Towards Sustainable Coffee Packaging

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FACULTY OF ENGINEERING LTH | LUND UNIVERSITY
2023

MASTER THESIS

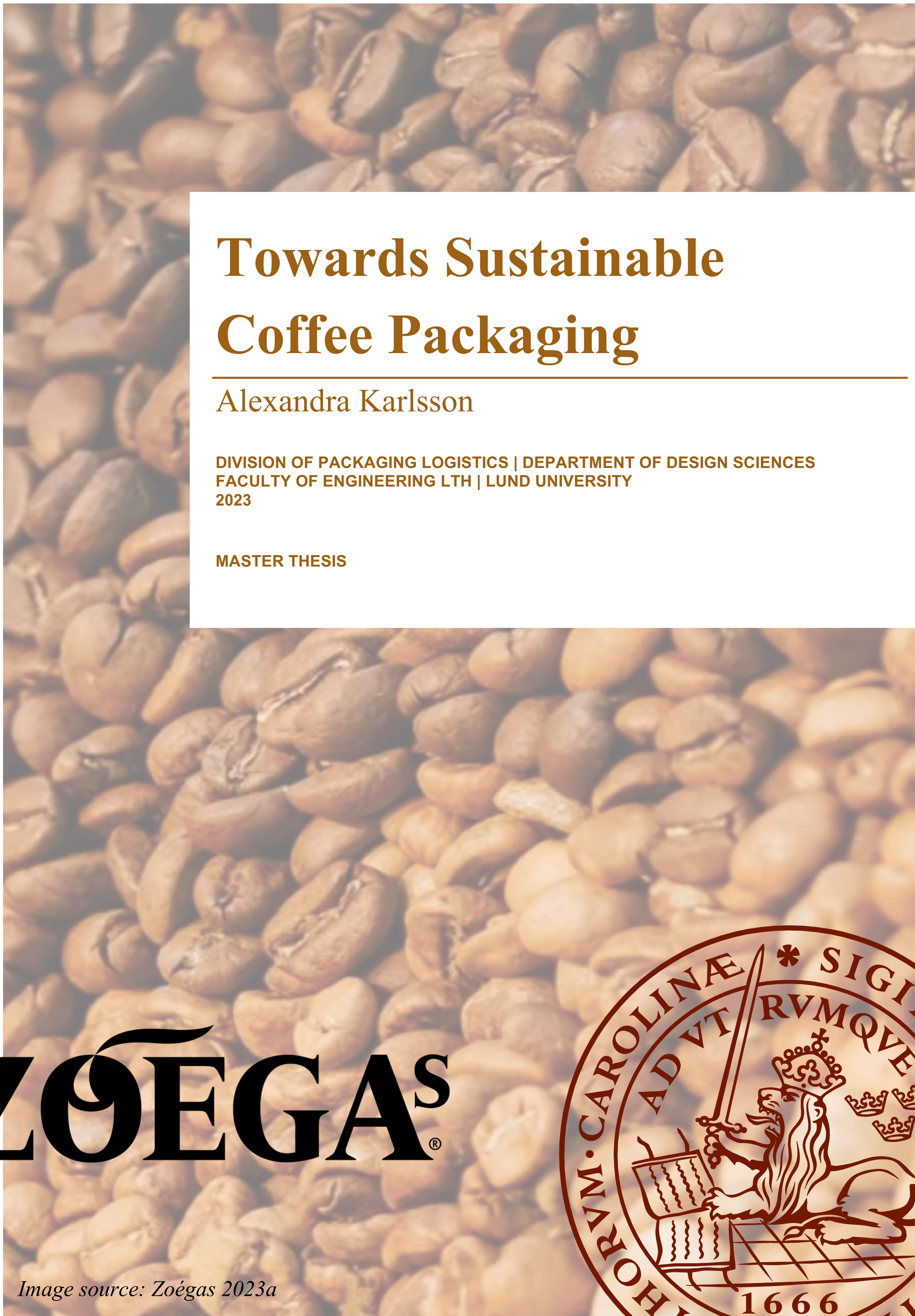

Image source: Zoégas 2023a

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A Comparative Study of Current and Future Materials for Zoégas Coffee

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Published by
Department of Design Sciences
Faculty of Engineering LTH, Lund University
P.O. Box 118, SE-221 00 Lund, Sweden

Packaging Logistics (MTTM10)

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Abstract

An important factor in preventing food waste is the ability to provide a product with a package according to its needs. The packaging material, in turn, needs to be recyclable in order to contribute to a circular use of materials rather than becoming waste. The aim of this thesis is to examine the difference between the current and future packaging material of coffee produced by Zoégas. The current plastic laminate consists of PE/SiO_x/PET while the future laminate will consist of PE/EVOH/PP. The shelf life of coffee is determined by its sensory performance and its major factors for deterioration are volatile losses, oxidative reactions, and loss of moisture. The laminates used for the packaging will therefore be rated based on their performance as gas and water vapor barriers, as well as their environmental impact. A barrier calculator will be used for guidance and aid in the comparison between theoretical and experimental data to assess possible further use of theoretical tools.

The report has found that the change of materials is beneficial since the future material will offer a better oxygen barrier. No changes were found in its effect on moisture. While the future material is recyclable given current recycling technology, the current material is not. However, there is no current standard on the handling of collected plastic waste, meaning that not all collected plastic waste will come in contact with the recycling techniques required to process the future material. Although more experimental tests would be needed for comparisons, the results indicate that the barrier calculator can be a useful guideline for assessing packaging materials under different conditions. Finally, further work is needed to attain the optimal coffee packaging material, but an examination of currently relevant materials has been conducted through this thesis.

Keywords: Food packaging, coffee, permeability, recyclability, shelf life.

