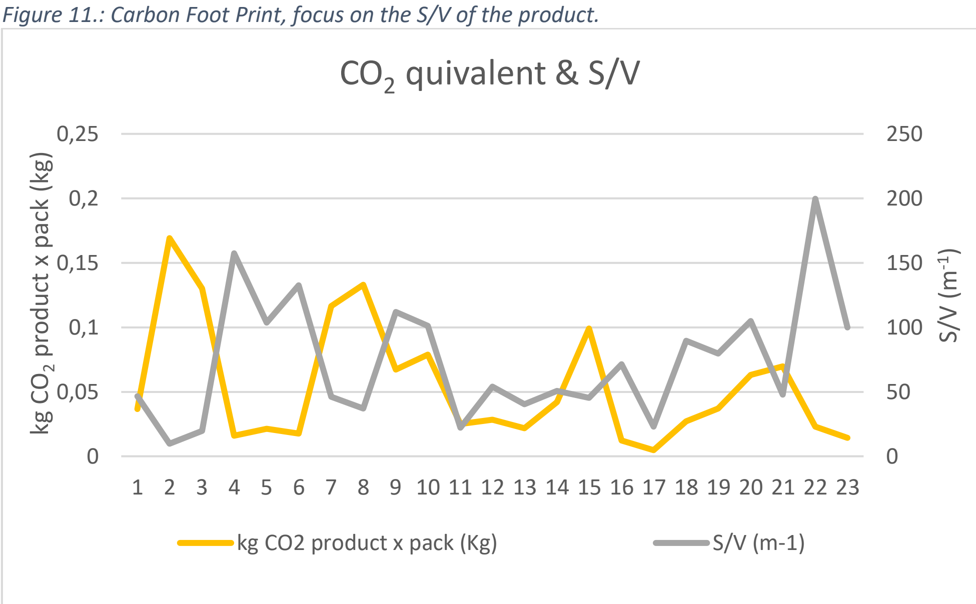


If for the water vapour the relation between the two parameters seems to be clear, for the oxygen permeance it is more complicated seeing the tendency.
Moreover, as in Figure 10, the frozen products 12, 13, and 14 (flexible packaging graph) have a low barrier property and a relatively high environmental impact, it could be interesting to evaluate the application of biopolymers to these products with the aim of reducing their Carbon Footprint.

In all the previous graphs all the characteristics of a package solution have been evaluated except for the dimension of the pack. In the following two graphs the dimension is presented using two parameters: The Surface/Volume ratio (S/V) (Figure 11) and the weight of the product packaged (Figure 12)

The parameter of the package Permeance (P) keeps into account the surface of the product. Therefore, it is necessary to consider the dimension and the shape of the package and to do that it has been chosen the surface-volume (S/V) ratio to compare properties of different sized packages (Figure 11). In fact, the bigger is the package the smaller is the surface-volume (S/V) ratio and the smaller is the amount of material used in proportion to the volume.

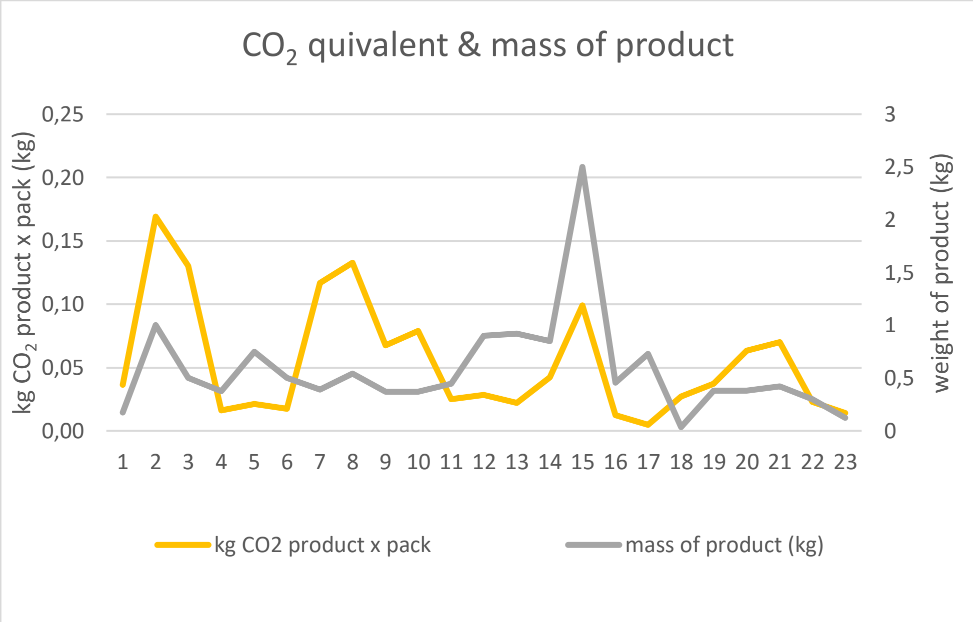
Figure 11.: Carbon Foot Print, focus on the S/V of the product.



