Relationship between food shelf life and environmental impact of Tetra Pak packages

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Abstract

Food packaging has long been recognized as a potential environmental burden within the food supply chain, with packaging production and waste often considered as key contributors to the overall environmental impact. However, there is a growing recognition of the need for a more holistic approach to assess the environmental performance of food packaging, taking into account various factors that influence sustainability. This Master's Thesis aims to theoretically investigate the potential environmental impact of three different barrier materials for current and future potential use in Tetra Brik Aseptic packaging. The study focuses on examining the relationship between direct environmental impact, assessed through a life cycle assessment (LCA) analysis with a specific emphasis on greenhouse gas (GHG) emissions, and the indirect environmental impact resulting from the performance of barrier properties, which can influence the shelf-life length and potentially contribute to food waste. To assess the environmental impacts of the packaging structures, SimaPro 9.3 software was employed, considering the raw materials and processing stages. The barrier properties were evaluated using the Norner calculator. The direct environmental assessment revealed a significant 25% reduction in CO_2 emissions for the new barrier structures compared to the existing one. However, the new barrier structures had higher oxygen permeability, which affected the packaging's ability to protect and maintain product quality, reducing its shelf-life. Moreover, the study identified a strong correlation between GHG emissions, barrier properties, and shelf-life length. These findings provide valuable insights for the company by presenting a preliminary environmental evaluation of a new barrier material structures, while also contributing to the academic knowledge in this field.

Keywords: LCA analysis, barrier properties, food packaging, food waste, environmental impact

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Table of contents

List of tables

List of figures

List of acronyms and abbreviations

FAO	Food and Agriculture Organization
TBA	Tetra Brik Aseptic
O_2	Oxygen
N_2	Nitrogen
CO_2	Carbon dioxide
GHG	Greenhouse gas
GWP	Global Warming Potential
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Inventory Assessment
FU	Functional Unit
P	Permeability
OTR	Oxygen Transmission Rate
WVTR	Water Vapour Transmission Rate
TR	Transmission rate
RH	Relative Humidity
HDPE	High density polyethylene
IoFs	Indices of failure
PET	Poly(ethylene) terephthalate
EVA	ethylene vinyl alcohol
EAA	ethylene acrylic acid

1 1. Introduction

This introduction section provides necessary background information, outlining the purpose and objectives of the project. Moreover, it also highlights the limitations that were applied in this study to achieve the desired outcome.

1.1 Background and motivation

Food packaging plays an important role in protecting food products from the chemical, physical and biological influences, as well as facilitating safe distribution and preventing food loss. Tetra Pak is a leading global company in food processing and packaging, which provides safe, innovative and environmentally sound products and solutions, that every day meet the needs of millions of people around the world. In the 2021 more than 192 billion Tetra Pak packages have been sold, delivering approximately 78 billion liters of product worldwide.

The main mission of Tetra Pak states that the company:

> *Commit to making food safe and available, everywhere and promise to protect what's good: food, people and the planet.*

For 70 years, sustainability has been a core value of Tetra Pak, to increase food availability, safety, reduce food waste and improve resource and logistics efficiency. Constantly developing new solutions for their packaging Tetra Pak aims to achieve its goal of net zero carbon emissions by 2030 through a four-pronged strategy that includes (1) using 100% renewable energy to lower energy-related emissions, (2) partnering with suppliers and stakeholders to significantly reduce the carbon footprint, (3) developing low-carbon, circular packaging materials, and equipment to help customers meet their sustainability goals, while keeping food products safe and reducing food waste, and moreover (4) to establish sustainable recycling value chains via collaboration with stakeholders, such as customers, waste management companies and governmental and non-governmental organizations (Tetra Pak, 2020).

This research will be focused on the third initiative of Tetra Pak's sustainable strategy, which involves the development of low-carbon, circular packaging materials, specifically the barrier materials for Tetra Brik Aseptic. The current composite packaging for Tetra Brik Aseptic Base consists of paperboard, aluminium and plastic layers (Zhang et al., 2014), with the aluminium layer playing a critical role in ensuring food safety, by providing absolute barrier effects to water vapour, gases, light and microorganisms for the packaging structure. However, this layer is also responsible for a third of the green-house gas emissions associated with the base materials used in Tetra Pak (Tetra Pak, n.d.). Therefore, in order to reduce the climate impact of their packaging, the company is continuously developing new barrier solutions made from more sustainable materials, with a goal of creating an aseptic package that is fully renewable, fully recyclable and carbon-neutral. The barrier materials that will be analyzed in this study are part of the Tetra Pak's long-term roadmap towards achieving this sustainability objective.

Tetra Pak's goal to create fully renewable, recyclable and carbon-neutral packaging aligns with important EU regulations aimed at promoting sustainable packaging. For instance, the company can assist their customers in meeting the requirements of Extended Producer Responsibility (EPR) schemes, which make producers responsible for the packaging sustainability. Additionally, considering the latest issued Packaging and Packaging Waste Regulations which are willing to ban the single-use packaging, Tetra Pak as a leading single-use packaging producer should meet these new regulatory requirements. Thus, by developing a fully carbon-neutral packaging structure, the company can contribute to the collective goal of achieving climate neutrality by 2050.

These EU regulations have been prompted by the increasing volume of packaging waste. On an average, every European individual produce around 180 kg of packaging waste annually. Furthermore, packaging accounts for a significant amount of raw materials usage in the EU, with 40% of virgin plastic and 50% of paper being used in packaging industry. Without these regulations, the EU could witness a 19% increase in packaging waste by 2030, and a staggering 46% rise in plastic packaging waste (European Green Deal, 2022).

Food packaging is an essential component of the food supply chain and is becoming a pivotal element of the sustainable food system, due to its controversial effect on the environment. For many years packaging has been blamed for representing the highest environmental burden in food production, however, recently, the focus from the packaging materials production and packaging waste has been shifted to the more holistic assessment taking into account their functional aspects.

Food packaging's protective function, among others, primarily involves controlling gas and vapor exchange with the external environment through barrier properties. By doing so, food packaging can preserve the beneficial effects of processing and increase the shelf-life of fresh and perishable food products (Marsh and Bugusu, 2007).

The environmental impact of the packaging can be reviewed from two perspectives. On one hand, sustainable development requires the preservation of limited natural resources and the mitigation of climate change by reducing greenhouse gas emissions from packaging materials. On the other hand, packaging's protective function can indirectly contribute to reduce food waste and loss, which cause more significant environmental burden. For example, a study of Chan *et al.* (2011) compared the environmental performance of polyamide and aluminium as a barrier material in aseptic liquid packaging. It was found that polyamide was more sustainable than aluminium due to the difficulty in separating and recycling the aluminium barrier layer. However, the study did not evaluate the effectiveness of aluminium in extending the shelf-life of the food products. While a life cycle assessment study made by Manfredi *et al.* (2015) compared the environmental impact of two milk packages, one coated with antimicrobial agent and the other one without. The results revealed that the package with antimicrobial agent had more environmental benefits than impacts due to extended shelf-life of milk, resulting in reduced milk waste.

Approximately one third of the food produced globally for human consumption is lost or wasted (FAO, 2011). This leads to direct greenhouse gas emissions accounting for 17% and a material resource use of 28% (Lundqvist, 2008). Recent debates on food waste have been highlighted that the indirect environmental impact of packaging is more important in many food supply chains than its direct environmental impact (Verghese *et al.,* 2015; Silvenius *et al*., 2014; Wikström and Williams, 2010). The direct environmental impact of food packaging results from the production and end-of-life stages of the packaging materials, whereas the indirect environmental impact caused by packaging's influence on the food products' life cycle (Molina-Besch *et al*., 2019). The protective function of packaging has been identified as an important environmental benefit, that can significantly influence the indirect environmental impact (Bertoluci *et al*., 2014). Moreover, nowadays, researchers suggest that the environmental assessments of packaging must consider both its direct and indirect environmental impact (Büsser and Jungbluth, 2009; Wikström and Williams, 2010).

1.2 Project Purpose and Objective

The aim of this thesis is to theoretically assess the feasibility of integrating new sustainable barrier materials into Tetra Brik Aseptic packaging structure by analyzing their environmental and barrier performance. Specifically, the aim is to investigate the relationship between the direct environmental impact, measured by greenhouse gas emissions, and the indirect environmental impact resulting from the barrier properties performance, which affects the shelf-life length and potentially contributes to food waste.

To achieve this aim, the following research objectives have been set:

- to investigate the barrier properties of a new barrier material structures
- to assess the direct environmental impact, caused by the production of the new barrier material structures
- to analyze the efficiency of a new barrier materials by estimating a potential shelf-life length
- to estimate the potential indirect environmental impact associated with the barrier properties performance.

1.3 Delimitations

The following delimitations have been set for the study:

- Barrier properties were estimated using only Norner Calculator, primarily relying on material permeability and packaging geometry, such as volume and metric size, without accounting for packaging folding.
- The environmental impact assessment mainly focuses on GHG emissions, following the primary interest of Tetra Pak.
- The Life Cycle Assessment is limited from raw materials extraction to packaging laminate production steps, excluding transport, usage and end-of-life stages.
- The assessed packaging is Tetra Brik Aseptic Base without any openings and headspace.
- The inside product for the shelf-life estimation is considered to be orange juice.
- The shelf-life of packaging is estimated based only on the potential Vitamin C degradation.

2 Theoretical framework

This chapter presents an essential theoretical background gathered from various literature sources and Tetra Pak to comprehend the study. It comprises three main topics. Firstly, the packaging's protective function and its associated barrier properties will be discussed. Secondly, the concept of Life Cycle Assessment method necessary for assessing packaging's direct environmental impact, will be examined. Finally, the indirect environmental influence will be analyzed.

2.1 Essential functions of food packaging

Food packaging is of a great importance in the food industry as it protects and preserves food products from physical damages, microbiological contaminations and chemical deteriorations during transportation, storage and distribution. Packaging designed to maintain the quality and safety of food products while allowing to provide food to as many people as possible in various parts of the world.

Generally packaging system distinct between different packaging levels: primary, secondary and tertiary. A primary packaging level is the package that is in direct contact with the food product and provides the initial and major protective barrier. Usually, consumers interact with primary packaging, which might be a paperboard carton, glass bottle, or plastic pouch. A secondary package is one that contains multiple primary packages. It can be represented by a corrugated box or a plastic creaser. A tertiary package consists of several secondary packages and resembles a wooden pallet with wrapped corrugated boxes (Robertson, 2016). All the levels of packaging system serve multiple vital functions beyond the conventional role of protecting the product.

The main six packaging functions of food packaging were summarized before by several researchers (Hellström, 2007; Hellström & Olsson, 2017; Pålsson, 2018):

1. Protection: a key packaging function that provides protection from the outside environment, such as water, gases, microbes, vibrations, and so on.
2. Containment: the function which means that the package should contain the product, to avoid any product loss and pollution.
3. Apportionment: allow to manage large outputs into small, convenient for consumers portions.
4. Unitization: allows for better material handling through modularization.

5. Communication: allow product to communicate with consumers, logistics actors and to fulfil legal and commercial demands.
6. Convenience: simplify the consumption of the product.

2.1.1 Food Packaging

Generally, the principal role of food packaging is discussed in terms of providing the following basic functions which were mentioned before (Yam *et al.*, 1992; Marsh, 2001; Robertson, 2006b):

1. *Protection.* The principal function of food packaging is to protect foods from outside influences and damage (Schmid and Agulla, 2012). The need to protect the food product is regarded as the most important food packaging function, since it involves safeguarding the product and preventing microbial spoilage, oxidation of vitamins or color, moisture change impacting food texture, aroma loss, and physical damages (Min *et al.*, 2007). Furthermore, the protection function is an important aspect of the preservation process for many food products. Aseptically packaged milk and fruit juices, for example, stay only aseptic for as long as the product provides protection. Similarly, vacuum packed meat is unlikely to achieve the required shelf life if the package allows O_2 to enter (Robertson, 2016).
2. *Containment.* The containment function contributes significantly to the environment by maintaining the integrity of the product and packaging and so protecting it from a wide range of product pollution and waste. Even today, poor containment functions of food packaging generate various dissatisfaction as a leakage of liquid food products, particularly around the closure and seals (Robertson, 2016).
3. *Apportionment.* The apportionment function provides clients with food packaged in convenient quantities that meet their exact quantity needs depending on their consumption habits. Correctly implementing apportionment can help reduce product waste by limiting the packaging of excessive amounts of food that cannot be consumed within the projected shelf-life and intended consumption time of the product (Hellström & Olsson, 2017; Pålsson, 2018).
4. *Unitization.* The unitization of a different levels of packaging system allows to facilitate the material handling during the different supply chain actors. It also, facilitates the repacking of food products in the warehouse and replenishment process in the supermarket (Pålsson, 2018).
5. *Communication.* Communication is a sophisticated and vital aspect of packaging that serves multiple functions. The one old saying states that "*a package must protect what it sells and sell what it protects*" (Judd *et al.*, 1989). This statement retains its importance even now, by facilitating marketing services by allowing the product to be distinguished by its shapes, branding, and labelling. Besides from the promotional messages declared on food packaging, it also fulfills regulatory requirements by stating a nutritional content, containing all

ingredients (including potential allergens), net content and place of origin (Krotcha, 2007). Furthermore, the communication function of the food product delivers track & trace data through labeling across the supply chain using barcodes and RFID (Pålsson, 2018).

6. *Convenience.* Together with the modern industrialized living pace and lifestyle changes, packaging should satisfy the needs of consumers in order to provide convenient food consumption. Convenience might include a variety of sizes, ease of handling, ease of opening, and reclosability (Krotcha, 2007). Considering convenience in the development of food packaging can result in the reduction of food waste in a household.

2.1.2 Packaging Development

Package design should ideally be considered during the product concept development stage, as new product development that is applied in the whole product concept including packaging is more successful (Coles, 2003). In order to produce a concept that aligns with the framework below Table 1, the development process should involve the collaboration of several stakeholders such as R&D, logistics, marketing, and environmental departments by implementing a holistic approach.

Table 1. The packaging design and development framework.

Market analysis
Food product assessment
Packaging material comparison
Package design, considering all the functions of packaging
Package manufacture and testing
Food shelf - life prediction and determination
Food Packaging law
Market testing

(developed from Krocha, 2006)

Further only the development stages that will be discussed in this study will be elaborated on.