Sammanfattning

En viktig faktor för att förhindra matsvinn är att förse ett livsmedel med lämplig förpackning utifrån produktens behov. Förpackningsmaterialet behöver i sin tur vara återvinningsbart för att bidra till ett cirkulärt användande av material. Syftet med detta examensarbete är att undersöka skillnaden mellan det nuvarande och framtida förpackningsmaterialet för kaffe producerat av Zoégas. Det nuvarande plastlaminatet består av PE/SiO_x/PET medan det framtida laminatet kommer att bestå av PE/EVOH/PP. Kaffets hållbarhet bestäms av dess sensoriska prestation och de främsta faktorerna för försämrad hållbarhet är oxidationsreaktioner samt förlust av flyktiga ämnen och fukt. Laminaten som används för förpackningen kommer därför att bedömas utifrån deras prestanda som gas- och vattenångsbarriär samt deras påverkan på miljö. En barriärkalkylator kommer att användas för vägledning och jämförelse mellan teoretiska och experimentella data för att bedöma dess framtida användningsmöjligheter.

Resultatet tyder på att bytet av laminat är fördelaktigt då det framtida materialet bidrar med en bättre syrgasbärriär. Inga förändringar återfanns gällande effekten på fuktnivåerna. Det nuvarande materialet är inte möjligt att materialåtervinna, men det finns återvinningstekniker som gör det möjligt att återvinna det framtida laminatet. Det finns emellertid ingen nuvarande standard för hur insamlat plastavfall hanteras, vilket innebär att det inte är säkert att plastavfallet som samlas in kommer i kontakt med de återvinningstekniker som krävs för det framtida materialet. Fler experimentella tester hade behövts för att med säkerhet avgöra barriärkalkylatorns pricksäkerhet, men erhållna värden indikerar att kalkylatorn är användbar för att uppskatta och utvärdera förpackningsmaterial under olika förhållanden. Slutligen så kommer framtida arbete behövas för att nå en optimal kaffeförpackning, men med detta examensarbete har en utvärdering mellan nuvarande aktuella material gjorts.

Nyckelord: Livsmedelsförpackning, kaffe, hållbarhet, permeabilitet, återvinning.

Popular science summary

Source: iStock

Can a change of plastic affect your cup of coffee?

Upon opening a new package of coffee, one is immediately greeted by the delightful aroma of ground coffee. No matter if you bought the package yesterday or several months ago, the aroma that sips out the moment that the seal is broken will probably fill you with the same joy.

This cherished characteristic is attributed to the packaging that has been developed specifically to keep the aroma and slight moisture inside, while effectively preventing oxygen ingress. Because no matter how dependent we are on both coffee and oxygen, the two do not really mix that well. This thesis project investigates the transition from one plastic packaging composition to another, analyzing the permeability of oxygen and moisture across the materials. The objective is to determine whether a substitution of plastic materials has any effect on the beloved product. The purpose of the change is to increase its recyclability and environmental effect, which is studied as well.

The packaging of Zoégas' Skånerost consists of two components; a plastic laminate which directly covers and encloses the product, and a final decorative and informational paper wrapping. The plastic laminate is made up by three components, two of which will be replaced by Zoégas during the year 2023. Each one of these components have different properties, which contribute to the laminate material and product quality in unique ways. Since the shelf life of coffee is determined by its sensory profile, it is important that the package effectively prevents the loss of aroma and moisture and acts as a barrier towards oxygen. Thus, a comprehensive comparison has been conducted between the current and future packaging to ensure that the latter offers equivalent protection for the coffee. And thankfully for all Skånerost drinkers – it does. In addition, the future package not only meets the required standards but exhibits even lower oxygen transmission.

Although plastic often encounters skepticism and is criticized for excessive usage, it plays an important role of reducing food waste. The environmental impact of food waste is larger than that of the plastic packaging itself. Nonetheless, it is crucial to ensure that the plastic can be part of a circular system, where the old coffee package can be recycled and repurposed, perhaps ending up as your next pencil or chair. With existing recycling systems, the future plastic laminate will have a chance to be integrated into the circular system – a win, win situation if you ask me.

Acknowledgements

In October 2018 I started my part-time job at Nespresso in Malmö. Here my job title has been “coffee specialist” for the past five years. Therefore, I find it fitting, and amusing, to finish my university studies with a project about coffee, and to truly earn my “coffee specialist” title.

I would like to start with expressing my gratitude to the team at Zoégas. Thank you to my supervisors, Eva Smidfelt and Ádám Németh, for letting me take part of this fascinating project and for their guidance and support throughout the semester. To Linda Linderoth, Patrik Erlandsson, and Dan Fredriksson – thank you for your wise input and support throughout the project. It has been a pleasure to join you and the rest of the team in Helsingborg during this spring.

To my supervisor Jenny Schelin: I am immensely grateful for your support, guidance, and for believing in this project from the start. Your constructive feedback and insightful suggestions have been instrumental in shaping this thesis. Thank you for ensuring that this project reached its full potential.

This thesis would not have been possible to write without the support from Åsa Halldén Björklund. Thank you for always being there to discuss every aspect of packaging, your near encyclopedic knowledge of packaging materials truly puts Google to shame. Your help has been fundamental for writing this thesis, and I owe you my new-found interest in the packaging industry.

Thank you to Lars Palm, who is responsible for putting me in contact with Tetra Pak, and therefore the subsequent data which has been fundamental to my research. I would like to express my gratitude to Martin Gunnarsson and the team at Tetra Pak. The possibility to perform OTR measurements has contributed significantly to both the quality and depth of my research.

Lastly, I want to express my gratitude towards my friends and family, who have always been there for me throughout this project and my education. I owe a lot to the people and institutions that I’ve mentioned in this acknowledgements section, but my biggest debt is to my favorite lab partner, Malin Gabrielsson. Thank you for all the years of undying love and support. You are *my* favorite woman in STEM.