With the introduction of the S/V ratio, it is easier to understand which packages can be consider "small" (higher S/V) or "big" (lower S/V) and its correlation to the environmental impact and the material barrier properties. In addition, the packaging with a high S/V ratio should use more packaging material than the products with a lower S/V. That means that it is expected that the Carbon Footprint increases with a higher S/V ratio.

As the calculation of the volume and the surface considered have been estimated using measurements of low accuracy, the following graph can be more precise than the previous one. In the figure 12 instead, the weight of the product packaged has been used.

Figure 12.: Carbon Foot Print, focus on the weight of the product.

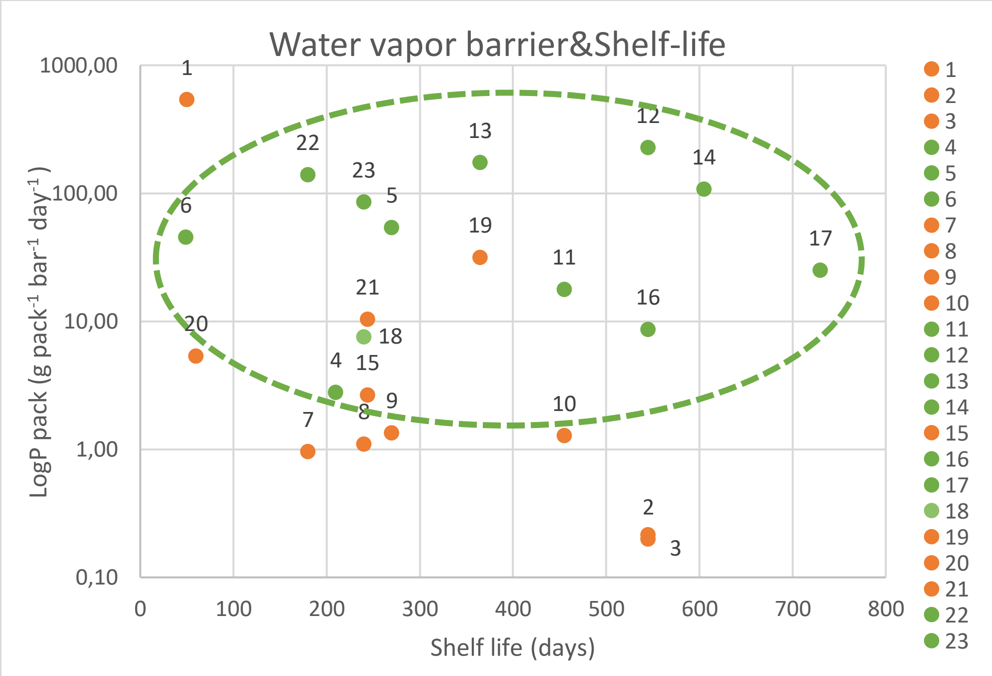


Following the concepts that are already known, from the graph shown in the Figure 11 and 12 it would be expected to see a different trend. The reason why results do not follow the expectations could be because both flexible and rigid packaging are shown in the graphs and the low Carbon Footprint of flexible material is related to the low thickness and not to the dimension.

4.3.2.2. Shelf-life

As the length of the shelf-life influenced by the barrier properties of the material, it is interesting to analyse how these they are linked each other. Figure 13 and 14 shows how both the Water Vapour Permeance (Figure 13) and the Oxygen Permeance (Figure 14) relate to shelf-life length. Furthermore, the different colours (orange and green) of dots refer to the flexibility of the packaging solutions.

Figure 13: Relation between length of shelf-life and the barrier properties of the packs, focus on Water vapor



In the figure 13 both the flexible and the rigid packaging solutions are presented. They are shown comparing the length of shelf-life and the permeance to the Water Vapour Permeance (logarithmic scale).