Food product assessment.

For the design and development of a new packaging concept, a full understanding of the extrinsic and intrinsic factors that affect the food product and cause it to deteriorate, degrade or lead to possible interaction with packaging materials is required (Coles, 2003). While selecting packaging material, it is critical to understand a product's requirements and examine its individual physico-chemical properties: pH, aw, sugar content, salt and spice content, additional preservatives or antioxidants, initial microbial load, and natural colors (Olsson, 2018). The most important extrinsic and intrinsic factors influencing on the product listed below Table 2.

Table 2. List of extrinsic and intrinsic deteriorative factors for food product.

Types of deteriorative factor	*Deteriorative changes*
Biochemical	Enzymatic reactions caused by
	Temperature increase
	Water activity
	Substrate alteration
Chemical	Non-enzymatic browning
	Lipid hydrolysis
	Lipid oxidation
	Protein denaturation
	Protein cross-linking
	Protein hydrolysis
	Natural pigment degradation
	Aroma loss through oxidation
	Loss of vitamins
	Glycolytic changes
Physical	Softening
	Toughening
	Loss of water holding capacity
	Wetting
	Agglomeration
	Emulsion instability
	Breakage/crushing
	Moisture loss/gain
	Aroma loss (volatility)
(Micro)biological	Microbial contamination and growth influenced by
	Initial microbial load
	pH
	Water activity
	Nutrients
	Storage temperature
	Relative humidity
	Concentration of gases in headspace (O_2, CO_2)

(Krochta, 2006; Petersen *et al.*, 1999)

Packaging material comparison. Packaging is continually being improved by the introduction of new materials, technology, and processes, which can be attributed to the desire to increase product quality, productivity, logistical service, environmental performance, and profitability (Coles, 2003). Several packaging material qualities must be addressed depending on the packaged product: barrier properties, mechanical properties, material component migration, etc. The resistance to gas permeability (O_2, CO_2, N_2), water vapor, aroma, and light permeability are all examples of barrier qualities. Mechanical qualities include tensile strength, tear strength, puncture resistance, among others. The food product has a direct interaction with the packaging material, which might change the material's performance depending on the type of food product (Stolberg, 2019). Consequently, it is critical to consider storage and distribution conditions to ensure optimal shelf-life, food product safety, and good material performance across the supply chain (Peterson *et al*., 1999).

Food shelf - life prediction and determination.

The shelf-life of a product is determined by the variance between its initial quality and the acceptable quality limit. Increasing this difference between acceptable and initial quality extends the shelf-life or lowers the package barrier requirements for the same shelf-life (Gyeszly, 1991). The shelf-life of a product directly depends on the food quality and safety and correlated to the degradation reactions occurring during each step of the product's life cycle. These degradation processes rely on the intrinsic properties of the product Figure 1. Thus, it is important to analyze the shelf-life of the future packaging based on the product's need and material properties. For instance, if the customer wants flexible packaging for a moisture or oxygen sensitive product, the shelf-life will have certain limitations due to the use of plastic. These limitations should be recognized and addressed early on to optimize resources and time and produce satisfactory results (Gyeszly, 1991).

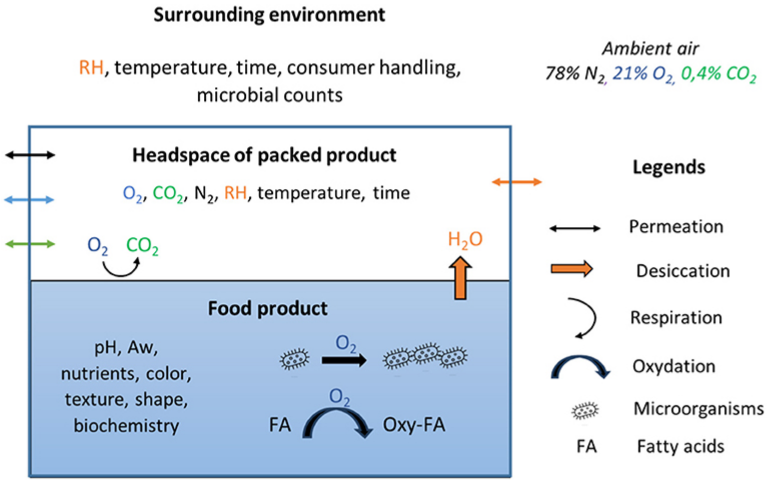


Figure 1. The transfer reactions of packed food depending on internal and external factors (Coffigniez *et al.*, 2021).

The estimation of the shelf-life related to the barrier properties of the packaging can be identified by the shelf-life models. To create such a model, it is necessary to identify the primary reaction that limits the degradation of the food and to use an equation that reflects the evolution of this degradation based on intrinsic and extrinsic factors (Coffigniez, 2021). The shelf-life assessment process described by Nicoli (2012) as a first and preliminary step includes Identification of the Early Critical Event, which means to identify the most critical impact on food quality at the storage conditions foreseen for the packed product. When all factors are taken into account, it is often possible to identify those that are shelf-life limiting because they induce early quality changes. Because the focus of this research will be on the packaging of orange juice, the Early Critical Event for this system will be vitamin C degradation, and the Critical Descriptor or IoFs (indices of failure) will be the minimal value of vitamin C concentration after a 12-month shelf-life, which is defined by Tetra Pak internal regulation (Tetra Pak, 2000).

2.1.2 Sustainable Packaging Development

One of another additional packaging functions described by Krotcha (2007) is a *minimal environmental impact*, which needs to be considered in the packaging design step. This includes minimization of packaging cost and packaging waste, to reduce the amount of packaging used, which refers to the source reduction. Because the production, usage, and disposal of packaging associated with various environmental consequences, there is an increasing need for the environmental assessment of packaging concept on the development process stage.

Environmental sustainability should be analyzed during the development process using methods that allow estimating the environmental consequences that could be produced during all phases of the package life cycle. Life Cycle Assessment (LCA) is the most widely used scientific tool for assessing the sustainability of products and services (De Feo and Ferrara, 2017). Numerous studies used LCA to assess the environmental performance of alternative packaging systems (Sazdovski *et al.*, 2021; Sundqvist-Andberg and Kerman, 2021).

Over the past two decades, packaging sustainability was addressed to minimize packaging waste. Efforts have been made to prioritize recyclability, reduce the usage of materials and better use of natural sources to have less carbon dioxide emissions. These actions are aligned with the goals outlined in Directive 94/62/EC on Packaging and Packaging Waste (Wikström and Williams, 2010).

However, the primary benefit of packaging in terms of sustainability is its ability to prevent food waste and facilitate efficient distribution (Verghese *et al.*, 2015). Thus, inadequate packaging can have adverse environmental effects, including packaging-related food losses and waste (FLW). These indirect effects of improper packaging practices contribute to larger environmental issues, emphasizing the importance of sustainable packaging solutions (Pauer, 2019). According to the FUSION EU report around 53% of the food waste was generated by consumers in 2012 (Stenmarck *et al.*,2016). According to (Wikström and Williams, 2012), Swedish households wasted approximately 20-25% of their food due to packaging solutions that were too difficult to empty, too large in volume for their needs, and so on. As a result, when developing sustainable packaging solutions, it is essential to keep in mind that food production in Europe accounts for approximately 20-30% of emissions, whereas food packaging accounts for just 5-10% of total environmental effect.

Sustainable packaging design requires a holistic approach by taking into consideration the product-packaging system as it was mentioned before. There are may be trade-offs between objectives, such as between material efficiency and the recyclability of plastic packaging, between improved recyclability and the expense of changing the packaging, and between the removal of heavy metal-based inks and marketing benefits. Thus, the design process should begin by answering a more open question in order to gain benefits from multiple perspectives (Lewis, 2012).

Grönman *et al*. (2013) has recommended that both the packaging and the product itself should be taken into account when designing the final package, in order to reduce both product losses and environmental impacts. Azzi *et al*. (2012) have stated that the impact of packaging design on supply chain costs and performance can be devastating.

Taking all the above findings into account, it is essential to consider various aspects in order to correctly evaluate the environmental sustainability of packaging. Which includes the direct environmental effects of packaging production and disposal, as well as the indirect effects of issues such as packaging-related food waste and packaging circularity. Taking all of these elements into consideration facilitates informed decision-making regarding sustainable packaging solutions for both consumers and producers.

2.2 Packaging barrier materials and properties

Food packaging serves a multitude of functions, but perhaps one of the most important is protection. Barrier materials are essential to achieving this goal, as they help to extend the shelf-life of food products by preserving their color, odor, taste and quality. As a results, these materials contribute significantly to the reduction of food waste. Specifically, barrier materials offer protection against oxygen and water vapor, which can give a detrimental impact on the vitamins and lipids degradation, causing browning or food deterioration. It is also worth noting that the use of barrier materials can reduce the need for preservatives, which is a major benefit in terms of both health and sustainability.

2.2.1 Permeation Theory

Permeability is described in many literatures as a measurement of the rate at which a resistant material allows the transmission of permeate which can be gas or water vapour (Pauly, 1999; Galic *et al*., 2000; Robertson, 2016). Thus, the concept of permeability is associated with the quantification of the barrier properties of the packaging materials. The permeation theory in a simple way is defined as the number of molecules that can pass through the barrier film. The permeation process starts when gas or water vapour molecules dissolve into the film from the side with a greater concentration of the permeates, then they dissolve through the film's structure and migrate to the side with a lower permeate concentration, this process can be seen in Figure 2 (Siracusa, 2012).

The transmission rate (TR) is the quantity of permeant that is transferred through a unit area film per time. Thus, the oxygen transmission rate (OTR) is typically expressed in cubic centimeters of gas passing through a square meter of film in 24 hours at a pressure difference of one atmosphere and at a specific temperature. While water vapor transmission rate (WVTR) is expressed in grams of water which passing through a defined area of material in a specific time in a grams per 1 square meter per 24 hours at a specific temperature and humidity differential (Massey, 2003).

It is worth mentioning that permeability (P) is a material property, whereas TR is a property of packaging and permeant under specified test conditions. Therefore, permeability is considered a material constant of the barrier polymers as long as the structure of the film does not change, and the thickness of the materials is measured based on the P value of the material to obtain the desired OTR values (Massey, 2003).

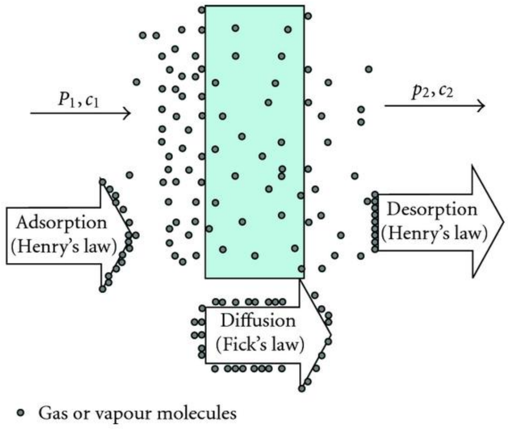


Figure 2. Gas or vapour permeation through the plastic barrier film (Siracusa, 2012).

2.2.2 Barrier materials

Barrier materials can be defined as materials that can prevent gases, vapors, and organic liquids from passing beyond their borders. Plastic films and sheeting, coatings, laminates, metal foils, and a variety of other materials are used to provide efficient barrier layer (Massey, 2003). The most common polymers used in food packaging industry due to their good chemical and heat resistance, low, medium and high gas permeability and water vapour transmission rate are:

- Polyolefins, including low-, linear low- and high-density polyethylene (LDPE, LLDPE, HDPE), polypropylene (PP), and biaxially oriented polypropylene (BOPP);
- Copolymers of ethylene, like ethylene-vinyl acetate (EVA), ethylene-vinyl alcohol (EVOH), and ethylene-acrylic acid (EAA);
- Regenerated cellulose
- Substituted olefins, like polystyrene (PS), high-impact polystyrene (HIPS), poly(vinyl alcohol) (PVOH), poly(vinyl chloride) (PVC)
- Polyamide (PA)
- Polyesters, like polyethylene terephthalate (PET), polyethylene naphthalate (PEN) and relative copolymer PET-PEN (Siracusa, 2012).

According to Lange & Wyser (2003) there are two methods by which the barrier function can be incorporated into a multilayer packaging structure: adding an extra layer of barrier material and creating a multilayer barrier structure. The first principal is currently integrated in Tetra Pak's packaging as an aluminium foil which provides absolute barrier effects to water vapour, gases, light and microorganisms (Lamberti, 2007). The second way is based on the features of the abovementioned polymers, which, despite their excellent qualities, cannot provide barrier properties for both oxygen and water vapour on their own. For example, ethylene vinyl alcohol (EVOH) or polyamide (PA) are good oxygen barriers, however are not resistant to the moisture. Thus, they need to be complemented with the polymer layer with a good moisture barrier via lamination. The main advantage of the multilayer barrier structures that they can combine more sustainable materials and reduce the amount of materials used.

The current study examined three types of barrier materials: Al-film-based, polymer-based, and paper-based barrier structures.

Paper based barrier materials such as, for example, a greaseproof paper, can be produced from both sulphite and sulphate pulp. The primary wood sources for these materials are spruce or pine, although bamboo and straw are also used which are considered a renewable source (Trivedi,1992). The two most important stages in the production of the barrier paper: refining and calendaring. Refining is considered the most important process step as it determines the final material's barrier properties. During the refining process, internal and external fibrillation occurs, the internal fibrillation makes the fibers flexible with an increased bonding surface, producing a dense and semi-transparent paper. The level of refining determines the proximity of fibers to each other, the density of the paper, and the bonding area. The larger the bonding area, the denser the paper, resulting in a reduction of air permeance and light scattering. The calendaring process resulting in a smooth surface which is important for the lamination with other barrier materials (Kjellgren, 2007). Previously, supercalendering was utilized as a substitute for the refining needed to achieve greaseproofness (Vähä-Nissi, 1998).

Furthermore, it should be noted that the estimation of barrier properties of the materials can be three times lower, compare to the barrier properties of the folded package. The converting process, which includes lamination and creasing

2.2.3 Tetra Pak's state-of-the-art barrier materials

Tetra Brik Aseptic packaging is the most common type of aseptic packaging in Tetra Pak. It consists of the paperboard laminated carton, polyethylene and an aluminium foil-incorporated. The laminated structure is impermeable to liquid, gas and light. The detailed structure of the Tetra Brik Aseptic packaging is shown in

Figure 3 (Clark *et al*., 2014).