Lund, May 2023

Alexandra Karlsson

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List of acronyms and abbreviations

AlO_x	aluminum oxide
ANOVA	analysis of variance
a_w	water activity
BOPP	biaxially oriented polypropylene
APET	amorphous poly(ethylene terephthalate)
CO_2	carbon dioxide
CPET	crystalline poly(ethylene terephthalate)
EVOH	ethylene-vinyl alcohol
FTI	Förpackningsinsamlingen *(company name)*
GTR	gas transmission rate
HDPE	high density polyethylene
H_2O	water
LDPE	low density polyethylene
MW	molecular weight
N_2	nitrogen
NIR	near-infrared
O_2	oxygen
OPP	oriented polypropylene
OTR	oxygen transmission rate
PE	polyethylene
PET	poly(ethylene terephthalate)
PP	polypropylene
R&G	roast and ground
RH	relative humidity
SiO_x	silicone oxide
STP	standard temperature and pressure
TMR	Tailor-made responsibility *(company name)*
VA	vinyl acetate
VOH	vinyl alcohol
WVTR	water vapor transmission rate

1 Introduction

1.1 Background

Coffee originated in the area of what is today Ethiopia, probably sometime around the year 800, and now enjoys the status as one of the most popular drinks in the world. Sweden is one of the leading coffee-drinking countries with the consumption per capita equaling 160 liters, or 7.6 kg, of coffee per year (NE 2023; Fairtrade 2023). Coffee is cultivated in tropical climates, and is grown in more than 70 countries, the largest producers being Brazil, Vietnam, Indonesia, and Colombia. Coffee is grown, harvested, and processed in the country of origin, and shipped to the consumption country where it is roasted, sometimes ground, and packaged (NE 2023). The packaging of the coffee is a central element of the coffee industry. The packaging of the product ensures that it is easily accessible, safe, possible to transport, and tastes just like the consumers expects it to. Not only does the packaging protect the product, but it also displays all the information that is of interest to the consumer (Robertson 2013, p. 2). This thesis is made in collaboration with Zoégas, a coffee producer in Helsingborg, Skåne, and will examine the packaging of their popular "Skånerost".

The packaging of Skånerost consists of two components; a plastic laminate which directly covers and encloses the product, and a final decorative and informational paper wrapping. The plastic laminate is made up by three components, two of which will be replaced by Zoégas during the year 2023. Each one of these components have different properties, which contribute to the laminate material and product quality in unique ways. The interaction between materials within the laminate and the effect on product relies largely on prior experiences and theoretical knowledge of the materials. Theoretical tools can therefore be used to estimate the efficiency of the material.

Furthermore, there is an environmental aspect to the packaging. In the 1800's, the plastic industry took off and the largest use of plastics in Sweden today are packages (Robertson 2013, pp. 11-12; Swedish Environmental Protection Agency 2021a, 50). Plastic packaging has a wide range of applications and is easily manufactured to fit the producer and consumer needs perfectly. However, plastic remains a material that is mainly made with fossil oils and takes hundreds of years to decompose (Swedish Environmental Protection Agency 2021a, p. 22; SSNC 2022). Circular economy is a concept that aims for reuse and recycling of plastic materials, rather than the linear flow of production – use – waste. In Sweden, only 15% of the plastic that was collected in 2020 was recycled due to its complex structure (FTI, 2023a).

1.2 Objectives

The main goal for the thesis will be to examine how a change in the primary packaging will affect the quality of the final product. Since the packaging material is changing from one plastic laminate to another, the difference in the environmental impact between the two will also be analyzed. The thesis will aim to investigate the following:

1. Examine the differences between the current and future packaging material.
2. Examine the recycling possibilities of the packaging material as well as compare it to other coffee packaging solutions.
3. Examine which factors affect the quality of roast and ground coffee to determine which packaging material components are needed.
4. Compare values from theoretical calculation tools to experimental data.

2 Theoretical background

2.1 Coffee

There are over 100 species of coffee, where the two most common and commercialized are *Coffea arabica* which is commonly referred to arabica, and *Coffea canephora* which is referred to as robusta. Arabica coffee is considered finer and accounts for 60% of the coffee produced, while robusta is cheaper to produce and contains higher levels of caffeine (Ramakrishna, Giridhar and Jeszka-Skowron 2022, p. 3). Coffee trees grow in tropical climate and the coffee fruit is harvested when ripe (fig. 1a, 1b, 2a). It undergoes either dry or wet processing to remove the pulp and is thereafter referred to as green coffee beans (fig 2b) (Farah 2019, pp. 65-82; Ramakrishna, Giridhar and Jeszka-Skowron 2022, pp. 3-13).

Figure 1. (a) Coffee plantation with trees planted in rows following the field topography (b) Coffee being harvested and sorted. Source: Farah 2019, chapter 2, pp. 40, 67.

Figure 2. (a) The different development stages of coffee beans where the ripe beans are marked in white. Source: Farah 2019, chapter 2, p. 34. (b) Green coffee beans after processing and discarding the pulp. Source: Nespresso 2023a.

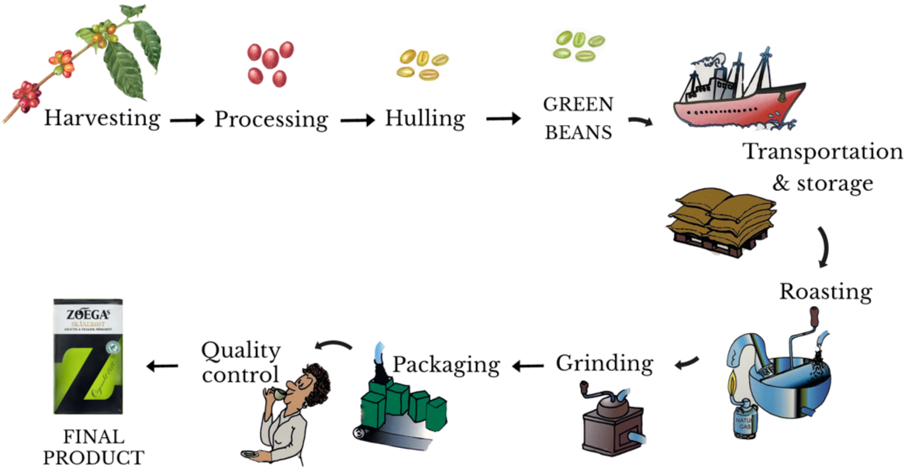

Figure 3. Flow chart of the process from harvesting of the coffee beans to the final product. Sources for illustrations: Nationalencyklopedin 2023, Zoégas 2023a.