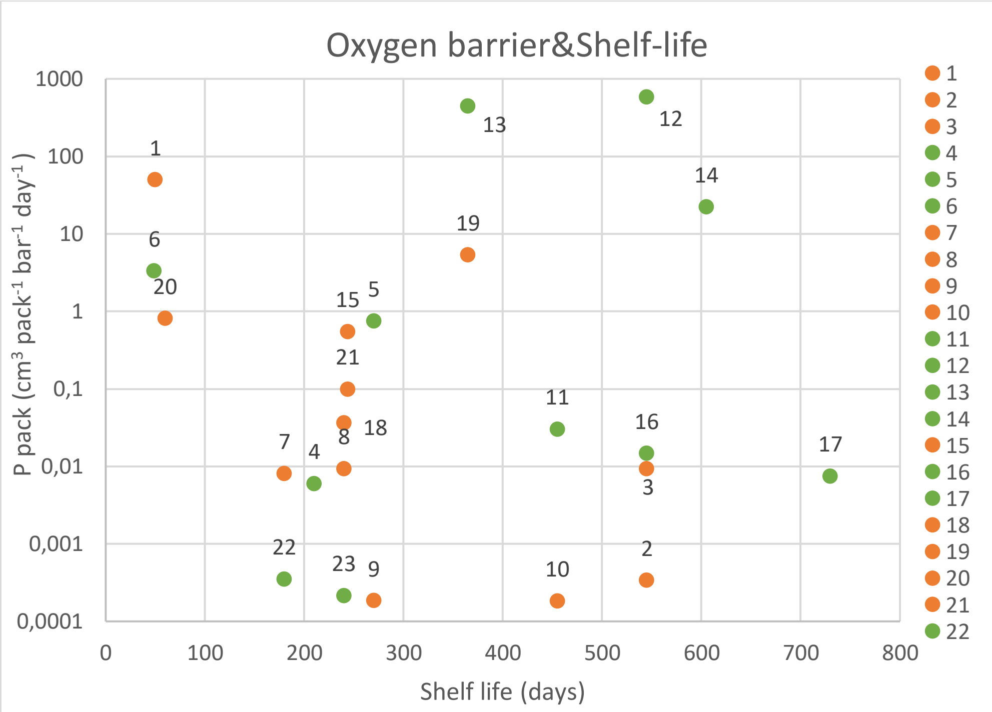
Logically thinking, it could be natural to think that the higher the barrier properties, the longer is the shelf-life, in fact, in the Figure 13 can be observed how the barrier properties influenced the length of the shelf-life. As an example, in the product number 1, the shelf-life is the shortest and, in fact, the permeance of the package to the Water Vapor is very high.

On the contrary, the products number 13, 14 and 15 are long shelf-life products despite using a non-barrier material as packaging material. Looking in details, these last three products are stored in frozen temperature, so the barrier properties of the materials is not important as for other products.

Then, it is possible to say that, as the sample is very heterogenous (many types of food and storage temperatures) it is difficult to detect a correlation between the shelf-life and the water vapour permeance. A classification of the products depending on the characteristics of the food needs to be done.

As highlighted by the circle, it is possible to notice how the flexible packaging solutions have a higher permeability to the water vapour and that could be for the less thickness and so less amount of material.

Figure 14: Relation between length of shelf-life and the barrier properties of the packs, focus on Oxygen



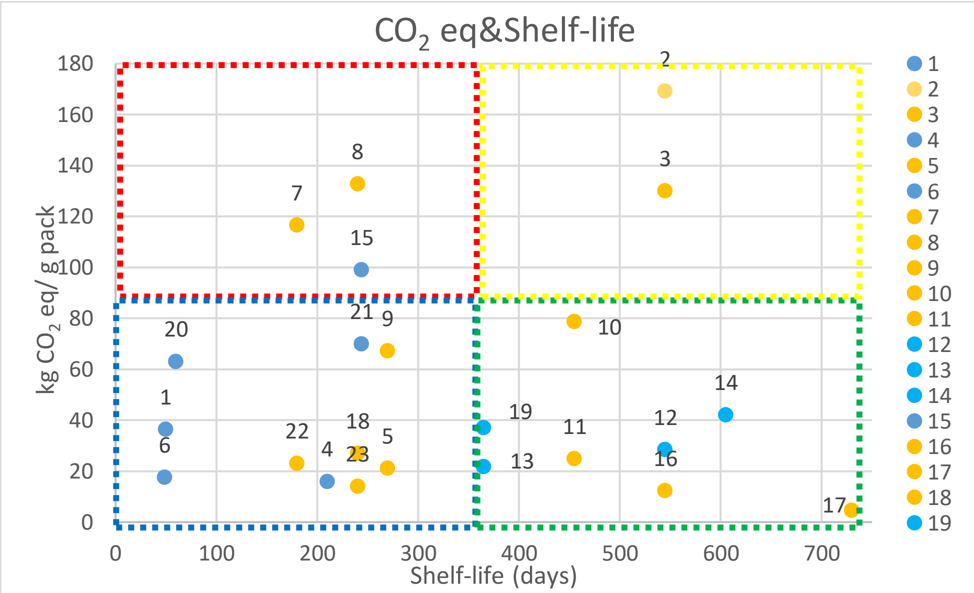
As presented for Figure 13, also figure 14 presents the relation between the shelf-life and the barrier properties, focusing, this time to Oxygen.