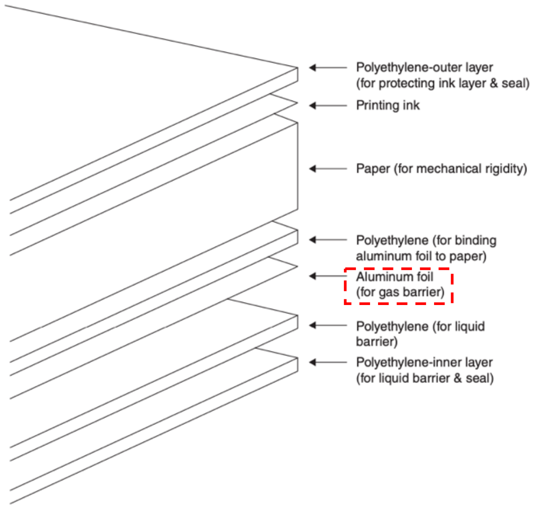


Figure 3. The structure of laminated paperboard carton aseptic packaging.

Aluminium foil is considered as a recyclable material. Once packaging has been separated through a re-pulping process, paper mills collect aluminium powder or polyethene-aluminium fraction to be recycled as a composite material. Recycling aluminium not only conserves the natural resources required for its production but also saves energy usage. In fact, for every ton of aluminium that is recycled, five tonnes of bauxite, the raw material from which aluminium is extracted, are saved (ACE, 2013; PlanetArk, 2012). However, the production of aluminium from bauxite requires significantly more energy than that of many other metals and produces large amounts of greenhouse gas emissions (GHG) (Norgate *et al*., 2007). Globally aluminum production is responsible for about 1% of the annual GHG emissions (IEA, 2009). Furthermore, aluminium is not renewable and due to its energy-intensive production represents around 20% of Tetra Pak's value chain emissions.

Thus, Tetra Pak is continuously innovating to decrease the environmental impacts by reducing the amount of aluminium and simultaneously investigating alternative barrier materials (TetraPak, 2021).

In a study on aseptic liquid packaging, Chan *et al*. (2011) compared the barrier properties of polyamide and aluminium and found that polyamide is more environmentally friendly than aluminium. The authors noted that this is because of its difficulty to separate and recycle the aluminium barrier coating from the primary packaging material. However, the study did not examine the effectiveness of polyamide compared to aluminium in extending the shelf-life of the food being preserved. While it is challenging to separate aluminium from polyethylene, Varžinskas *et al*. (2012) observed that the composite can still be recycled to produce roof shingles, granules, and other items. China produced 2500 tons of composite packaging waste from aseptic cartons each day in 2010, according to Xie *et al*. (2013), which was disposed of in landfills due to the lack of appropriate separation and recovery techniques. The authors conducted a life-cycle analysis (LCA) study and discovered that separating aluminum from polyethylene in composite packaging reduces environmental impacts by nearly 13% compared to incineration and allows resources to be recovered for their material value, which is not possible with landfills. Recycled aluminum, like glass, retains its physical qualities and is suitable for food packaging. When compared to natural aluminum production, using recycled aluminum can save 75-90% of the energy (Dainelli, 2008).

Therefore, when considering the environmental impact of aluminum foil as a barrier material, it is important to carefully consider all potential opportunities for reducing greenhouse gas emissions, both from direct and indirect packaging impacts. A holistic decision-making approach should consider emissions from production and sourcing, as well as potential food waste and the benefits of recycling and regeneration.

2.3 Packaging emissions assessment: direct environmental impact

2.3.1 LCA framework

Nowadays, environmental concerns have become increasingly prominent, prompting governments, companies, and other organizations to take action to reduce the negative impact of their products. To archive that, the areas with potential improvements should be identified. This requires a proper understanding of how the product impacts the environment and which specific steps in its life cycle are responsible for these impacts. By gaining this knowledge, these entities can work towards reducing the burden placed on the environment and creating a more sustainable future for all.

One of the most applied tools to understand and quantify the environmental impact of a product or service through its lifetime is a Life Cycle Assessment. This methodology allows to estimate the level of greenhouse gas emissions, the amount of energy consumed and the level of hazardous substances emitted by a product through its life cycle.

The first LCA-like research in history was conducted by the Midwest Research Institute for the Coca-Cola company in 1969-1972 which was called "Research and Environmental Profile Analysis" (Baumann *et al*., 2004). The first definition of LCA was adopted in 1993 by the Society of Environmental Toxicology and Chemistry (SETAC) in the Code of Practice. Nowadays, LCA is defined by the international standards ISO 14040 as follows:

> *LCA studies the environmental aspects and potential impact throughout a product's life (i.e. cradle-to-grave) from raw material acquisition through material processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences.*

International standards ISO 14040 and ISO 14044 define the general principals and framework of LCA, which describe the guidelines and requirements for performance of LCA analysis.

The European Commission considers LCA as the "best framework for assessing the potential environmental impacts of products" (European Commission 2003). However, LCA analysis has been criticized from industries as taking too much time and cost, thus a simplified version gained popularity. The main focus in simplified LCA analysis lies on the goal and scope definition phase, as the complexity of the system boundary reduces in accordance with the goal of the study. There are two types of simplification approaches: quantitative, which is reducing the effort for required data collection and qualitative approach, which allows to omit certain life cycle stages. Furthermore, qualitative approach includes focusing only on particular environmental impacts or issues (Todd *et al*., 1999).

According to ISO standards, the LCA methodology consists of four distinct phases: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), interpretation, with an iterative approach as shown in Figure 4

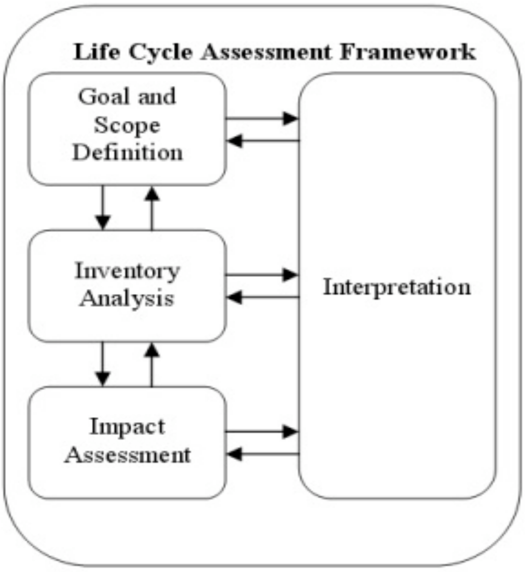


Figure 4. LCA framework.

2.3.2 Goal and scope definition

The first step in the LCA analysis as in any other scientific research is to identify the motivation and the purpose of the study. According to ISO standard the goal of an LCA should state the reason and intended application of the study, the audience and by whom this LCA was conducted. The scope of the study should define the system boundary, functional unit, allocation procedures and limitations. The product system can be described in a system flow chart. The system flow chart includes unit processes and their interrelations, which usually represented by boxes with all inputs and outputs of the process. These units as shown on

Figure 5 make more complex product tree or production system which define the system boundary of the study. The system boundary clearly states which unit processes will be included and investigated in the analysis with regards to the goal and scope.

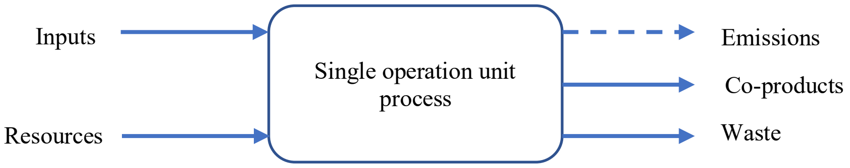


Figure 5. Unit process.

The concept of a functional unit is critical in defining the purpose and scope of an LCA analysis. A functional unit is defined as the "quantified performance of a product system utilized as a reference unit" by ISO 14044 (2006). It serves as a baseline for comparing other packaging structures with the current base structure, which comprises aluminum foil, in this study. Functional unit of the system should be clearly defined in the beginning of the LCA analysis in order to be consistent with the goal of the study. Allocation procedures define partitioning of the inputs and outputs flows of the product system when the production line involves different product streams. Thus, allocation is needed when a product system includes energy and material flows, apart from the established FU, which provides added values.

2.3.3 Life Cycle Inventory (LCI)

According to ISO standard this step involves data collection and calculation of the quantified inputs and outputs materials and energy associated with a product throughout its entire life cycle. Data collection can include a various data source such as literature data, internal reports or databases. Collected data should be verified as the accuracy of the study will depend on its quality.

2.3.4 Life Cycle Impact Assessment (LCIA)

The third step of the LCA analysis includes the evaluation of the significance of the potential environmental impacts of a product system. Evaluation is based on the results from the life cycle inventory considering impact categories. These impact categories can be connected to the inputs (e.g., water consumption) or to the outputs (e.g., global warming, eutrophication, etc.). The LCIA includes several steps: classification, characterization, normalization and weighting. Classification is the first important step during which all the inputs and outputs listed in LCI results are assigned to the selected impact categories. For example, if in the LCI we analyzed CO2 emissions it will refer to GHG impact based on the cause-effect relationship, it worth be noted that one parameter can affect more than one impact category. The next step is characterization which provides quantification of each inventory parameter to the assigned impact category. Quantification is only made within a chosen impact category. During quantification, each pollutant or action has a numerical factor which is multiplied by the output/input amount, while each impact category should be quantified in comparable units. The normalization process includes the division of the characterized impact values by the normalization reference. A normalization value, which is the outcome of this step represents the fractional contribution of the product system to a given impact category. While weighting is the process of assignation of value to the impact categories.

2.3.5 Interpretation

The final step of a life cycle assessment is interpretation, which includes identification of the major impacts, evaluation and drawing a conclusion with recommendations. This process includes identification, checking, qualifying and evaluating data obtained from the inventory analysis and impact assessment. The outcome of this step should clearly state the answer to the question posed in the scope definition.

2.3.6 Packaging Life Cycle Assessment

Food packaging has attracted considerable attention for its significant role in environmental issues across the entire life cycle of a food product. The increasing global demand for food, driven by a growing world population, has resulted in a corresponding rise in packaging waste, including bottles, boxes, and foils (Gómez *et al*., 2009). It is widely acknowledged that the production and disposal of packaging materials have substantial environmental implications (Gallucci *et al*., 2021). Nowadays, increasing awareness of environmental issues and stricter legislation force companies to focus their attention more on the development of sustainable packaging concepts using new innovative solutions with renewable sources, recyclable materials or returnable options concept, in order to decrease the environmental impact of the food product. This development process requires a deep understanding of the environmental impact assessment throughout all the stages of the packaging life cycle, in order to make a deliberate choice in the development step. Full LCA analysis is an iterative process, that can take up years of work and engage a number of experts (Center, 2010). However, there is also a possibility to perform a simplified form of LCA, which is often used in the design process stage. In this case, Life Cycle Assessment can help to estimate and support the decision-making process in an environmentally favorable way.

In the last decades, the LCA methodology has been widely used for an assessment of the environmental performance of food packaging by many researchers (Brock *et al*., 2019; Bertolini *et al*,. 2016; Gutierrez *et al*., 2017). In many of them, LCA analysis was performed only on the material's production and disposal stages, then the packaging production and use have been included, while nowadays, researchers claimed that to assess the total environmental impact of food packaging it is important to consider its indirect impact, that will be further investigated in the following chapter (Wikström and Williams, 2010; Silvenius, 2012; Büsser and Jungbluth, 2009).

2.4 Packaging shelf-life assessment: indirect environmental impact

The indirect environmental impact of packaging is an influence of packaging performance on the product, which includes the amount of food waste or logistics properties caused by packaging design (Verghese *et al.*, 2015). Thus, according to Verghese *et al.* (2015), Williams and Wikström (2010) in order to evaluate the total environmental impact of packaging, it is important to consider not only the direct influence that LCA analysis includes, but also the indirect attributes of food packaging.

It becomes clear that any LCA of packaging materials (including barrier coatings) is incomplete and misleading if the effect on shelf-life and therefore food spoilage/wastage is not factored in (Castelanelli *et al.*, 2011; Wikström *et al.*, 2016). The contributions of Wikström and Williams to this topic is significant in terms of creating awareness about the importance of considering food waste in the design and sustainability of food packaging (Williams *et al.*, 2008; Wikström and Williams, 2010; Williams and Wikström, 2011; Williams *et al.*, 2012; Wikstrom *et al.*, 2014; and Wikström *et al.*, 2016). They have used mathematical models to illustrate the relationships between food waste, food packaging, and their environmental impact from a life cycle perspective. Additionally, they have emphasized the necessity of using a functional unit that is based on the food that is actually consumed to accurately account for consumer-level food losses.

Silvenius *et al.* (2014) conducted a comparative life cycle assessment (LCA) of ham, dark bread, and a fermented soy-based drink in Finland. The research has found that the environmental impact of packaging (production and waste management) alone was not significant, contributing less than 15% to the overall environmental footprint of the product system (food and packaging). However, household food waste accounted for as much as 26% of the environmental impact. Manfredi *et al.* (2015) emphasized that packaging materials play an important role in preventing or reducing food waste. The study has found that the environmental benefits of reducing milk wastage far outweighed the environmental costs of adding an anti-microbial coating (a synthetic derivative of lauric acid) to milk packaging.

Kliaugaite and Staniskis (2013) conducted a study in which they compared three barrier alternatives, with the system boundary to include raw material extraction, adhesives, printing ink, plastic polymers production, and multilayer high-barrier plastic package manufacturing. They found that the use of a multi-layered film, including a barrier layer, was not recommended due to poor or nonexistent recyclability, which is in line with Toniolo *et al.* (2013) findings. However, it should be noted that if the disadvantage of poor recyclability is outweighed by the environmental impacts associated with food waste that would have occurred otherwise, a more holistic perspective (a proper systems approach) may not prioritize the environmental performance of the packaging alone when making comparisons among packaging options. This should be taken into account when evaluating different packaging options.