In many cases, the green beans are dried and shipped to the production site where the coffee is roasted. The roasting is carried out in temperatures up to 220°C and the effects of roasting is water removal, pyrolysis, Maillard reactions, and release of carbon monoxide and carbon dioxide. During the roasting, there is also a production of brown pigments from monosaccharides as well as the development of substances related to the taste and aroma of coffee. The time and temperature of the roasting depends on the desired results, where roasting time can range from 90 seconds to 40 minutes. After roasting, the coffee is degassed to remove the excess carbon dioxide. Thereafter, it can either be packed and sold as whole beans or ground coffee (Manzocco et al. 2016, pp. 375-377; Buffo et al. 2004).

There are quality controls made throughout the production line, starting at picking of the ripe fruits, and discarding the overripe or underripe fruit. During the washing, all fruits that have a lighter density and float on the surface get discarded. The green beans are also sorted to not contain any defects such as being immature, broken or insect-damaged (Farah 2023, pp. 73, 81-82). After roasting the coffee, the quality control is highly focused on sensory analysis to control the aroma and flavor (Ramakrishna, Giridhar and Jeszka-Skowron 2022, pp. 95). As a part of the quality assurance process of industrially roasted coffee, the color of the coffee is analyzed. The machines commonly used illuminate the sample, and the reflection is given as a number. The color is dependent on the type of roasting and a standard is usually set from the individual companies for each coffee type produced and is used to confirm that the correct roasting is obtained. Moisture measurements are also carried out to ensure that the product has a moisture level within an acceptable range (Farah 2019, p. 235; Zoégas, 2023; Nicoli, Calligaris and Manzocco 2009; p. 162).

The content of the coffee varies by type, as well as if the beans are green or roasted. In table 1, the contents of roasted arabica and robusta coffee are presented.

Table 1 . Main compounds of roasted arabica and robusta coffee presented as percentage of the contents. Source: Ramakrishna, Giridhar and Jeszka-Skowron 2022, p. 34.

Compounds (%)	*Arabica*	*Robusta*
Water	1.5-5.0	1.5-5.0
Proteins	7.5-10.0	7.5-10.0
Carbohydrates	36.3-42.5	42.3-43.9
Lipids	17.9	11.0
Acids	7.0	10.0

The percentage of each compound in table 1 varies in literature, reflecting the variations of different coffee beans. The composition will vary as a result of different climate conditions during the growth such as location, altitude, soil and temperature, amongst other factors. The harvest process and storage conditions will also further affect it (Ramakrishna, Giridhar and Jeszka-Skowron 2022, p. 34).

The coffee referred to in this report has been grown and harvested in South America and Africa, and then shipped to Sweden where the roasting and grinding process take place. Roast and ground coffee, often referred to as “R&G”, is packaged at the production site and then shipped out. Zoégas coffee is mainly distributed in Scandinavia and the report will focus on the packaging in a Nordic climate (Zoégas 2023b).

2.2 Quality and safety

2.2.1 **Shelf life**

Shelf life is defined as the period in which the product meets its quality standards and is acceptable. The factors that make a product unacceptable varies with product type, and can be dependent on microbiological growth, nutrient loss, or the development of off-flavors. For coffee, the main factors are oxidative reactions and consequently a sensibility to light, and moisture (Farah 2019, p. 265; Belitz 2009, pp. 941-942). Coffee obtains a low water activity due to the roasting process, which in turn causes there to be no threat of enzymatic or microbiological damage (Farah 2019, p. 267).

Since coffee that has been vacuum packaged does not pose any safety hazards, the shelf life is individually determined by each producer and is mainly related to the quality of the product. The shelf life is rather determined by its sensory profile after a certain time and the risk for consumer rejection. For roast and ground coffee, the main factors that affect the sensory profile are oxidative reactions and volatile losses. The roast and ground coffee contains compounds such as aldehydes, ketones, and thiols which affect the aroma (Manzocco et al. 2016, pp. 376-378). Methanethiol and acetaldehyde are two examples of substances that evaporate easily and are highly volatile (Belitz, Grosch, Schieberle 2009, p. 946). The ground coffee will additionally have a larger surface area prone to reactions. (Manzocco et al. 2016, p. 378).

The changes of the coffee are inevitable, but are dependent on the oxygen and moisture levels, as well as temperature to determine at what rate it happens. Once a coffee package has been opened, it will be exposed to oxygen and moisture from the surrounding air, which leads to a quicker degradation (Farah 2019, 266-267). For Zoégas roast and ground coffee, the shelf life is 12 months. The shelf life has been determined through sensory tests to ensure a good cup quality throughout the period. Once the package has been opened, the general recommendation is to consume the product within 10-21 days. (Zoégas 2023b).

2.2.1.1 Oxygen

As mentioned above, the roast and ground coffee contains high concentrations of compounds that can react with the oxygen. Examples of these compounds are aldehydes, ketones, and thiols which affect the aroma. Methanethiol is a type of thiol contributing to the typical sense of fresh coffee, and it makes a considerable impact even at low concentrations. It is highly volatile and prone to oxidation. The loss of methanethiol has been related to the staling of roast and ground coffee

(Dulsat-Serra 2016, pp. 983-984, 987). In general, loss of volatiles and oxidation of aroma compounds lead to staling of the coffee (Nicoli, Calligaris and Manzocco 2009, p. 161). The oxidative reactions can furthermore contribute to the development of off-flavors in the coffee (Manzocco et al. 2016, p. 378). Coffee contains between 11-18% lipids (Ramakrishna, Giridhar and Jeszka-Skowron 2022, p. 34) which are prone to oxidation. The coffee obtains a larger surface area due to the grinding process, and the roasting process causes oils to migrate to the surface. This increases the contact between oils at the surface and the oxygen in the air (Manzocco et al. 2016, pp. 376, 378).

A study shows that when the partial pressure of oxygen is reduced from 21.3 kPa to 0.5 kPa, the shelf life increases approximately by a twentyfold. Oxygen is the most critical factor affecting the shelf life compared to water activity and temperature. (Cardelli and Labuza 2001, pp. 276-277). By reducing the oxygen concentration in the packaging, the shelf life can be prolonged. Coffee packaging is manufactured to contain as low oxygen concentrations as possible, and the air is either replaced with inert gas such as N_2 or CO_2, or removed with vacuum (Robertson 2013, p. 587; Manzocco et al. 2016, p. 381). The temperature has a very small effect on accelerating the deterioration rate when the oxygen levels are low but becomes more significant at higher oxygen levels (Manzocco et al. 2016, p. 382).