Differently to what has been showed in Figure 13, in the Figure 14 there is not a trend for the products and the entire set occupy all the surface of the graph. Going into details, as noticed for the Figure 13 the products 12, 13 and 14 have bad barrier properties but, as they are frozen products, the barrier performances are not so important as for other types of products.

Once again it is clear how the difference type of food products influences a lot the interpretation of these results.

As the barrier properties are correlated to the amount of material used in the packages (it is directly linked to the Carbon Footprint) it is also useful to evaluate how the environmental impact is linked to the shelf life of the products. In the graph shown in the figure 15 the Carbon Footprint (kg CO_2 equivalent per 1000 packs) on the ordinate axis (this time expressed grams of pack) and the length of the shelf life (in days) on the x axis.

Figure 15: Relation between Carbon Footprint and shelf life



As presented for figures 7 and 8, the same method to split the products set is used in the Figure 15; four areas, and so four products categories, have been highlighted. The red area represents the worst case in which the products have a shorter shelf-life using high environmental impact material (Short SL-High impact), the blue area (Short SL-Low impact) with short shelf-life products with low impact materials, the yellow one which presents products with a long Shelf-life but a higher environmental impact (Long SL-High impact) and, finally the best case, the green one with long shelf-life products but low Carbon Footprint (Long SL-Low impact). In this case the most efficient solutions are shown by products with long shelf-life and lower environmental impact (green area) whereas, in the opposite corner, the worst efficiency is presented by short shelf-life and higher environmental impact packaging solutions. As for Figures 7 and 8, the yellow and the blue squares represent efficient products just for the length of shelf-life (yellow area) or the environmental impact (blue area).

Moreover, to characterize even more the graph, the dots are presented using three different colours depending on the storage temperature of the products. The same colours as in table 2 are used.

As the sample is very heterogenous it has been interested to consider the different temperatures of storage that need to be kept during the shelf life of the products. As seen in the barrier properties paragraph, Table 11 shows the different type of packaging solutions presented in each category. The same colours used in the Table 2 will be used.

Table 11: Packaging solutions classification based on Figure 15

Carbon Footprint&Shelf-life		
Short Shelf Life-High impact		
Code of product	*Flexibility of package*	*Storage temperature*
7 – Strawberry jam, squeeze bottle	Rigid	Room
8 – Strawberry jam XL, squeeze bottle	Rigid	Room
15 – Cured herring bucket	Rigid	Chilled
Short Shelf Life-Low impact		
1 – Rice pudding with jam	Rigid	Chilled
4 – Cured flavoured herring	Rigid	Chilled
5 – Lingonberry jam, refill	Flexible	Chilled
6 – Rice pudding, rullpack	Flexible	Room
9 – Dressing	Flexible	Chilled
18 – Jam minipack	Flexible	Room
20 – Chilled soup	Rigid	Room
21 – Herring flavoured ready-to-eat	Rigid	Chilled

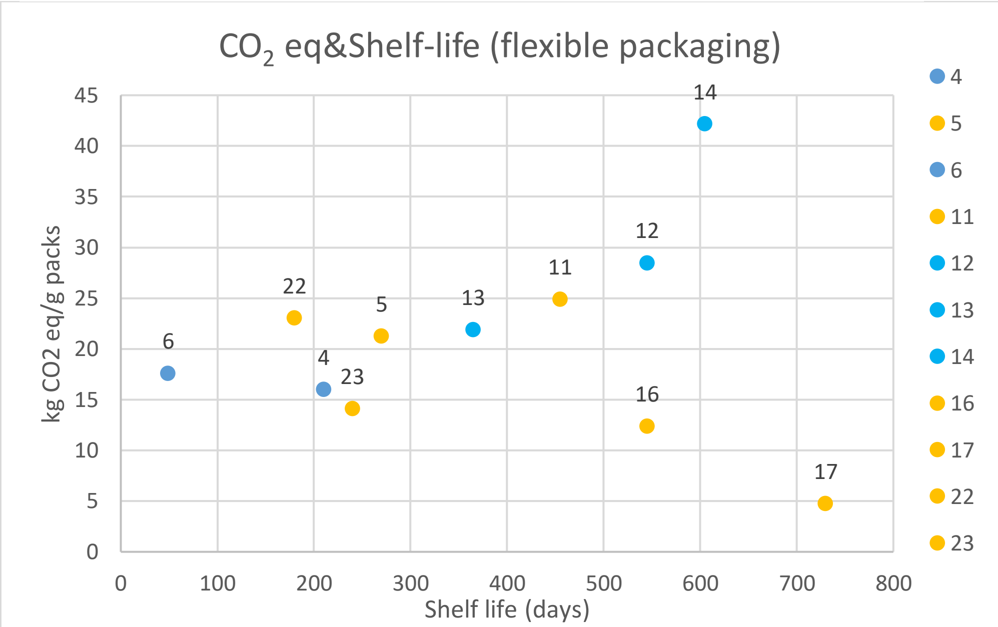
22 – Tortilla wrap	Rigid	Chilled
23 – Tortilla chips crisp	Flexible	Room
Long Shelf Life-High impact		
2 – Ketchup 1 kg	Rigid	Room
3 - Ketchup 500g	Rigid	Room
Long Shelf Life-Low impact		
10 – Sauce	Rigid	Room
11 – Potato powder	Flexible	Room
12 – Frozen fries	Flexible	Frozen
13 – Frozen meat balls	Flexible	Frozen
14 – Minced vegan meat	Flexible	Frozen
16 – Blueberry powder	Flexible	Room
17 - Roseship powder	Flexible	Room
19 - Frozen ready meal	Flexible	Frozen