The shelf-life that packaging provides to the food product strongly correlated to the caused food waste, that was proven by different studies. In the study of Settier-Ramirez *et al*. (2022), the results revealed that increasing the shelf-life of a pastry cream from 3 to 13 days resulted in a subsequent reduction of waste, namely, generating only 8% of waste with 13 days, compared to prior 55,8% of food waste with 3 days of shelf-life. According to the study, there is relatively little milk waste connected with bottles of milk having a shelf life of more than 10 days, and the majority of the waste is related with milk with a shelf life of fewer than 7 days. Thus, the percentage of short shelf-life milk predicted to be over 60% for bottles with one or two days shelf life, while milk with five days shelf life is predicted to waste 18% of purchases (WRAP, 2013).

Currently, it is difficult to determine the exact amount of food waste resulting from packaging design. However, estimating the duration of shelf-life can provide an indication of its indirect impact. By determining the shelf-life of a new packaging structure, we can get an initial idea of how much food it can preserve and prevent from going to waste. Nevertheless, it's important to verify these initial findings by actually testing the real shelf-life of the food product inside the package.

3 Methodology

In this chapter, the author explains their approach to the study. The study is carried out as a case study and is comprised of two main parts: a data collection part (which is further subdivided into primary and secondary data collection) and data analysis part.

3.1 Study approach

This study is focused on the following research objectives:

1. *To compare the barrier properties of new material structures with existing solution, and to evaluate its environmental impact.*
2. *To estimate the efficiency of new barrier structures by estimation of the shelf-life length of liquid products.*
3. *To evaluate the overall packaging environmental sustainability by exploring the relationship between shelf-life and greenhouse gas emissions.*

The overall research approach of this study has been adopted to address these objectives and provide a more holistic view on the environmental impact of the packaging barrier structures studied. The goal of this research was to collect information and data using different methods, analyze it, and eventually provide Tetra Pak with a theoretical recommendation on the environmental performance of a new barrier structures. Recommendation will be based on the results of barrier properties evaluation by using a Norner calculator software. The values of OTR and WVTR will be assessed by simulation with modeled packaging multilayer structure and two volume sizes (200ml/1000ml) of Tetra Brik Aseptic Base. Furthermore, the environmental impact of the three examined packaging structures obtained by performing a LCA analysis on the SimaPro software will be taken into consideration to make a final recommendation.
Figure 6 represents the barrier materials structures examined in in this study.

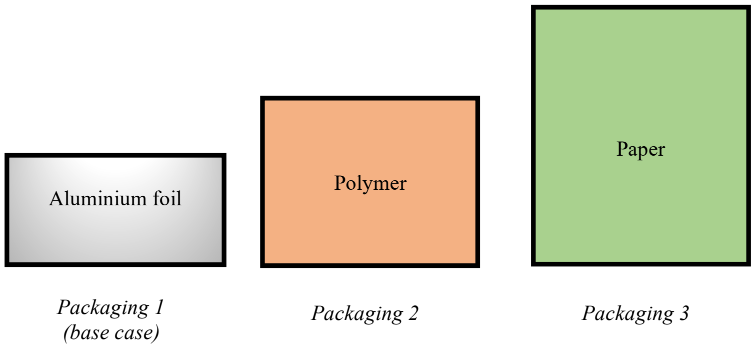


Figure 6. Analyzed multilayer barrier materials

3.2 Barrier properties evaluation

To evaluate the barrier properties of the new packaging structures, the Norner barrier calculator was used. This tool performs simulation on oxygen and water vapour permeation behavior of the different materials and shapes over specific time and conditions. The simulation was performed according to the Tetra Brik Aseptic packaging storage requirements, which are also in a line with Tetra Pak standard conditions to evaluate the barrier properties of the package for ambient storage. Firstly, multilayer structure film was modeled and each material layer was simulated with specific thickness, optical density and permeation values which were obtained from Tetra Pak. The geometry parameters of the sizes of TBA 200 (200ml) and TBA 1000 (1000ml) were introduced to the Norner Calculator to model the packaging (Table 3). However, the permeation value for paper was obtained from Kjellgren, (2005) study where barrier properties of some papers were analyzed. Packaging 1 with aluminium foil were simulated for direct comparison and was used as a reference material which guarantee a strong barrier property.

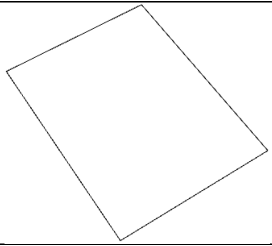
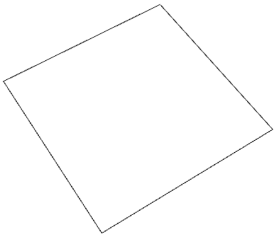
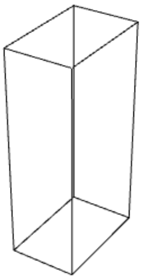
The analysis of oxygen transmission rate (OTR) for a packaging structure requires consideration of multiple input parameters, including relative humidity (RH) inside the packaging and the headspace volume. The RH input parameter in this study were based on the Tetra Pak internal reference, which normally corresponds to 90%, but may vary between 80-90%. It is worth noting that while some Tetra Pak packages have a headspace, Tetra Brik Aseptic does not. Therefore, the headspace volume was not considered in this study. However, it is important to mention that headspace volumes can vary between 1-5%.

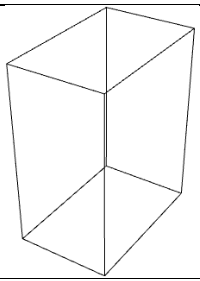
Therefore, the quantitative results obtained from this analysis may not be completely reliable, and further testing is recommended to confirm the OTR and WVTR values. The recommended testing methods for OTR include ASTM D3985 or ASTM F1927, which specifies the standard protocol for measuring the rate of oxygen gas transmission and aid in estimating the degree of OTR for a certain packaging material (Ebnesajjad and Landrock, 2015). For the WVTR the standardized method

ASTM F372-99 and ASTM F1249-13 can provide the rate of vapor transmission level by using an infrared detection technique (Robertson, 2006).

The purpose of this analysis was to compare the performance of different materials to the currently applied barrier material, as well as to visualize the extent to which their performance can differ. Thus, it was important to ensure that the input parameters were identical and closely correspond to original Tetra Brik Aseptic packaging. The results gave an indication towards the performance of the materials in relation to their barrier properties, which further were correlated with the environmental performance of the materials to investigate the relationship between these two parameters.

Table 3. Models considered in the Norner Calculator.

Variables	*Dimensions (mm)*	*Model*
Analysis 1		
TBA 1000	322x245 A=0,079m^2	
TBA 200	174x174 A=0,030m^2	
Analysis 2		
TBA 1000	Width - 58 Height – 195 Length – 92	

TBA 200	Width - 40 Height – 82 Length – 63	

Assumptions in the Norner calculator

The calculation models developed under following assumptions:

1. Surface top of the container (lid or cap) is assumed to be impermeable
2. Calculations are based on an empty container
3. The oxygen level inside container is initially assumed to be 0%
4. Diffusion takes place in one direction only
5. The permeability coefficient is assumed to be constant and does not depend on the thickness of the material

3.3. Life cycle assessment analysis

3.3.1 Goal and scope definition

The aim of this study is to conduct a comparative Life Cycle Assessment (LCA) of three different types of packaging structures for the Tetra Brik Aseptic (TBA) packaging. The focus of the LCA is to investigate the environmental impact, particularly the greenhouse gas emissions (GHG), associated with the use of current and potential barrier materials in the TBA packaging.

To achieve this goal the study will compare different barrier structures including aluminium foil, polymer based and paper based. The evaluation will consider global warming potential, mineral resource scarcity and fossil resource scarcity to evaluate the effectiveness of replacing aluminium foil. Furthermore, the study will conduct the sensitivity analysis to validate the reliability of the obtained results.

Sensitivity analysis in LCA analysis aims to test the robustness of results and their sensitivity to data, assumptions and models used. As in this study several assumptions will be made for the input parameters, the sensitivity analysis will be conducted to check effect of an individual input parameters on LCA results by inputting different data setup into SimaPro.

The findings of this research will provide valuable information and preliminary data to decision-makers on the level of CO_2 emissions resulting from the use of potential new barrier structures. This study specifically examined the Global Warming Potential (GWP) of the new barrier materials, using an appropriate impact assessment method (explained in section 3.3.3).

The functional unit of this study is defined as a packaging unit that contains 1000 ml and 200 ml of orange juice.

The product system examined in this study includes existing and potential enhanced structures of Tetra Brik Aseptic packaging used for ambient juice storage. The current packaging structure utilize an aluminum foil which, provides the principal barrier qualities to protect the product from oxidation and light damage, allowing perishable food goods to remain safe without refrigeration. In this LCA analysis, two potential improvements will be examined and compared to current base structure of Tetra Brik Aseptic. The study will investigate three packaging structures with different volume sizes. The following Table 4. Product System demonstrates a description of each packaging structure that will be investigated in this LCA analysis.

Table 4. Product System.

Sample	***Weight (g)***	***Volume (ml)***	***Structure***
Packaging 1 (base case)	26.9	1000 200	Liquid packaging board LDPE **Aluminum foil** Adhesive mPE
Packaging 2	28	1000 200	Liquid packaging board LDPE **Polymer based** Adhesive mPE
Packaging 3	30.2	1000 200	Liquid packaging board LDPE **Paper based** Adhesive mPE

The product system in this study consists of three types of different structures of Tetra Brik Aseptic. The original structure (*Packaging 1-base case*) has 5 different materials with aluminium foil as a key barrier material. Aluminium foil is replaced in *Packaging 2* by a structure based on polymer. Furthermore, in Packaging 3, the barrier layer replaced by structure based on paper.

System Boundaries of this LCA analysis is defined in the scope of the “cradle-to-gate” from the extraction of raw materials to the gate of the production facility. Raw materials and processing stages are always considered in the similar LCA studies since they often account for a large portion of life cycle impacts (Siracusa *et al.*, 2014; Xiie *et al.*,2011; Kang *et al.*, 2013). Moreover, the primary greenhouse gas contributions of aluminum foil are related to electricity production for electrolysis and thermal energy production for alumina refining (56% and 13%, respectively) (Nunez and Jones, 2016). Thus, studying material extraction and production stage of new potential material structures might provide valuable insights for environmental effect comparisons between three packaging alternatives.

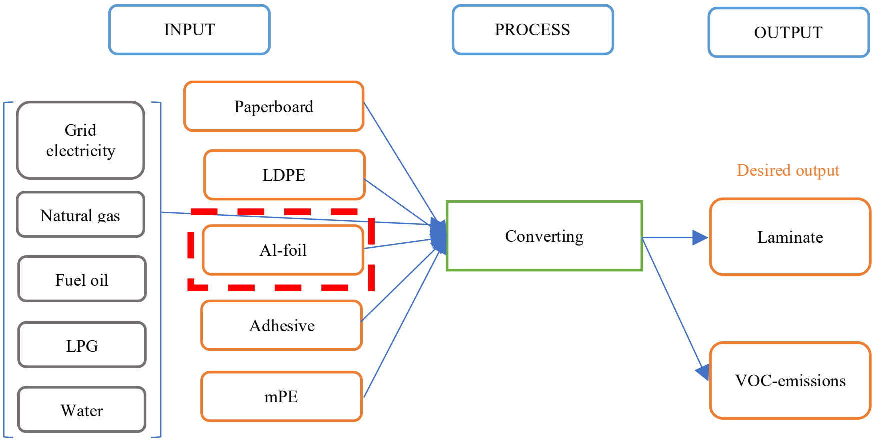
The analyzed processes are separated from other steps in the Table 5. Figure 7 depicts the general system boundary used in this LCA for the life cycle of three packages, highlighting the barrier layers. For each stage, the life cycle material inputs, energy requirements, and environmental outputs of all unit processes are included.

Table 5. The scope of the study.

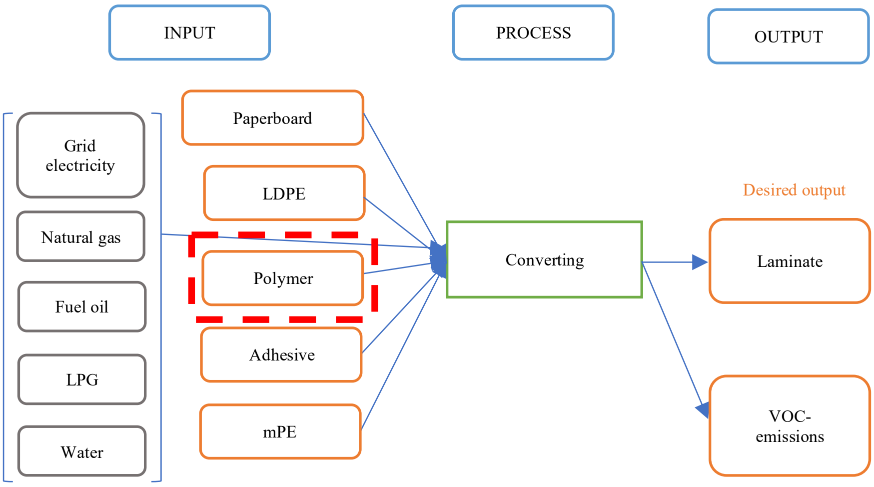
Scoped In	*Scoped Out*
• Extraction of virgin materials • Manufacture of packaging laminate	• Transport -during all the stages • Filling • Product manufacture • Distribution • End of life treatment

The converting process, which produces a roll of laminated and creased packaging material, was included in the scope of the system boundary. A calendaring device is used to laminate multiple layers of paperboard, plastics, and aluminum. At the same time, creasers are formed on the package material to facilitate folding.