According to literature, roasted coffee has an oxygen tolerance of approximately 110 mg O_2/kg of product. (Singh, 2017. pp 51-52). This includes the initial oxygen content which according to Robertson (2013, p. 584), can be assumed to be about 0.5% of the volume. For one package of Zoégas coffee, this would correspond to an initial oxygen content of 6.8 mg O_2/package. The calculations can be found in the box below. The oxygen level will vary with different batches and products, but if assumed that a coffee package has an initial content of 0.5% oxygen, the maximum oxygen that can enter the package before it is spoiled will be 95 mg O_2/kg product. In a Zoégas package, this would translate to 42.7 mg of oxygen entering the product.

Calculating the oxygen content in a coffee package

Zoégas coffee package: 1.4 dm · 0.8 dm · 0.85 dm = 0.952 dm^3 = 0.952 liters

0.5% of the volume = 0.952 liters · 0.005 = 0.00476 liters O_2/package

Density of air at standard temperature and pressure: 1.429 g/l

Initial oxygen content: 0.00476 l · 1.429 g/l = $6.8 \cdot 10^{-3}$ g O_2/package = 6.8 mg O_2/package

Oxygen per kilo product: 6.8 mg O_2/g · $\frac{1000}{450}$ = 15.1 mg O_2/kg of product

Maximum oxygen content: 110 – 15.1 mg O_2/kg of product = 94.9 mg O_2/kg of product

Maximum oxygen content in a package: 94.9 mg O_2/kg product · $\frac{450}{1000}$ = 42.7 mg O_2/package

However, it is difficult to measure the oxygen content in a vacuum sealed package, and the initial as well as final oxygen content can be estimated by calculations and by assessing the oxygen transmission rate, OTR, of the packaging material. According to Singh (2017, p. 58), the required oxygen permeability for coffee packaging is 0.87-1.3 cm^3(STP)/(m^2·d·bar) at a temperature of 23°C.

2.2.1.2 Water activity

Water activity, a_w, is a measurement of available water in a food product and its values range between 0 to 1. It is the ratio between the partial pressure of water in the food to the partial pressure of pure water in the same conditions (Robertson 2013, p. 314). As coffee is a dry product, the a_w will reach a maximum of 0.4. (Roberson 2013, p. 585). The water activity in coffee is the second most important factor affecting the shelf life of coffee. The same study as mentioned in *2.2.1.1. Oxygen* determined that with an increase of water activity from 0.106 to 0.248, the shelf life is reduced by 60% (Cardelli and Labuza 2001, pp. 276-277).

According to Singh (2017, p. 55), the initial water content in coffee is 20-25 g H_2O/kg product which equals 2-2.5% of the weight. The acceptable uptake of water is between 25 and 30 g for each kilo of product. The theoretical maximum final water content is therefore 55g H_2O/kg product which equals to a 5.5% moisture content in the product. The required water vapor transmission for a coffee package is 0.61-1.1 g/(m^2·day) at the conditions of 23°C and 85% RH (Singh 2017, pp. 55-58).

2.2.1.3 Temperature

Higher temperature accelerates the rate of chemical reactions according to the Arrhenius equation. This will increase the rate of the oxidation process, volatile release amongst other reactions (Manzocco 2016, p. 380). Hydrolysis of triacylglycerol and the oxidation of free fatty acids will occur as well and increase as a result of a higher temperature (Farah 2019, p. 267).

According to the study conducted by Cardelli and Labuza (2001, pp. 276-277), the temperature had an increasing effect on the oxidation process when measured at oxygen levels of 10%. Coffee is packaged at oxygen levels under 0.5%, making the temperature effect relevant mainly with increasing oxygen levels. At low oxygen rates, storage temperature increases ranging from 25-40°C will be equivalent (Manzocco 2016, p. 382).

2.3 Packaging

Food packaging is used to protect the product and by that, extend the shelf life and prevent food waste. Depending on what factors a food product is sensible to, the packaging must be customized to retain the wanted substances while preventing unwanted substances to enter. Different food products require different types of packaging, and the producer must consider the environmental impact as well as cost as a factor when deciding what type of material should be used and its composition (Robertson 2013, p. 2). As mentioned in *2.2.1 Shelf life*, roast and ground coffee is mainly sensible to oxygen, moisture, and volatile loss. The packaging is therefore expected to retain the aroma and to prevent oxygen and moisture from passing through.

Prior to vacuum packaging, coffee was sold mainly as whole beans in cardboard packages (Farah 2019, p. 264). Ground coffee releases substances as well as react with other substances quicker since it has a larger surface area (Manzocco et al. 2016, p. 376) and whole beans was therefore a more convenient way to sell coffee. Roasted whole beans contain cavities in their structure that slowly releases a substantial amount of CO_2 during the storing time (Farah 2019, p. 263) and are therefore packed in soft packs made of laminate. The packages are either permeable to CO_2 or have a one-way valve to release the gas to avoid build-up. An abundance of CO_2 is released rapidly when the roasted coffee beans are ground, and it can therefore be packed in both hard packs and soft packs (Robertson 2013, p. 586). Roast and ground coffee used to be sold in metal cans, something that is rarely seen today due to its higher weight and inconvenience of packaging for transport. Nowadays the two most found packages are hard packs and soft packs, as seen in figure 4 (Wrede 2007). Both soft and hard packs are made with laminate, and the exact composition varies depending on the producer. Polymer laminates are common, as well as laminates with a metallized layer. Hard packs are made with a flexible laminate and obtain a brick-like structure after being treated with vacuum. Soft packs are not treated with vacuum, but flushed with inert gas to lower the oxygen content. The barrier properties of the laminates are important for both hard and soft packs to reduce the permeability of oxygen and water vapor (Robertson 2013, pp. 586-588).

Figure 4. Zoégas Skånerost, roast and ground coffee in a hard pack and whole beans in a soft pack (Zoégas 2023).