From the Table 11. it is clear that the products with the best packaging solutions (Long Shelf-life and Low impact) are mostly stored in frozen temperature (13, 14, 15, 20) and packaged with flexible materials. Nevertheless, these products will probably have a higher impact in the production, logistics and distribution phase as they require to keep a low temperature during the chain. It would be very interesting to deepen these branches of the supply chain.

As noticed for the table 9 and 10, in the Table 11 it is possible to see how, generally speaking, the flexible materials are classified as low impact solutions. In particular in the last table (Table 11) it is notable that a lot of flexible packaging and frozen products belong to the last category (Long Shelf Life-Low impact), that make them suitable for a material replacement with biopolymers.

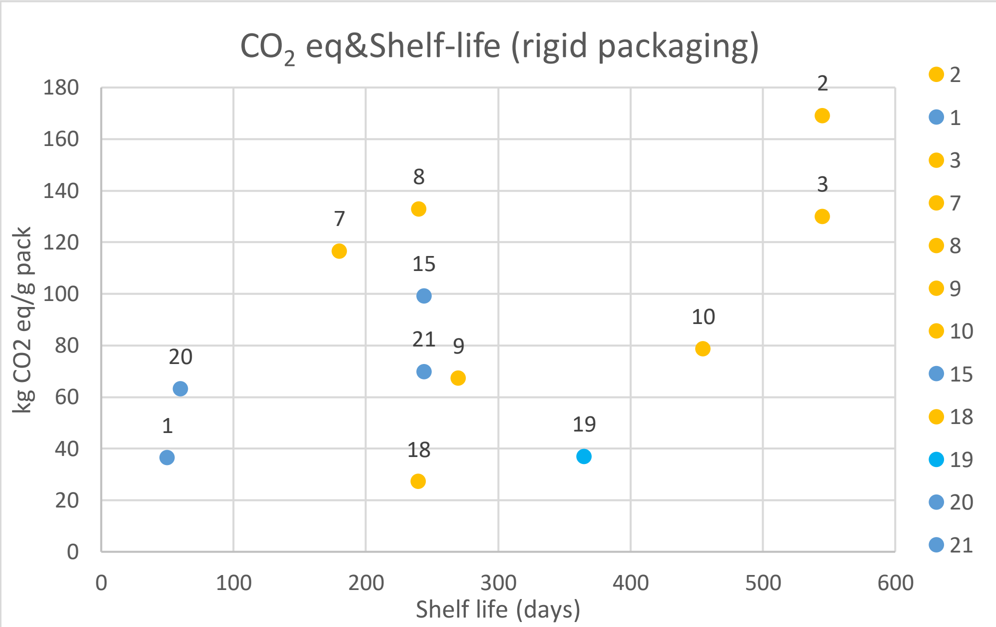
To highlight more how the relation between the Carbon Footprint and shelf-life changes based on the type of material, in the following graphs (Figures 16 and 17) the products are split respectively in flexible and rigid packaging as shown in the table 2.

Figure 16: Relation between Carbon Footprint and Shelf life for flexible packaging



In the Figure 16 it can be seen a tendency of a linear correlation between shelf-life and packaging Carbon Footprint, in fact, with the growing Carbon Footprint (supposingly due to the increase of material used) the shelf-life becomes longer. The products number 16 and 17 seem to be the good packaging solutions both for the properties of the materials used (good shelf-life length) and for the less environmental impact and so, they are the example that it is possible to reach a long shelf-life even using less packaging material.