Packaging 1 (base case)



Packaging 2



Packaging 3

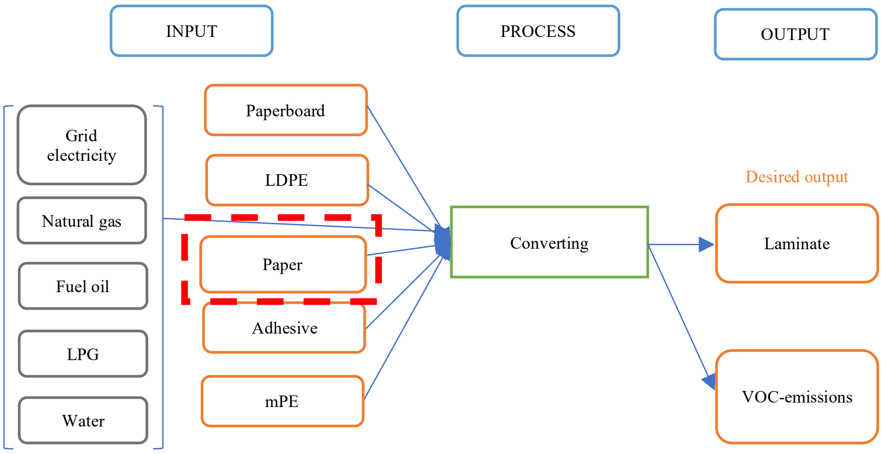


Figure 7. The system boundary of alternative packaging laminate structures production, with emphasized barrier layer replacement.

Limitations and assumptions

Transportation of the materials, packaging folding, and end-of-life were excluded from the system boundaries, because the purpose of the study was to evaluate the CO_2 emissions from the production and converting process of a new possible structure with a focus on the barrier layers.
The waste rate was not included in this analysis since the new potential structures are not yet in the production line, making it impossible to determine the waste rate from the production of Packaging 2 and 3.

3.3.2 Life Cycle Inventory

The dataset for the converting process was gathered by collecting primary information from TetraPak records, which the company uses for internal LCA research. To get all of the essential information within the study's system boundaries, data collection sheets were collected electronically. Collected data included amounts of all input variables: materials, fuels, and VOC emissions as a system's output flow. The remaining information was retrieved as a secondary data source from the Ecoinvent database version 3.9. All data collected was entered into the SimaPro LCA software (version 9.3). Data collected from the company were refined to meet the software's unit of measurement (gram and KWh). For comparing large sizes, packaging with an area of 0,07889 m^2, which contains 1 L of product was assigned as the reference flow. For the comparison of small volume sizes, a packaging with a materials area of 0,030 m^2 and a capacity of 0,2 L was used as the reference flow. The environmental impact of two volumes was assessed in order to compare GHG (greenhouse gas) emissions results with the results of barrier characteristics in the next chapter.
Life Cycle Inventory data for cardboard, LDPE, aluminium foil and mPE were taken from the EcoInvent database. Data that was taken from EcoInvent database has been checked with Tetra Pak's internal environmental specialist. Finally, for the converting process, data was taken directly from the company.

Table 6. Inventory data analysis for Packaging 1 referred to two functional units (1000 ml and 200 ml).

Packaging 1 (base case)

Input			***Output***		
Materials			***Materials***		
Cardboard	21	g			
LDPE	2,52	g			
Aluminum foil	1,34	g	Packaging carton	1,00	L

Adhesive	0,47	g			
mPE (LDPE/LLDPE)	1,49	g			
Cardboard	5,73	g	Packaging carton	0,2	L
LDPE	0,96	g			
Aluminum foil	0,51	g			
Adhesive	0,18	g			
mPE	0,57	g			
Energy			***Emissions to air***		
Grid electricity	2.3×10^{-2}	MJ	VOC-emissions	7.1×10^{-3}	kg
Natural Gas	6×10^{-3}	MJ			
LPG	1×10^{-3}	MJ			
Fuel oil light	31×10^{-5}	MJ			
District heating	15×10^{-4}	MJ			
Grid electricity	8.76×10^{-3}	MJ	VOC-emissions	2.7×10^{-6}	kg
Natural Gas	2.47×10^{-3}	MJ			
LPG	2×10^{-4}	MJ			
Fuel oil light	28×10^{-7}	MJ			
District heating	6×10^{-4}	MJ			

3.3.3 Life Cycle Impact Assessment

The software SimaPro 9.3 created by Pre-Consultants was used to model the LCA. To characterize the life cycle inventory data into midpoint impacts the IPCC 2021 method was used within SimaPro. This method is a successor of IPCC 2013 which was developed by the Intergovernmental Panel on Climate Change. It contains only Global Warming Potential (GWP 100) as an impact category and it presents climate change factors with a timeframe of 100 years. (SimaPro 9.3) As it was stated in the goal and scope definition, the primary focus of this study is the estimation of CO_2 emissions, following the main interest of Tetra Pak.

However, to further understand the environmental impact of replacing aluminium foil and verify the results obtained from IPCC 2021 method, the ReCiPe 2016 v1.1 (H) method was used to perform an environmental impact assessment. The assessment focused on mineral resource scarcity and fossil resource scarcity, these categories are important to evaluate the impact for metal resources and irreversible impact to non-renewable fossil resources.

3.4 Shelf-life estimation

The methodology for estimating the shelf-life of the future packaging structures was based on the following assumption: (1) that packed product was orange juice and (2) the level of degraded ascorbic acid was measured. Oxygen is known to cause two major losses in orange juice, namely vitamin C degradation and browning (colour change) (TetraPak, 2017b). Thus, the ascorbic acid (Vitamin C) degradation caused by oxygen permeation through the package is the IoFs for the shelf-life estimation in this study.

The package shelf-life criterion for filling products like orange juices has been set by Tetra Pak as no less than 2/3 of the vitamin C content remaining after 12-month storage at 23 °C. Based on the needed values of OTR to reach the goal and have a Vitamin C content of 300 ppm out of 450 ppm the estimations are made.

These criterions were used to further calculate the shelf-life length of the new structures, using also the determined earlier OTR values. The shelf-life can be estimated by using the following equation (Kim, 2009):

$$t_s = \frac{O_2,max}{OTR} \tag{1}$$

Where, t_s = shelf-life, day

O_2, max = maximum allowable oxygen, cm^3 O_2

4 Results and discussion

The present chapter aims to present the finding of the study, which are divided in three main parts based on the conducted analyses and the investigation of the relationship between them. The first part highlights the outcomes of the barrier performance simulation analysis. The second part provides in-depth discussion of the results of the Life Cycle Analysis (LCA), with a focus on the greenhouse gas (GHG) emissions. Lastly, the third part establishes the connection between these parameters and evaluates the overall environmental performance of a new sustainable packaging materials. The outcomes of the study will be thoroughly assessed, resulting in a final material preference recommendation.

4.1 Barrier properties analysis

The Norner barrier calculator was used to evaluate the barrier performance of the future sustainable packaging materials. This tool was employed to simulate the Oxygen Transmission Rate (OTR) and Water Vapor Transmission Rate (WVTR) of different barrier materials structures for two packaging sizes (1000 ml and 200 ml). The current packaging structure with aluminium foil was used as a reference point. The analysis was divided into two parts. Firstly, the multilayer barrier structures with different sizes were examined as a film. Secondly, the whole Tetra Brik Aseptic packaging structure were modeled with the respective sizes.
The following input parameters were used for the barrier simulation.

Table 7. Norner calculator input parameters.

Parameter	***TBA 1000***	***TBA 200***
Area	0,079m^2	0,030m^2
Width/Height/Length	5,8/19,5/9,2 (cm)	4/8,2/6,3 (cm)
Time	1 day	1 day
Temperature	23°C	23°C
RH inside	90%	90%
RH outside	50%	50%
Oxygen level	21%	21%

The following results were obtained after simulation of the barrier materials:

Table 8. Barrier material film properties for TBA 1000 (0,079 m^2) and TBA 200 (0,03 m^2).

Barrier material	*OTR at 23^{o}C 50% RH [ml/0,079m^2 · day]*	*OTR at 23^{o}C 50% RH [ml/0,03m^2 · day]*	*WVTR at 23^{o}C 90% RH [g/0,079m^2 · day]*	*WVTR at 23^{o}C 90% RH [g/0,079m^2 · day]*
Aluminum foil	0	0	0	0
Polymer based	0,076	0,029	0	0
Paper based	0,071	0,027	0	0

The first simulation was performed by analyzing a multilayer film sample and modeled according to the packaging area for the TBA 1000 and TBA 200. The Table 8 shows results obtained from simulation of the barrier layers indicating that in comparison to aluminium foil which possesses absolute barrier properties for oxygen and water vapour, the new sustainable alternatives exhibit lower oxygen barrier properties (OTR). The difference of OTR between the two alternatives was negligible for the TBA 1000 and TBA 200. The observed difference can be explained by the OTR properties of polymer and paper. As research conducted by Kjellgren (2007) compared the OTR values for coated paper and chitosan coating, which resulted in difference where greaseproof papers contributed to lower OTR values. Moreover, other studies have demonstrated that greaseproof paper coated with PE-extrusion exhibit lower OTR than what would be expected from the PE-coating solely (Kuusipalo *et al*., 1994; Vähä-Nissi *et al*., 2001; Furuheim *et al*., 2003). While the OTR properties of polymer are characterized by a low oxygen transmission rate.

In terms of the WVTR results, the simulation demonstrated impermeable barrier (0 transmission rate) for the water vapour provided by all the barrier structures. This can be attributed to the thickness and high crystallinity of polymer (Todd, 2015; Hedenqvist, 2005). According to Kjellgren (2007), the coated greaseproof paper demonstrated a high water vapour transmission rate (WVTR), while exhibiting a superior oxygen barrier property. However, the research of Nilsson (1993) reported the correlation between oxygen and water vapour transmission rate, indicating that gas diffusion is the primary transport mechanism that governs WVTR. Moreover, Kjellgren (2007) have found that the porosity and density of the paper have an impact on the WVTR rate. Lower porosity and higher density resulted in decreased WVTR values. Thus, the WVTR rate of paper is dependent on its structural characteristics, such as density, porosity and thickness. However, when coated or laminated with other barrier materials, it exhibits a good water vapour barrier property.

To conclude, it can be inferred from the results that external layers provide effective moisture protection, which results in a relatively low oxygen permeation by polymer. However, these results can be influenced by different factors such as temperature and relative humidity and WVTR rates may vary depended on the external conditions.

Table 9. Barrier properties for TBA 1000 and TBA 200 structures.

Packaging	OTR at 23°C 50% RH [ml/pack · day] 1000 ml	OTR at 23°C 50% RH [ml/pack · day] 200 ml	WVTR at 23°C 90% RH [g/pack · day] 1000 ml	WVTR at 23°C 90% RH [g/pack · day] 200 ml
1	0	0	0	0
2	0,01	0,003	0	0
3	0,01	0,003	0	0

The second simulation focused on the analysis of a multilayer structure with a modeled shape of the Tetra Brik Aseptic Base. In this case the total thickness, the surface area and the volume of the packaging were considered. The results obtained from this simulation are presented in Table 9. The findings indicate that when considering other layers of TBA packaging structure, the overall barrier properties improved, resulting in a lower difference with the reference structure. However, it is important to note that these values were obtained only through simulation using Norner calculator, and laboratory testing of the folded packaging is necessary to confirm these results. Additionally, the results primarily reflect the OTR and WVTR values based on the materials properties only. It is possible that the laboratory analysis on MOCON may yield higher values due to factors such as folding, creases, cracks and other aspect of the packaging design. The external factors as a temperature and relative humidity can also affect these results. Moreover, it worth noting that according to the Tetra Pak's confidential reports the OTR of the packaging structures in real environment might be three times higher than the OTR in laboratory conditions (DR31305).

4.2 LCA results and interpretation

This section provides an analysis of the overall greenhouse gas (GHG) emissions associated with three distinct packaging structures. Additionally, a comparison of the environmental impacts produced by three different packages and three barrier solutions is presented. To assess the GHG emissions, the Intergovernmental Panel on Climate Change (IPCC) 2021 assessment method was utilized, and the results were reported in kilograms of CO_2 equivalents (CO_2e). The objective is to showcase the disparity in environmental performance among the three packaging types, emphasizing the variation in CO_2e emissions attributable to the various barrier layers structures.

Packaging 1

Table 10 shows the total greenhouse gas emissions generated by the first currently existing packaging structure, which includes an aluminum foil as a barrier layer.

Figure 8 depicts the same values represented on a 100% scale. As shown in Table 10 and Figure 8, the biggest quantity of emissions come from cardboard and aluminum manufacture, which contribute 36,3% and 36,7%, respectively. The significant contribution of cardboard is due to its proportion in the overall structure, which accounts for 70%. While aluminum foil produces the biggest amount of greenhouse gases during its manufacture which are attributable to electricity production for electrolysis and thermal energy production for alumina refining (56% and 13%, respectively) (Nunez and Jones, 2016). The next less substantial contribution comes from LDPE production, which accounts for 12,5% of total emissions. In contrast, the impact of the converting process is rather minor, accounting for only 5,7% of emissions per packaging.

Table 10. GHG emissions generated by individual components of Packaging 1 in Kg CO2 eq. (1000 ml) (base case).

Material	*Kg CO_2 eq.*
Cardboard	1,80E-02
LDPE	6,22E-03
Aluminium foil	**1,8E-02**
Adhesive	9,87E-04
mPE (LDPE/LLDPE)	3,35E-03
Energy	***Kg CO_2 eq.***
Grid electricity	2,49E-03
Natural Gas+LPG	3,58E-04
Fuel oil light	3,31E-7
District heating	1,35E-5
Total	***4,97E-02***

The total CO_2 emissions from Packaging 1 with aluminum foil are equal to 0,049 kg CO_2 eq. These findings are consistent with those of other research that conducted the same study (Stramarkou *et al.*, 2021; Finkbeiner *et al.*, 2010).

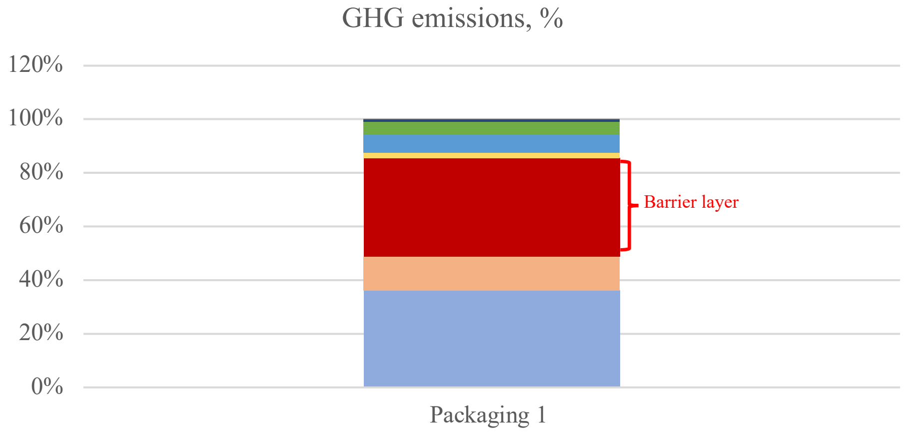


Figure 8. Percentage contribution of each material to GHG emissions in Packaging structure 1.