The product focused on in this report is a hard pack and consists of a clear polymer multilayer laminate. In the current laminate, low density polyethylene (LDPE) is used closest to the product and Poly(Ethylene Terephthalate) (PET) as an outer layer. The PET-layer is coated with SiO_x which is positioned between the two layers. In the future laminate, LDPE is still used closest to the product, followed by a layer of ethylene-vinyl alcohol (EVOH). Lastly, the PET has been replaced by oriented polypropylene (OPP). In the future material, the thickness of the LDPE has been reduced with roughly 10%. The laminate is sealed using heat and then wrapped with a layer of paper that offers shield from light and a base for the print (Zoégas 2023b). In section *2.3.1* to *2.3.5*, each material that has been used in the current and future laminate will be further described.

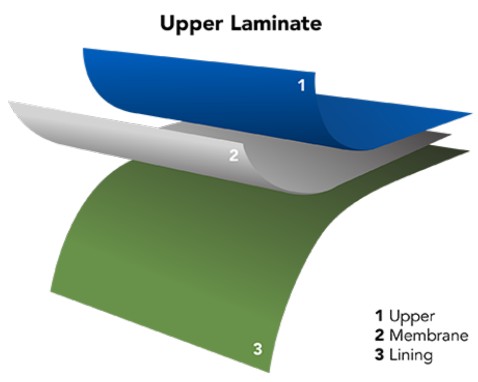

Figure 5. A visual representation of the laminate layers used for the roast and ground coffee. Image source: Eagle Flexible Packaging 2023.

2.3.1 **Polyethylene - PE**

Polyethylene is a type of polyolefin, which is a group of plastics that are based on ethylene or propylene with a carbon-carbon double bond. Polyethylene is a polymer of ethylene which can be obtained by petroleum refining where it is a byproduct. To polymerize the ethylene, pressures between 1000-3000 atm are used at temperature between 100-350°C. The pressure causes the polymer to branch which can either result in shorter chain branches, such as in high density polyethylene (HDPE) or longer chain branches such as in low density polyethylene (LDPE). The long branches in the LDPE are responsible for the lower density of 910-940 kg/m^3, as the branches prevent the polymer from being packed closely. The density for HDPE is 945-967 kg/m^3. Each branch ends with a terminal methyl group of -CH_3, and to analyze the branching, the amount of methyl groups per 1000 carbons can be compared between different PE's. LDPE has 20-33 methyl groups per 1000 carbon atoms while HDPE has less than 1.5 methyl groups per 1000 carbon atoms. The crystallinity for LDPE ranges from 55% to 70%. (Robertson 2013, pp. 20-24). Crystallinity refers to the ordered structure where the polymer chains are packed parallel to each other. The rest of the polymer is amorphous, meaning a lack of structure (Robertson 2013, pp. 16-17; Singh 2017, p. 5).

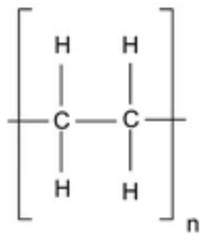

Figure 6. Basic structure of polyethylene. Source: Piergiovanni and Limbo (2016, p.39)

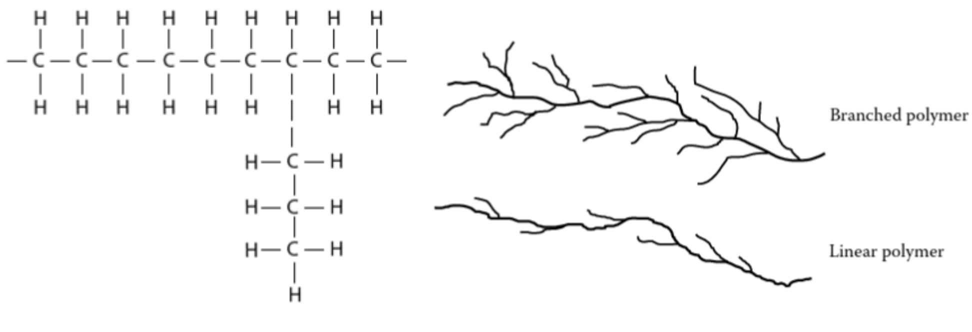

Figure 7. (a) Branched polyethylene structure. (b) Branching of PE, the upper representing long branched LDPE and the lower representing short chain branched

HDPE. The long branches prevent the polymer from being packed closely and consequently leads to a lower density. Source: Robertson 2013, pp. 14, 21.

LDPE is the most frequently used polymer used in food packaging. It is inexpensive and it is a tough material with good tensile, tear and burst strength even at temperatures down to -60°C. It is a great barrier to water and water vapor as well as it has a chemical resistance to acids, alkalis and inorganic solutions. However, it is a poor barrier to gases, aromas and fats on its own (Robertson 2013, p. 21). In a laminate, the LDPE is often used as an inner layer due to its ability to fuse to itself and offer a tough enclosure when heat sealed (Robertson 2013, p. 21; Piergiovanni and Limbo 2016, p. 38).

Barrier properties increase with increasing densities of PE, but the toughness of the material and its resistance towards lower temperature will decrease. The LDPE is therefore not a good barrier by itself, but is a good mechanical barrier with resistance to stress (Buchner et al. 2003, pp. 701-702).

2.3.2 **Poly(Ethylene Terephthalate) - PET**

Poly(Ethylene Terephthalate), PET, is a type of polyester, meaning that it is based on carbon-oxygen-carbon links. To form a polyester, the molecules are joined by condensation polymerization. PET is a linear thermoplastic with repeating units, each with a MW of 176, leading the final MW up to 27 000. PET in its amorphous form, APET, provides a tough, transparent structure often used in bottles for carbonated drinks and films. It has small amounts of crystallites. PET in its crystalline form, CPET, is opaque and can withstand higher temperatures. Both APET and CPET are biaxially oriented when used in packaging. Orientation restructures the molecules and increases the crystallinity. Oriented films are generally tougher, and in the case of PET, the unoriented form causes the material to be either brittle or not resilient.