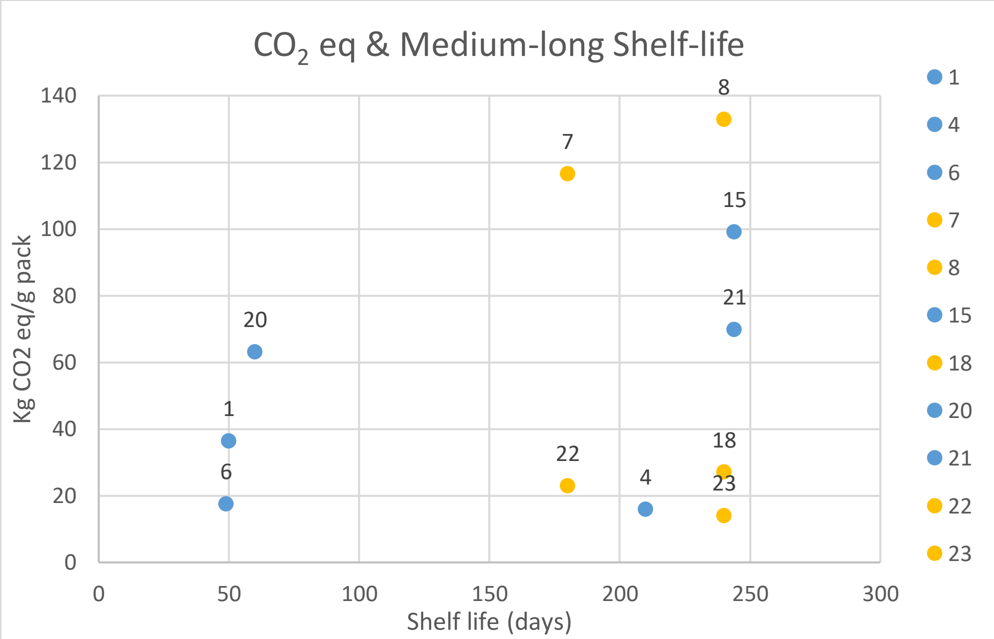
Figure 17: Relation between Carbon Footprint and Shelf life for rigid packaging



The correlation between the length of the shelf-life and the Carbon Footprint seen in Figure 16, does not to be present in Figure 17. It seems that the amount of packaging material of the products 2, 3, 7 and 8 (all rigid packaging) do not contribute to the shelf-life but maybe it has other functions like, for example, providing convenience.

As a confirmation for the data shown before, the products 2 and 3 are the worst packaging solution from an environmental point of view although their long shelf-life. Considering that the food product (ketchup) and the packages size (500g and 1000g) of the number 2 and 3, could be interesting to change the packaging solution by sacrificing the shelf-life length in order to reduce the amount of material used.

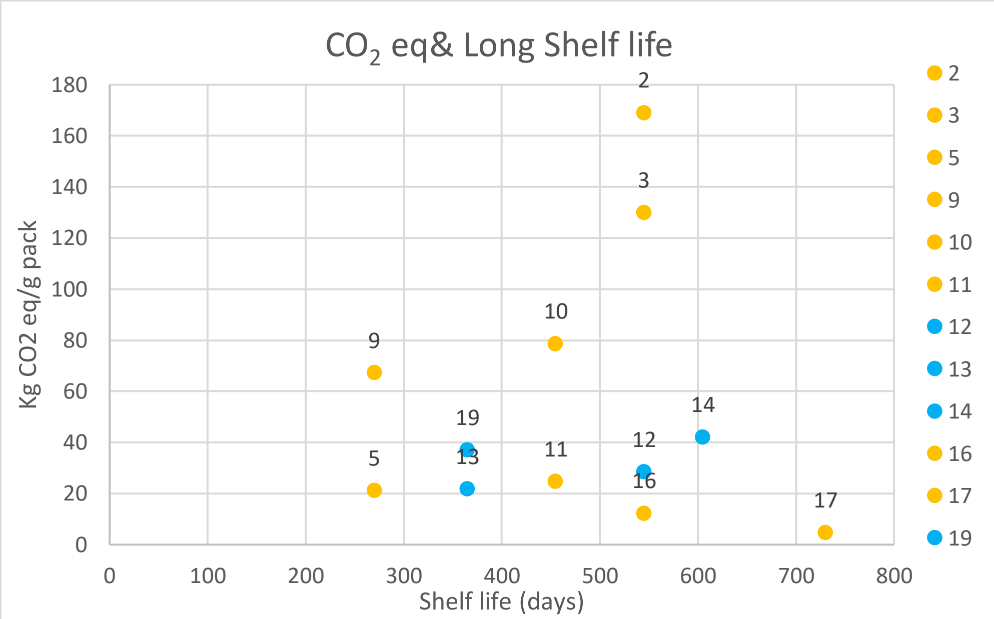
Figure 18: Relation between the Carbon Footprint and the shelf-life of medium-long shelf-life products



In the Figure 18 the products with a medium-long shelf-life (49-250 days) and their environmental impact are shown.

Except for chilled products 1, 6 and 20, the majority of the products of this category can be considered long shelf-life products with an environmental impact very heterogenous. As shown in the table 6, the products with the higher environmental impact for this category are the number 7 and 8 (Squeezy Jam small and XL) that is because both their packaging solution are bottle PET one of the materials with the higher environmental impact, and moreover the packaging solutions used for these kinds of products supplies to the convenience function and that causes an increasing of material used.