Packaging 2

Table 11 shows the overall impact of Packaging 2 with a barrier layer (Polymer based). As shown in Figure 9, and similarly to Packaging 1, the primary source of GHG emissions is cardboard production, which accounts for 48,4% of total emissions. However, in comparison to the first structure, the barrier material structure provides only 15,57% of the total in which Polymer contributes to 8,79%. Particular outcome in this structure observed from LDPE, which contributes to 16,7% of CO_2 emission.

Table 11. GHG emissions generated by individual components of Packaging 2 in Kg CO2 eq. (1000 ml).

Material	***Kg CO_2 eq.***
Cardboard	1,80E-02
LDPE	6,22E-03
Polymer	**3,27E-03**
Adhesive	9,87E-04
mPE (LDPE/LLDPE)	3,35E-03
Energy	***Kg CO_2 eq.***
Grid electricity	2,49E-03
Natural Gas+LPG	3,58E-04
Fuel oil light	3,31E-7
District heating	1,35E-5
Total	***3,72E-02***

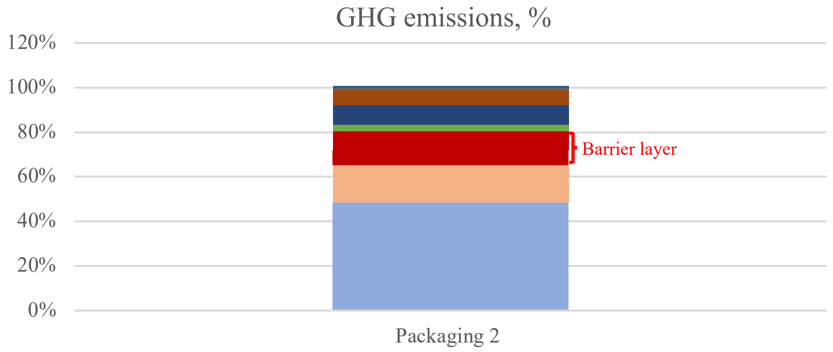


Figure 9. Percentage contribution of each material to GHG emissions in Packaging structure 2.

Packaging 3

The total quantity of GHG emissions caused by Packaging 3, which includes a barrier layer (Paper based), is shown in Table 12. Figure 10 depicts the contribution of each material used in the structure. Similar to the previous structures, cardboard contributes the most, accounting for more than 47% of the total. When looking at the barrier material structure in this case, the total impact is only 17,06%. In comparison to polymer based barrier layer in the second structure, paper based contributes to around 10,4% which can be attributable to fiber processing, which requires a significant amount of energy for numerous time calendaring processes.

Table 12. GHG emissions generated by individual components of Packaging 3 in Kg CO2 eq. (1000 ml).

Material	***Kg CO_2 eq.***
Cardboard	1,80E-02
LDPE	6,22E-03
Paper	**3,96E-03**
Adhesive	9,87E-04
mPE (LDPE/LLDPE)	3,35E-03
Energy	***Kg CO_2 eq.***
Grid electricity	2,49E-03
Natural Gas+LPG	3,58E-04
Fuel oil light	3,31E-7
District heating	1,35E-5
Total	***3,79E-02***

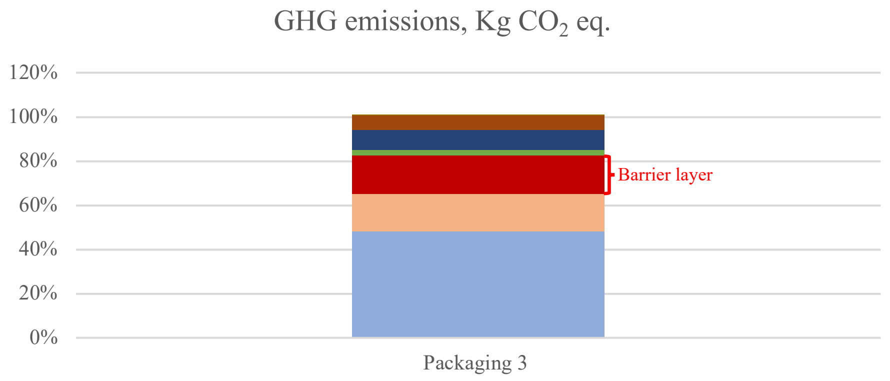


Figure 10. Percentage contribution of each material to GHG emissions in Packaging structure 3.

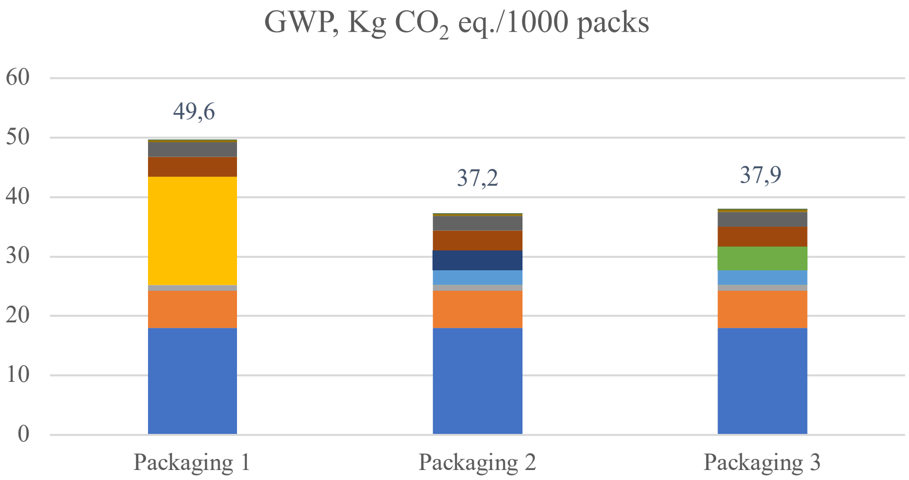
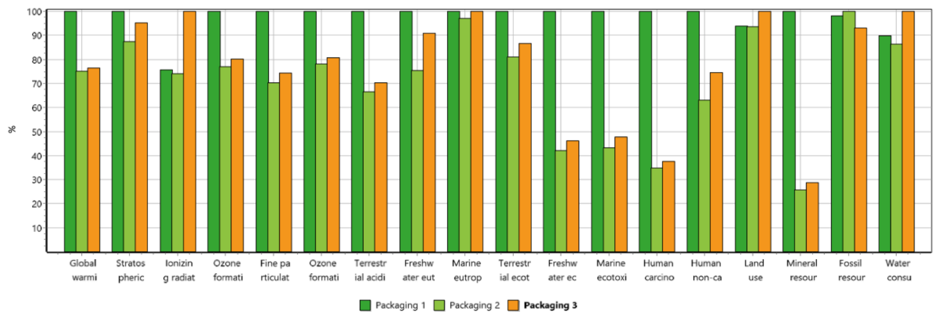


Figure 11. The global warming impact of three package structures from raw material extraction and production. (expressed in kg carbon dioxide equivalent – kg CO2 eq. per 1000 packages).

Looking at Figure 11, it can be observed that Packaging 2 has a superior environmental GHG profile than Packaging 1 and almost Packaging 3 which is matter of barrier materials layers. The production of raw materials for a new barrier materials structure yields a beneficial result, lowering the CO_2 emissions of packaging by 25%. When comparing the functional unit (1L packaging, which is 0,0789m^2 of packaging laminate), the difference appears minor, but when the number of packages increase for 1000, the difference becomes significant. Furthermore, as can be seen from the results the raw material is the largest contributor to the impacts, thus the material choice is essential in providing less environmental impact.

The environmental impact evaluation using the ReCiPe 2016 v1.1 (H) method was done in order to evaluate the impact of replacement of aluminium foil on the mineral and fossil resources scarcity, as aluminium sourcing and production have a significant impact on these categories. The results presented on Figure 12 indicating that the structures with new sustainable materials had a threefold lower impact on mineral resource scarcity than the base structure with aluminium foil. Regarding fossil resource scarcity, while Packaging 3 had the lowest impact, the impact of Packaging 2 is 2% higher than aluminium foil, which can be attributed to its higher proportion fossil-based plastic compared to other structures.
This method also confirmed the results of a comparison of three packages on the global warming impact, giving the same results.



eCiPe 2016 Midpoint (H) V1.07 / World (2010) H / Characterization
1 l 'Packaging 1', 1 l 'Packaging 2' and 1 l 'Packaging 3';

Figure 12. Comparison of three types of packaging production on different environmental categories

The total amount of GHG emissions created by the manufacture of raw materials for barrier layers was determined for three alternative structures. These findings will be useful in future studies that compare the barrier properties to the environmental performance of the new structures.

Table 13. The GHG emissions generated by different barrier layers

Material	***Volume***	***Kg CO_2-eq/1000pack***
Alu-foil	1000 ml	18
	200 ml	6,94
Polymer based	1000 ml	5,79
	200 ml	2,20
Paper based	1000 ml	6,49
	200 ml	2,43

According to Table 13, GHG emissions from barrier materials are not affected by package volume, and as the least ecologically damaging structure (polymer based) will still be preferred in the scope of the examined system boundary. However, it can be seen that the converting process has no major impact on the GHG emission burden of the packaging, as the same trend can be seen in this situation.

4.2.1 Sensitivity analysis

As previously stated, due to a lack of dataset for polymer manufacture, it was replaced by the similar process. The emission factor for polymer in the original scenario is 2,1kg CO_2-eq/kg, but this figure varies greatly depending on the data source. According to the internal Tetra Pak report, the approved emission factor for polymer is 4 kg CO_2-eq/kg, hence it was decided to conduct a sensitivity test on the input variable by doubling the amount of polymer in the LCI while keeping the other materials unchanged. Because there are no standard techniques of sensitivity analysis stated in ISO standards, the method described by Qiao-Li Wang *et al.* (2016) was used. The sensitivity value is defined as the ratio of the difference between the results acquired from the set scenario and the results gained from the original scenario, as illustrated below:

$$S = \frac{n-m}{m} \tag{2}$$

where S denotes the sensitivity of different variation ranges, n the results acquired from the set scenario, and m the results gained from the original scenario.

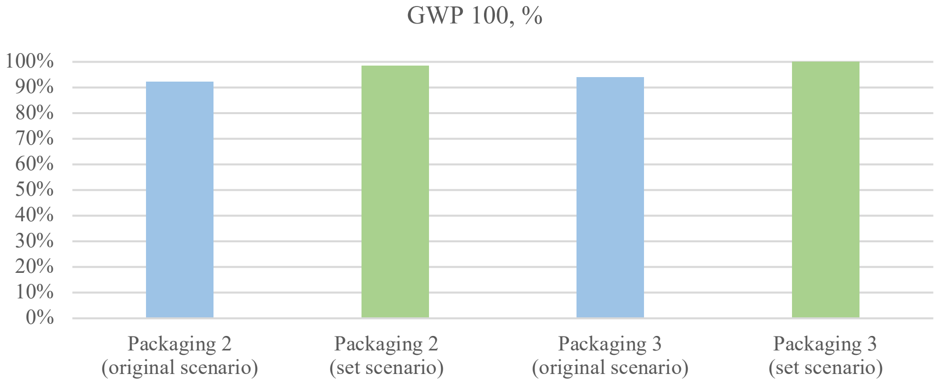


Figure 13. Sensitivity of different scenarios refers to the polymer quantity range.

The results reveal that doubling the amount of polymer input quantity has no substantial effect on the overall packaging performance, accounting for only 6% of the sensitivity value for the Packaging 2 and Packaging 3 structures (Figure 13).
Another sensitivity test was performed to check the input parameter of paper; the original scenario was compared to two alternatives, in which the quantity of paper was increased by 10% in the first scenario and lowered by 10% in the second.

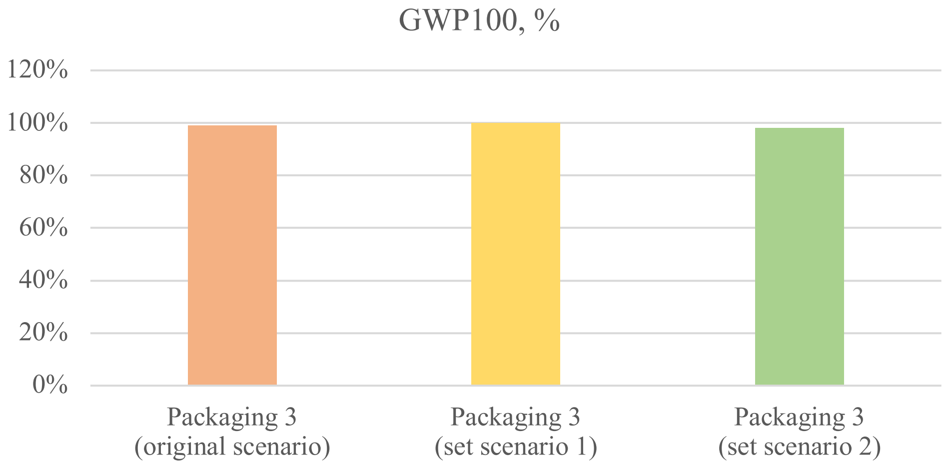


Figure 14. Sensitivity of different scenarios refers to the paper quantity range.

The results showed that increasing the amount of paper by 10% (scenario 1) changes the total outcomes by only 1%, while decreasing the number of materials (scenario 2) likewise has a 1% sensitivity effect on the results.

Furthermore, a sensitivity analysis was run on all of the input materials in order to assess the validity of the results and form a solid conclusion about the current study. A comparison of the outcomes of several assessment methods was performed. For this reason, the CML-IA baseline methodology was used for evaluating three types of structures. The CML-IA is a mid-point method that involves the evaluation of multiple impact categories, the most important of which for this study was the evaluation of Global Warming Potential for a time horizon of 100 years (GWP100). As a result of the data acquired from this assessment method, the deviation value may be calculated by subtracting them from the values obtained earlier using the IPCC100a method for each material.