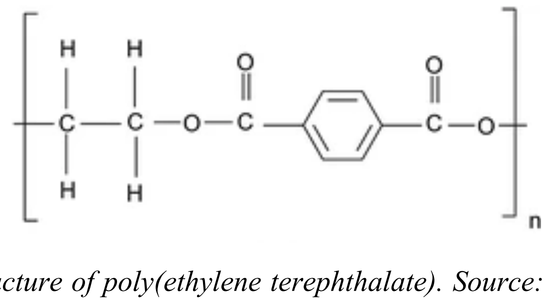

Figure 8. The structure of poly(ethylene terephthalate). Source: Piergiovanni and Limbo (2016, p.39).

PET is an excellent packaging material, as it is stiff and has great tensile strength. It offers good mechanical strength to the laminate. It is a good barrier against both gases, water vapor, fats, and aromas. It can withstand a large range of temperatures, from -60°C up to 220°C, and has good elasticity. It has a density between 1380-1410 kg/m3 and high transparency (Robertson 2013, pp. 35-37; Singh 2017, p. 5; Távora de Mello Soares 2022, section 1.1).

2.3.3 **Oriented Polypropylene – OPP**

Like polyethylene, polypropylene is an inexpensive polymer widely used within food packaging. To produce polypropylene, a stereospecific catalyst is used to create a structured, linear polymer. The density of PP is 900-915 kg/m^3 and it has a temperature range between -40°C to 120°C (Singh 2017, p. 5). Polypropylene offers a good barrier towards water vapor, fats, and chemicals. However, the gas barrier is intermediate (Robertson 2013, pp. 24-27). Compared to PET, the oxygen permeability is roughly 20 times bigger for polypropylene (Robertson, 2013; Lange and Wyser 2003, p. 150). When used in food packaging with higher standards on the barrier properties, it can be coated or coextruded with a barrier polymer (Robertson 2013, p. 26).

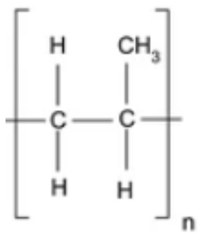

Figure 9. The structure of polypropylene. Source: Piergiovanni and Limbo (2016, p.39).

Non-oriented PP, also called cast PP, has only a few applications in food packaging due to its brittleness – something that becomes more apparent in lower temperatures. On the other hand, oriented PP (OPP) increases the moisture barrier as well as strength, both in general and in lower temperatures. The tensile strength of oriented PP is about four times higher than that for non-oriented PP. Biaxially oriented PP (BOPP) is often used as a component in laminates as it is inexpensive and provides the final film with stiffness and strength. However, there is a risk of shrinkage if heat sealing is needed, but this can be counteracted by coating the OPP with a lower melting point polymer, e.g. LDPE (Robertson 2013, p. 26).

2.3.4 **Ethylene-Vinyl Alcohol - EVOH**

Ethylene-vinyl alcohol is a copolymer that is produced from ethylene-vinyl acetate. Ethylene-vinyl acetate is a random copolymer, and by hydrolyzing the VA-group with NaOH to become a VOH-group, EVOH is produced. EVOH is a material that is a great barrier towards gas and aromas but has a poor barrier towards water vapor. When in contact with water it gets plasticized and the barrier against gas decreases. Therefore, it needs to be kept dry which is done by using it as an inner layer between materials that are better water vapor barriers (Robertson 2013, pp. 28-29).

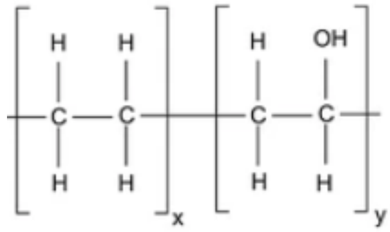

Figure 10. The structure of ethylene-vinyl alcohol. Source: Piergiovanni and Limbo (2016, p. 39).

The ethylene content in EVOH generally varies between 25% and 50%. Increasing ethylene content causes the water barrier properties to become better. However, it decreases the gas barrier properties. When used in a multilayer, EVOH is often coextruded between two materials that have higher water vapor barrier, and it can therefore be of interest to keep the ethylene content low if the intent of adding EVOH is to utilize it as a gas barrier (Buchner et al. 2003, p. 707). When used in packaging materials, the recommendation from FTI is to use a maximum of 5 weight% of EVOH in a laminate (FTI 2023b, p. 37).

2.3.5 **Silicone oxide – SiO_x**

Silicone oxide is used as a barrier in polymer applications. It developed in the 1980's and can be described as a thin glass-like layer that is often coated on a polymer (Lange and Wyser 2003, pp. 152-154). Compared to EVOH, where 5% weight% can correspond to roughly 3-5 µm, SiO_x is often present as a very thin layer, about 40 nm. Coated on PET, the oxygen transmission rate, OTR, is around 0.3-0.5 $cm^3/(m^2 \cdot day)$, which is relatively high for a barrier material. This can be explained by macroscopic defects due to the glass-like structure of silicone oxide which creates "pores" for the oxygen and water to be transported through (Roberts et al. 2002).

Silicone oxide can be coated on PET, OPP or LDPE amongst other, but the barrier properties of SiO_x is better when coated on PET than on OPP (Mount and Wagner 2001, p. 233).

2.3.6 **Permeability and transmission rate**

Gas and water vapor will diffuse through a polymer at varying rates, which is referred to as permeability. Since different types of food products are sensible to different substances, it is important to consider what the product in question can withstand and match the packaging material according to it.

Permeability can occur in two different ways; either by molecules being transported through the material through microscopical pores, or by "true permeability". With true permeability, the molecules dissolve into the material and diffuse through it to evaporate on the other surface (Robertson 2013, p. 98). Different materials have varying permeabilities to different substances, which is a set characteristic of that material (Singh 2017, p. 128).