Figure 19: Relation between the Carbon Footprint and the shelf-life of long shelf-life products



As described for Figure 18, in the Figure 19 are presented the long shelf-life products (250-730 days) compared with their environmental impact.

As was predictable, all the frozen products (12, 13, 14, 19) are present in this category and they show a low environmental impact because the shelf-life of frozen products is mainly dependent on temperature and less on barrier properties of the packaging.

Moreover, the products number 2, 3 and 17 present the packaging solutions with extreme characteristics. In fact, the number 17 in addition to being a dry product, it seems to be the best solution as it has the longest shelf-life and the lowest environmental impact. Finally, the ketchup products 2 and 3 are, once again, the packaging solutions with the higher environmental impact in the category.

4.4 Discussion

This project tries to combine the LCA methodology with the performances of the plastic packaging materials. In general, in literature there are a lot of examples in which the LCA are lead for one single product analysing the Carbon Footprint of different types of materials (Dalla Riva et al., 2017; Girgenti et al., 2013; Tasca et al., 2017). The new approach presented in this project can evaluate a big sample of products using the barrier properties and the CO_2 equivalent as parameters. For that reason, it could be interesting to apply this methodology in industries, including both packaging producers and packaging consumers. Usually, as the set of products can be big and heterogenous (as in this case) it is suggested to categorize the sample to make the analysis easier.

Considering the two main analyses of this project, the material and the packaging analysis it is possible to say that the materials analysis can be considered the first step of a company evaluation. Choosing, between two materials with the same barrier properties, the one with the lower environmental impact can be a possible solution (Figure 5).

Thinking about the packaging solution analysis, a lot of comments and discussions can be done.

The first result shows how the type of the packaging solution is decisive to evaluate the environmental impact. Some of the flexible packaging solutions, in fact, have good barrier properties and lower environmental impact (due to the small quantity of material used). Whereas, generally speaking, rigid packaging provides good barrier properties but with higher environmental impact.

The relation between the two different barrier properties considered (Water Vapour Transmission Rate and Oxygen Transmission Rate) and the Carbon Footprint can be evaluated and it is possible to try to find if there is any correlation. For the WVTR and rigid packaging it has been found that the thicker the packaging the higher is the Carbon Footprint. For the OTR this relation is not so clear. For the flexible packaging and the WVTR, instead, there is no clear correlation but, for the packaging solution that are chilled or frozen, biopolymers can be used as the shelf-life for them does not need to be long (Girgenti et al., 2013; Girgenti et al., 2014).

Moreover, it is important to consider that the rigid packaging has other functions like, for example, convenience. In this case an evaluation of the requirements of the food products is needed to choose, through analysis of both the shelf-life and the environmental impact, the best packaging solution. Looking at these results and considering the convenience and the other functions of packaging, the presence of trade-offs in the plastic field is even more evident. To clarify which are the most important properties and functions for the different packaging solutions is the main challenge for the food packaging suppliers and consumers.

From the results obtained, it is clear that a lot of parameters and types of products are evaluated. To have a complete overview the solution is to categorize the set of products. In Figure 13 and 14, for example, the types of packaging (rigid or flexible) are highlighted with different colours. It can be noticed that the flexible products might have a various shelf-life length due to the different processes and ingredients (like salt, condiments or preservatives).

In addition, to have a complete evaluation of the environmental impact of the packaging solutions, it is important to evaluate also the effects of the logistics, storage and disposal segments.

5 Conclusions, Limitations and Recommendation for Future Research

This chapter presents the conclusions of the study organized as the results chapter, the limitations of the method used for the study and, finally, the recommendations and the suggestions for future research.

5.1 Conclusions

This project focused on the plastic field and its aim and research objectives are:

- To compare a set of different food packaging solutions from the environmental and barrier performances points of view.
- To evaluate the efficiency of food packaging solutions using as the parameter the shelf-life length.
- To find methodology and parameters that can be used by food industries to lead the green packaging development comparing the environmental impact of the production of plastic packaging materials with their barrier properties.

These research objectives were answered collecting primary and secondary data related to a set of 23 Orkla Foods packaging solutions. During the packaging solutions analysis, the relation between the environmental impact of the packaging material production and the barrier properties was evaluated. To estimate the environmental impact a simplified Life Cycle Assessment has been performed. Due to the heterogeneity of the sample, it has been necessary to categorize the set of products in different categorize like rigid and flexible packaging, long and short shelf-life and chill, room temperature and frozen storage temperature in the results presentation.