Table 14 displays the results, which reveal that the deviation values are quite low, with a maximum level of 0,0001 among all of them. As a result, it can be concluded that total GHG emissions values obtained from two evaluation methods differ only little, indicating that these data can provide qualifiable guidance to decision-makers about the environmental impact of these three package structures.

Table 14. Sensitivity analysis (CML-IA (GWP100a) – IPCC100a) for three packaging structures

Kg CO_2 eq/kg	*Packaging 1*			*Packaging 2*			*Packaging 3*		
	CML-IA	**IPCC 100a**	**Deviation**	**CML-IA**	**IPCC 100a**	**Deviation**	**CML-IA**	**IPCC 100a**	**Deviation**
Cardboard	1,79E-02	1,80E-02	-1E-4	1,79E-02	1,80E-02	-1E-4	1,79E-02	1,80E-02	-1E-4
LDPE	6,16E-03	6,22E-03	-6E-5	6,16E-03	6,22E-03	-6E-5	6,16E-03	6,22E-03	-6E-5
Alu-foil	1,80E-02	1,80E-02	0	-	-	-	-	-	-
Adhesive	9,76E-04	9,87E-04	-11E-5	9,76E-4	9,87E-04	-11E-5	9,76E-4	9,87E-04	-11E-5
mPE (LDPE/ LLDPE)	3,31E-03	3,35E-03	-4E-5	3,31E-03	3,35E-03	-4E-5	3,31E-03	3,35E-03	-4E-5
Paper	-	-	-	-	-	-	3,95E-03	3,96E-03	-1E-5
Polymer	-	-	-	3,24E-03	3,27E-03	-3E-5	-	-	-

4.3 Shelf-life estimation

The shelf-life of the future packaging structures was estimated based on the assumption that package OTR is influenced by base materials (components), converting and filling (processes) and package design (Tetra Pak, 2018). In this study the results obtained by Norner calculator represents only permeation of O_2 through the packaging materials, without consideration of other parameters. However, the permeation of the current packaging materials, with aluminium foil as a barrier layer, allows almost 0 permeation of oxygen. Therefore, as Norner calculator does not take into account creases, cracks and other issues (see Chapter 2.2.2), which can occur during the packaging folding or filling processes to achieve more closer OTR values to the current packaging structure of TBA base, the obtained from Norner calculator values were added to the current reference OTR rate.
The following length of shelf-life were obtained, resulting in 30% of possible reduction in shelf-life days with new sustainable barrier materials.

Table 15. Estimated shelf-life length based on the Vitamin C degradation.

Packaging	***OTR (ml/pack/365day)***	***Estimated shelf-life (days)***	***Estimated shelf-life (month)***
Packaging 1 (1000 ml)	-	365	12
Packaging 1 (200 ml)	-	365	12
Packaging 2 (1000 ml)	12,41	257	8,4
Packaging 2 (200 ml)	3,28	243	8
Packaging 3 (1000 ml)	12,41	257	8,4
Packaging 3 (200 ml)	3,28	243	8

However, these values are just a theoretical estimation based on the vitamin C degradation. Taking into consideration the established Tetra Pak's threshold for the degraded vitamin C and the oxygen ingress over time. Therefore, it is important to note that these values are only theoretical estimations and cannot provide a realistic representation of the actual shelf-life of the product. To obtain accurate results, it is necessary to conduct shelf-life testing with a filled product. While this type of estimation can be useful for comparative understanding of different barrier materials.

4.4 Data analysis

In this chapter the relationship between the environmental impact of examined packaging solutions and their barrier properties will be analyzed. This will involve an analysis of the relationship between the multilayer barrier material structures and the overall packaging structures, in order to provide a more detailed understanding of the environmental impact of sustainable barrier structures. Additionally, the relationship between shelf-life length and greenhouse gas (GHG) emissions will be examined, and a conclusion will be drawn based on that.

4.4.1 Barrier material analysis

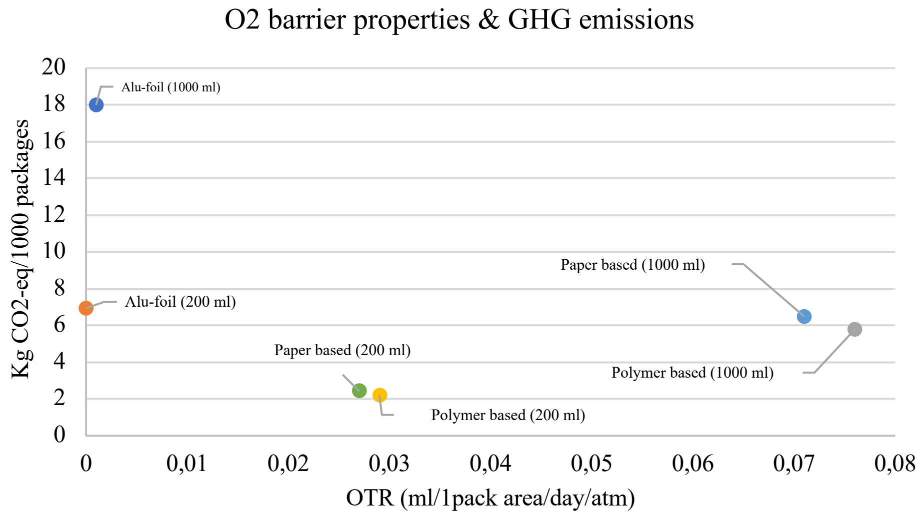


Figure 15. O_2 barrier properties and GHG emissions, focus on barrier material layer.

The relation between the oxygen transmission rate (OTR) and greenhouse gas emissions (GHG) of barrier structures is presented on the Figure 15. Comparing a reference aluminium layer to the new sustainable multilayer structures, it can be observed that the current structure exhibits the best barrier properties for both packaging volumes, however generates the highest amount of GHG emissions in the same time. Two sustainable options were compared, and it was observed that the difference between them is not significant in terms of barrier properties and emissions. However, a closer examination reveals that the barrier structure (Paper based) generates more emissions than the structure with polymer based barrier layer, despite having better barrier properties. It is worth noting that the amount of materials used in multilayer structure for 1000 ml packaging generates almost the same amount of emissions as an Al foil used in the small (200ml) packaging in the base case.

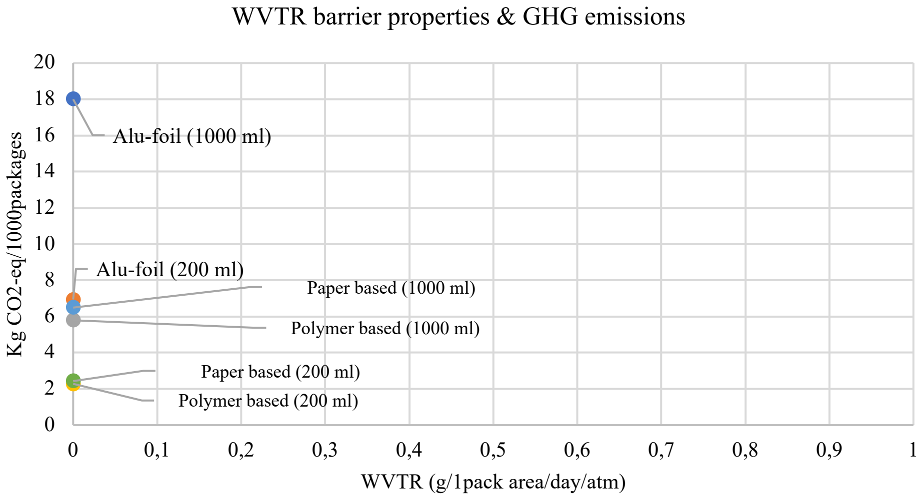


Figure 16. WVTR barrier properties and GHG emissions, focus on barrier material layer

In the Figure 16 the relationship between the water vapour transmission rate (WVTR) and greenhouse gas emissions (GHG) is presented, and no correlation between the barrier properties and emissions generated was observed. All the tested barrier structures, according to the Norner calculator, showed perfect water barrier properties. Therefore, in this case, the decision to select a sustainable barrier structure can be based on the amount of emissions generated. Where the most sustainable one was found to be the Polymer based structure.

4.4.2 Packaging Analysis

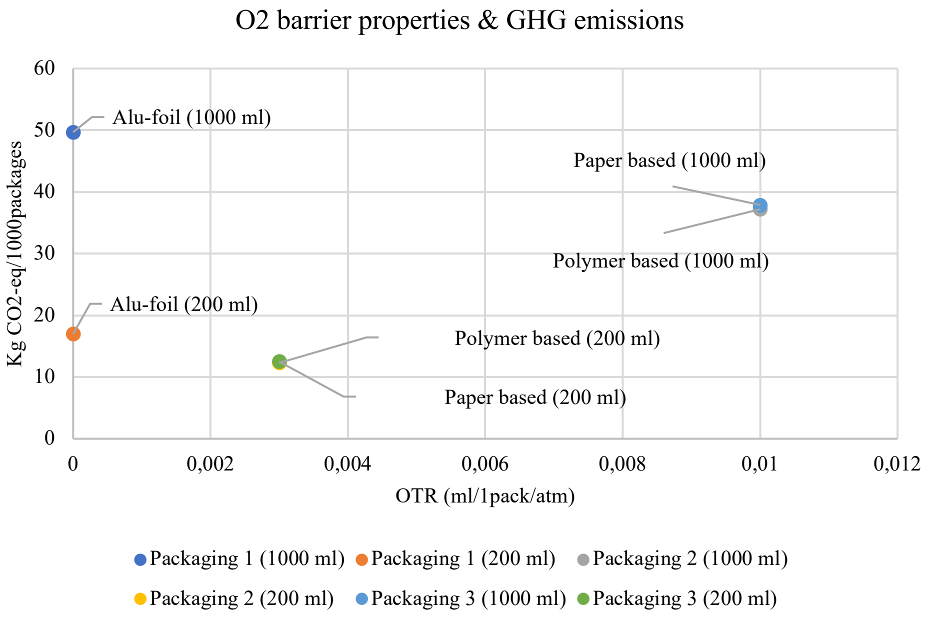


Figure 17. OTR and GHG emissions, focus on multilayer packaging structure.

Figure 17 illustrates the relation between the O_2 barrier properties of the entire packaging structures and the emissions generated during production. The results indicate the complete structures with both sustainable barrier layers provide the same barrier properties and emit the same amount on greenhouse gas emissions. Comparing the sustainable options with the base case, the total emissions of the package decreased by 25%. However, the barrier properties for the 1000ml package also decreased, resulting in OTR value equal to 0,01 (ml/pack/atm). Additionally, comparing the small packages (200ml), the OTR values were slightly different compare to the original structure, while the emission value decreased by 29% compare to the structure with Al foil.

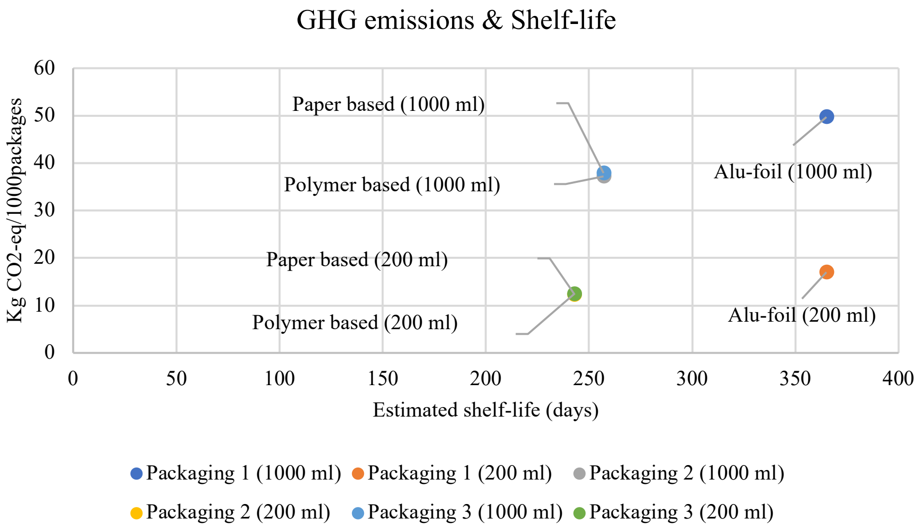


Figure 18. Relation between GHG emissions and Shelf-life based on Vitamin C degradation for packaging.

The relation between the greenhouse gas emissions generated during the production of packaging and its shelf-life length (based only on the Vitamin C degradation) presented in the Figure 18. There is a linear correlation between GHG emissions and shelf-life, where increased emissions is associated with longer shelf-life due to the influence of barrier properties. Analysis of the graph reveals that both new sustainable structures have the same shelf-life length. However, comparing them with the current base structure the shelf-life length for both 1000 ml and 200 ml volumes decreases by 29% and 33%, respectively. Furthermore, the new sustainable structures result in a reduction of GHG emissions by 29%, and the estimated shelf-life, based on the correlation between the OTR and Vitamin C degradation, decreases by approximately 30%. Therefore, the implementation of new sustainable materials has an equivalent effect on both direct and potential indirect environmental factors, which will be assessed further.

4.5 Indirect environmental assessment

The environmental impact of food packaging is not only determined by its direct effect, but also by its potential to reduce food waste. Packaging has a significant influence on the food waste by keeping food fresh longer, making it easier to empty, and by better fitting consumer's needs (Williams & Wikström, 2008). Food and drinks are responsible for a significant portion of the environmental impacts associated with consumption in the EU, ranging from 20-30% (Tukker and Jansen, 2006). In comparison packaging accounts for only 5-10% of the total environmental impact of the food product, thus it is crucial to consider its impact on food waste during its environmental evaluation (Tempelman, 2004). In order to understand the potential effect of the food waste, it is important to know the environmental impact caused by the production of the product itself. The carbon footprint of orange or apple juice was estimated to be approximately 1 kg CO_2e kg/1kg of juice according to Beccali *et al*. (2009) and Angervall and Sonesson (2011). Furthermore, Angervall and Sonesson (2011) calculated the carbon footprint of juice made from concentrate to be around 0,6 kg CO_2e kg/1kg. For soy milk and grain drinks, the average carbon footprint from cradle to retailer was estimated to be 0,15 kg CO_2e kg/1kg based on the studies of soy milk (Ecofys, 2009) and an oat drink (Dahllöv and Gustafsson, 2008). Comparing these results with the examined packages, the new packaging structures have carbon emissions of only 0,037 kg CO_2e kg/1 pack and while the current structures have emissions of 0,0497 kg CO_2e kg/1 pack. This highlights the minimal impact of the packaging production compared to the food product itself.

Many studies in the literature have been primarily focused on quantifying food waste that occurs during the consumer stage in the household. However, it is worth noting that the packages investigated in this study should be considered in the context for the potential food waste within supply chain and retail stores. Previously research on food waste quantification has indicated that a relatively small proportion of overall food waste is generated at the retail level, such as 2% in the UK (WRAP, 2016) and 5% in the EU (Stenmarck *et al*., 2016). Furthermore, it is important to consider that products with longer shelf-life, compared to perishable food items with shorter shelf-life, potentially pose a lower risk of contributing to food waste. In the study by Eriksson *et al*. (2016) reducing the storage temperature for chilled juice and dairy products from 8°C to 5°C extended their shelf-life by 30% and led to the potential waste reduction of 15%.

Based on the short interviews and observations of the three supermarkets (Coop, ICA and Willys), it was found that the percentage of food waste resulting from juices and milk drinks stored at ambient temperature is approximately 0-0,5% annually. Which has been also reported before by WRAP report, that around 0,4% of liquid food waste is produced at the retail level (Lee et al., 2015) .

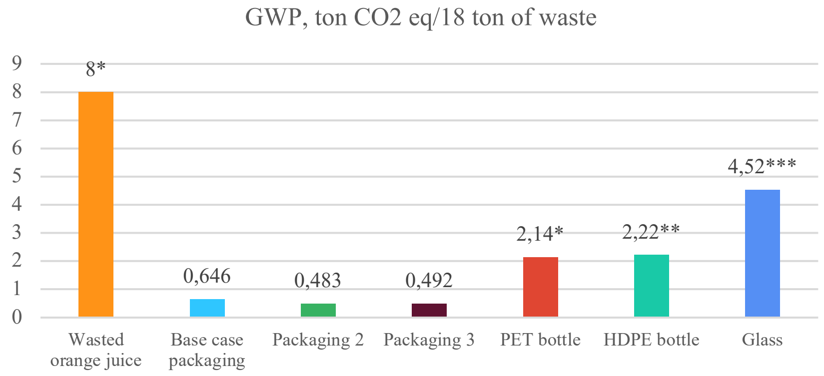
The main cause of product expiration dates was identified as improper replenishment, where items with close date are left in the back and not sold. Additionally, it was observed that the approximate shelf-life of juices stored in the ambient temperature after receiving the product in the store is around 5 months.

The investigation of the correlation between the shelf-life and the potential food waste currently mostly addressed to the consumer stage, implementing the survey, diaries or interview approaches. However, a study conducted by Quested (2013) examined and reported a correlation between the shelf-life extension and food waste reduction for milk products. Furthermore, the comparative LCA study by Manfredi *et al*. (2015) evaluated the environmental impact of 1 L milk packages with and without antimicrobial coating, which included milk waste. The study found that, on average, milk waste was the second-largest source of impact and contributed to 8-

37% of the overall impact. The packaging with antimicrobial coating, which extended the shelf-life of the product, resulted in 6-28% of the overall impact. Thus, the shelf-life extension from 3 to 13 days resulted in 10% reduction of emissions coming from food waste. According to the report by WRAP (2013), there is a correlation between food waste and shelf-life extension of milk. The study revealed that the most significant reduction in food waste occurs within the first 1-5 days of extended shelf-life. However, after day 10, the curve representing the relationship becomes steady.

The literature investigating the relationship between shelf-life and food waste, mostly focusing on perishable food products with shorter shelf-lives. These studies show that the impact of shelf-life changes has a greater impact on food waste within first 2-5 days. However, in this study, the product under investigation has a longer shelf-life, and the correlation should be investigated for a reduction from 12 to 8 months.

To assess the indirect environmental impact, Figure 19 represents the comparison of the emissions coming from the wasted orange juice and three examined packaging structures. The graph is based on the assumption that the waste rate would remain constant for packages with a shorter shelf life. Data from Eriksson's (2015) study was used to compare the effects of wasted juice and three packaging structures. Over a five-year period, this study quantified and investigated food waste from six stores in Sweden, results revealed 13 tons of wasted mass for orange juice and respectful 8 tons of CO_2 eq emissions.



* value was taken from Eriksson (2015)
**value was taken and recalculated from Bertolini (2016)
*** value was taken and recalculated from Stefanini (2021)

Figure 19. Comparative evaluation of potential direct and indirect environmental impact.

Figure 19 clearly demonstrates that food waste has a substantial carbon footprint, making it a major contributor to overall greenhouse gas emissions. Therefore, reducing food waste should be a priority in sustainability efforts, by addressing food waste through better storage, safe distribution and consumer behavior, the associated greenhouse gas emissions can be minimized. However, choosing packaging with lower CO_2 emissions, such as Packaging 2 or Packaging 3, can further contribute to reducing the overall environmental impact. Further, the comparison with other types of packages for orange juice is presented in the graph, which also highlights that examined packages can significantly contribute to the reduction of environmental impact, considering only cradle-to-gate boundaries.

In summary, the findings from Figure 19 emphasize the importance of tackling both food waste and packaging impact for sustainable practices. While reducing food waste should be primary focus, selecting packaging alternatives with lower CO_2 emissions can provide an additional avenue for mitigating environmental impact.

4.6 Discussions

This project tries to theoretically assess and compare the environmental performance of current and future sustainable barrier materials used in Tetra Brik Aseptic packaging. The study employed a combination of different methodologies, including LCA analysis, evaluation of barrier properties, following the estimation of a shelf-life and investigation of the correlation between packaging and potential food waste. The results from the LCA analysis indicated a significant 25% reduction of CO_2 emissions for the new barrier structures in comparison to the existing packaging. However, it is important to note that these results solely address only the raw materials production and converting of packaging laminates. Previous studies have emphasized that the raw material stage has the most significant impact and highlighted the importance of material selection in reducing the environmental impact of packaging laminates (Bayus, 2016; D. Kliaugaitė, 2013). It should be acknowledged that the inclusion of the end-of-life stage in the LCA analysis could influence these results. Three examined barrier structures have different recycling methods, leading to varying energy demand. While, the transportation and usage stages according to the previous studies have not significant impact on the overall environmental impact.

The barrier properties of the materials were evaluated using the Norner barrier calculator. It is important to note that the results obtained from this calculator are estimates and may not be accurately represent the actual barrier properties of packaging in different environmental conditions. The simulation was based on the base materials permeability and packaging design (shape and size). The results revealed that new structures exhibited higher oxygen transmission rates (OTR) in comparison to the base case structure, however it should be noted also, that the headspace of the bottle was not considered.

Regarding the water vapour transmission rates (WVTR), all the structures exhibit impermeability, according to their material properties. This can be attributed to the barrier properties of polymer, as well as the thickness of paper. It is important to note that the OTR and WVTR analysis was based only on the material properties and did not consider the potential impact of lamination, converting and folding processes, and other environmental factors which can affect the final barrier performance.

The barrier analysis of the complete packaging structures (Packaging 1, 2 and 3 (1000 ml)) resulted in OTR values of 0; 0,01 and 0,01, respectively. These values serve as an indicator of material performance during the preliminary evaluation stage, but should be recognized that the actual barrier performance may differ due to the manufacturing processes and different supply chain conditions.

In summary, the barrier analysis provided insights into the oxygen and water vapour permeability of the new barrier materials, which were further used to estimate the possible shelf-life length and correlate to the GWP impact. However, it is essential to conduct further testing and consider the impact of manufacturing processes to accurately determine the barrier properties of the materials under real-world conditions.

The relationship between the barrier properties (OTR and WVTR) and greenhouse gas emissions (GWP) of the barrier films was examined to determine any potential correlation. The results indicated that higher oxygen permeation was associated with higher carbon emissions, suggesting a positive correlation between OTR and GWP. Notably, the barrier used for small packaging (200 ml) Polymer based and Paper based demonstrated low oxygen permeation and low carbon emissions compare to the base case (200 ml). For the WVTR no correlation have been found as all the materials exhibit the same barrier properties.

Furthermore, the analysis was extended to encompass the complete packaging structures, including all base materials. The results revealed the same trend of a direct correlation, indicating that higher permeability led to higher emissions. Moreover, Packaging 2 and 3 exhibit similar performance in both OTR and GWP parameters.

The correlation between estimated shelf-life length and GHG emissions was investigated, and the findings revealed that decreasing in GHG emissions correspond to a decrease in shelf-life days. This correlation resulted in approximately 30% reduction in shelf-life days and a 29% reduction in GHG emissions when comparing the new structures to the base case. These results are consistent with previous studies by Luz, (2012), Williams, Wikström, & Löfgren (2008), which also indicated that materials enabling longer shelf life have a higher environmental impact. However, it is important to note that the shelf-life length in this study was estimated solely based on the Vitamin C degradation. Further research is required to perform accurate estimations of real shelf-life under various conditions and factors.

Furthermore, the potential food waste impact and packaging production impact was analyzed. Highlighting a huge difference and great impact of food waste in comparison to the packaging production. The findings highlight the need for integrated solutions that consider both food waste and packaging impact.

5 Conclusions and recommendations for future research

This chapter provides a summary of the key findings and conclusions derived from the study, addressing the research question that guided the investigation. Additionally, recommendations for future research opportunities are proposed.

5.1 Conclusions

This study was conducted to answer the following research objectives:

- to investigate the barrier properties of a new barrier material structures
- to assess the direct environmental impact, caused by the production of the new barrier material structures
- to analyze the efficiency of a new barrier materials by estimating a potential shelf-life length
- to estimate the potential indirect environmental impact associated with the barrier properties performance.

The research objectives of this study aimed to apply a comprehensive theoretical approach in evaluating the environmental performance of existing and future barrier materials for Tetra Brik Aseptic packaging. The methodology employed in this study provides a preliminary analysis of packaging solutions with the goal of minimizing the overall environmental impact of the food packaging system. A key consideration in reducing the environmental impact of the packaging system is understanding the relationship between packaging type, shelf-life, and potential food waste (Gutierrez et al., 2017). Therefore, this study sought to establish correlations among these various attributes in order to shed light on their interconnection and implications for sustainability.

Key findings from the study include:

1. Barrier properties assessment demonstrated higher oxygen transmission rate (OTR) and impermeability for water vapor transmission rate (WVTR) for the new barrier materials.
2. Direct environmental assessment showed a 25% reduction in CO_2 emissions for the new barrier structures compared to the base case packaging. LCA

analysis showed that material selection playing a crucial role. Comparison of two new barrier structures revealed that polyethylene-based barriers exhibiting lower emissions than fiber-based barriers.

3. Shelf-life length estimation based on OTR value and Vitamin C degradation indicated a potential 2-month reduction in shelf-life length for the both new barrier structures.
4. The correlation between barrier performance and greenhouse gas (GHG) emissions confirmed that higher barrier properties were associated with higher emissions. Aluminum foil performed best in terms of barrier properties but had the least desirable GHG emissions.
5. The relationship between estimated shelf-life and GHG emissions revealed that new barrier structures could potentially lead to shorter shelf-life due to higher oxygen transmission rates, but resulting in lower emissions.
6. The investigation of the potential indirect environmental impact associated with barrier properties performance highlighted the significant impact of food waste compared to packaging. However, further investigation is needed to assess and quantify the effects of shelf-life reduction.

In conclusion, this study provides valuable insights into the environmental performance of new barrier materials for Tetra Brik Aseptic packaging. It highlights the importance of material selection, the potential trade-off between barrier properties and emissions, and the need for integrated approaches to minimize the overall environmental impact of packaging systems.

5.2 Future research recommendations and implications

The environmental assessment of the barrier materials in this study was conducted based on the mere theoretical approach. Thus, to validate the estimations made, it is strongly recommended to conduct practical assessments of the barrier properties and perform shelf-life testing for the packaging with product. To extend the study and provide a more comprehensive analysis, the following research recommendations are proposed:

- Conducting a life cycle assessment (LCA) analysis which includes the end-of-life stage of the packaging structure. As studied barrier structures have different recycling methods, which can vary the energy demand, thus including this step will enable a more complete evaluation of the direct environmental impacts associated with the new barrier materials.
- To analyze thoroughly the WVTR and OTR barrier properties under supply chain conditions on the folded package, this will provide a more accurate depiction of barrier properties, taking into account the potential impact of folding and transportation.
- Practically investigate the food waste from the retail stage and to incorporate it into LCA analysis. By considering these values in the LCA analysis, a more accurate assessment of the overall environmental performance can be achieved.
- To analyze the examined barrier materials for the product with a shorter shelf-life and evaluate the food waste impact.
- After evaluating the WVTR barrier properties in real-world conditions, the impact of food loss can be also investigated. By understanding the relationship between WVTR properties and food loss, valuable insights can be gained into the potential reduction of food waste.
- It can be interesting to assess the impact of aluminum production using the solar power, renewable energy, or wind power, in order to evaluate the potential reduction of impact.

The findings and conclusions of this study have important implications for the industry. They highlight the potential for reducing greenhouse gas emissions by selecting low-carbon emission raw materials. The study demonstrates that the environmental impact is largely driven by raw material extraction and production. These results can inform decision-making processes, such as Environment Product Declaration (EPD), facilitating the selection of resource-efficient and environmentally low-impact materials.

Additionally, the study raises a new research question regarding the trade-off between shelf-life and environmental impact in new packaging structures. Exploring the impact of decreased shelf-life of the shelf-stable food products on food waste and its potential indirect environmental consequences presents a novel perspective for academia. These aspects can be integrated into the Life Cycle Assessment (LCA) analysis, further enhancing the understanding of the relationship between shelf-life, food waste, and environmental sustainability.

In conclusion, the methodology employed in this study to examine the relationship between direct and indirect impacts can serve as a model for other companies during the packaging material selection process. By adopting a similar approach, companies can assess the potential trade-offs and make informed decisions. It is important to emphasize the significance of this decision, particularly for perishable food products, as the potential reduction in shelf-life can outweigh the environmental impact of the packaging materials themselves.

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