The parameters used in this work related to barrier properties and Carbon Footprint seem to be adequate to analyze the performances of the packaging solutions and the methodology here shown can be applied in the industrial field. Nevertheless, it is clear how the Carbon Footprint and the barrier performances are correlated to multiple factors like the length of the shelf-life, the storage temperature, the size of the package and, last but not least, the food product requirements. In fact, the highest impacts have been seen for products which have a long shelf-life or need to be stored in room temperature.

It is also clear how the nature of the packaging solution influences the environmental impact. In fact, the rigid packaging presents, in mostly of the graphs, a higher environmental impact then the flexible one. Speaking about utility and convenience in the food packaging, marketing and consumers habits affect significantly packaging development and not to renounce to any functions is challenging. But, as shown by the results, a higher environmental impact is the price to pay for the convenience and this, for a sustainable future, cannot be accepted anymore.

Regarding the use of S/V parameter to evaluate the size of the product, it can be said that could have good applications but needs accurate measurements.

Focusing on the different type of products, the most important result that is common in mostly of the graphs presented is the high environmental impact of the Ketchup packages (number 2 and 3). In fact, even if they have a long shelf-life, their environmental impact could be decreased using different types of packaging solutions and considering the hypothesis of reducing the shelf-life length.

As a conclusion it is possible to say that if the shelf-life was shorter would have been possible to reduce the amount of material used and, in this way, also the Carbon Footprint impacts.

5.2 Limitations

The main limitation of this project is that most of the values presented, like surfaces and areas originate from calculations and that could represent a lower level of accuracy.

The greater example of this limitation regards the barrier properties values: using Norner Calculator software, although it is a useful tool, the data found were not as accurate as possible. In fact, the permeability data found from Norner Software about the rigid packaging, are related to the film of material. In general, the films of materials have different thickness and barrier properties from the shaped package and that because the process of shaping tends to press the layer and makes it thinner.

For the same reason, the calculations done about the Volume and the Surface of the packages were approximations. Regarding the dimension, the shape and the total amount of material used in the packaging solutions, it is necessary to keep into account that, during the development or the choosing of packaging, also other aspect and packaging functions need to be considered. For the same reason, as presented in the discussions, it is not possible to evaluate the quantity of materials used for flexible and rigid packaging in the same way.

Another important limitation is that the environmental analysis that has been led considered just the CO_2 emitted for the production of the materials. In fact, the End-of-Life of products is not considered in the evaluation and the risk of not considering the entire supply chain is that it is not possible to have an overview about the environmental impact of the packaging solution. For example, if the flexible packaging on one hand has been evaluated positively for their low environmental impact during the production phase, on the other hand most of them are multilayers and non-recyclable materials.

An additional limitation could be that in this study just the Carbon Footprint is the only environmental impact considered. The risk of excluding other types of environmental impacts is that it is not possible to consider the other direct or indirect impacts that plastics have on the environment such as littering and water pollution.

5.3 Recommendations for future research and industrial applications

For the limitations presented in the previous paragraph, for future research it is suggested to find more accurate permeability data related to the final packaging. For a more complete environmental impact evaluation it would be necessary to consider both the End-of-Life of the products and the total CO_2 emitted also for the storage and the logistics parts of the food supply chain. In addition, it would be interesting to analyse the Global Warming Potential considering different geographical areas depending on the origin of the raw material and the production system.

It could be interesting also to perform the same analysis considering the food product and the impact of its production including the environmental impact of both ingredients (raw materials) and final product production.

As new types of packaging materials, like bioplastics, are currently evaluated in many research projects, it could also be interesting to apply the same approach on bio-plastics to compare them between themselves or the traditional, fossil-based plastic materials.

From the industrial point of view, the results and the conclusions of this thesis suggest to better evaluate the type of plastic packaging material in the first phase of

the packaging solution development. For example, increasing the use of flexible packaging could be the first step to reduce the environmental impact whilewhere the performances of the rigid packaging are required (for convenience, for example) could be interesting to evaluate other type of materials (for example, paper) as an addition to the flexible primary packaging. Moreover, the application of biopolymers or bioplastics could be considered to reduce the environmental impact as well.
Generally speaking, the knowledge of performances, characteristics, limitations, and environmental impact of the different packaging materials could help the industry to choose the best solution for the consumers and for the environment.

With this aim and for the results shown in this work, Orkla Foods could use the method presented in this project to deepen the analysis of its portfolio in order to identify the products of which packaging re-evaluation need to be done. Reviewing the design and the efficiency of food packaging solutions means also identifying the most important properties (among protection, convenience and marketing) in order to create intelligent solutions for a sustainable future and to guide the consumers towards more sustainable choices.

Lastly, introducing more information about the packaging environmental impact and the materials used on the packages itself could help the consumers to choose the products with a conscious attitude. Unfortunately, in fact, consumers are not familiar with the different type of plastics used in the food packaging field, guiding them through the best choice is the only way to make the innovations useful and successful.

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