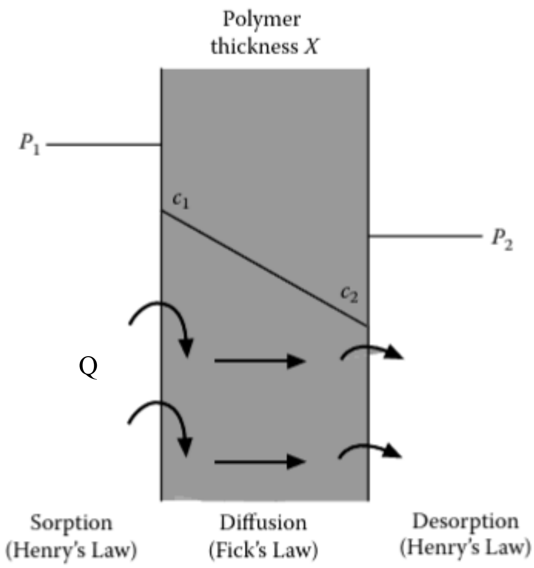

Figure 11. Permeability through a polymer where molecules are present at different pressures (P_1, P_2) on each side of the material. The molecules are dissolved into the material, diffuse though it towards a lower concentration and evaporate on the other side. Source: Robertson 2013, p. 100.

The transmission rate, TR, can be described as the amount of permeant, *Q*, passing through a polymer divided by area, *A*, and time, *t*. The transmission rate is also dependent on the pressure difference of the permeant on the inner and outer side of the laminate, as well as the thickness of the laminate. In general, increasing the thickness by doubling it results in the transmission rate decreasing in half. The gas transmission rate is referred to as GTR, but more often the oxygen transmission rate, OTR, is used when referring to polymers. Water vapor transmission rate, WVTR, is used when referring to the water vapor diffusing through the material.

The polymers used for a food product are chosen depending on their barrier properties and the demands of the product to obtain a good quality. The aim of coffee packaging is to have a good barrier against oxygen and water vapor, therefore striving for low transmission rate through the laminate. As polymers have different characteristics, a laminate with several layers is often used to reach the intended quality. Multilayers, or parts of it, are often manufactured through coextrusion, meaning that two materials are fed into an extruder that fuses the materials together. Sometimes parts of the film are created this way, and then laminated to another layer. Each layer has varying permeabilities, but the overall permeability of the laminate is constant if steady state is assumed. Some polymers are chosen for their physical properties and strength, while others are chosen for their barrier properties, called barrier polymers. The coffee packages in this project have used SiO_x and EVOH as barrier polymers, meaning that they are only present as a thin layer, usually in the middle of the laminate surrounded by thicker polymers. These types of superior barrier polymers have made it possible to obtain barrier properties comparable to those of metal and glass. EVOH is a highly polar polymer due to its hydroxyl-group, which is a common characteristic for good gas barrier polymers. Non-polar hydrocarbons such as PE and PP are good water barriers (Robertson 2013, p. 111). PE, PP and PET are also used for their physical strength and ability to provide the laminate and final product with structure and puncture resistance (Roberson 2013, pp. 28-29; Buchner et al. 2003, p. 707).

2.3.6.1 Oxygen transmission

The rate of oxygen transmission through a laminate can theoretically be calculated depending on the individual permeability rates of the included materials. It can also be experimentally tested with oxygen permeability analyzers. The oxygen can be analyzed through pressure or gas increasing methods, iso-static steady state methods or dynamic accumulation methods.

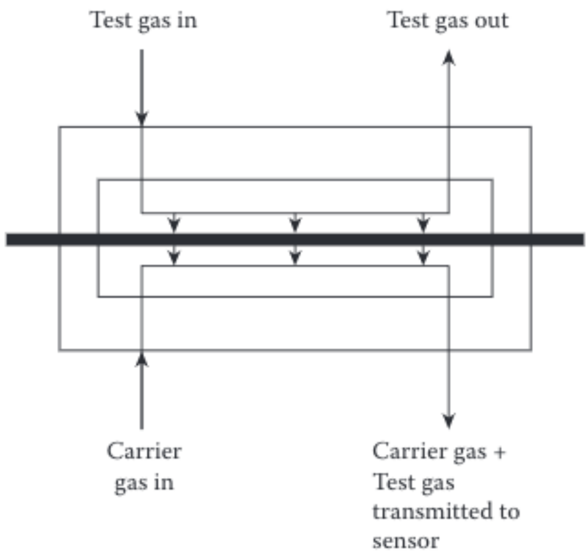

Figure 12. Overview of how OTR is calculated. The film is placed between the chambers. The version with a carrier gas is associated to the iso-static steady state method. Source: Singh 2017, pp. 129.

The basis of the methods mentioned above is to place the film between two chambers to separate them. In pressure or gas increasing methods, one chamber contains oxygen at a high pressure that is thereafter transferred to the other chamber through the material. The change in volume or pressure is measured. In the dynamic accumulation method, one of the chambers is flushed with carrier gas to ensure that there is no oxygen and thereafter sealed. Oxygen is then flushed through the other chamber and will pass through the film to the empty chamber until the oxygen has accumulated and the concentration is equal on both sides.

In the iso-steady state method (fig. 12), one of the chambers has a flow of test gas, in this case oxygen, and a carrier gas on the other side. The oxygen that passes through is picked up by the carrier gas and thereafter transported to a sensor. Since the oxygen molecules contains four electrons each, a small current is generated. The current is measured and transferred to a computer that converts it to amount of oxygen that has passed though the film. The OTR is obtained once the system has reached steady state (Singh 2017, pp. 128-134).

The OTR is dependent on the temperature since the molecules will move faster at a higher temperature. It is therefore important to test different films in the same conditions to be able to compare them (Gunnarsson 2023).

2.3.6.2 Water vapor transmission

The WVTR is dependent on the pressure of water on both sides of the laminate. A higher relative humidity, RH, in the surrounding air will result in a larger pressure of water vapor towards the package. Likewise, a higher RH inside the package will result in a pressure of water vapor towards the outside. When calculating the WVTR, assumptions of the RH and temperature must be made. In temperate climates such as large parts of Sweden, 23°C and 50% is representative of normal indoor conditions. However, 25°C and 75% RH can be used as when measuring to obtain a top value of the transmission rate that can be expected. In tropical conditions, 38°C and 90% RH is often used (Robertson 2013, p. 117). In contrast to the oxygen levels, which are always constant, the moisture level varies between different locations, homes, seasons of the year and time of the day (Pearce and Smith 2000). Testing the WVTR can therefore give an indication of expected water vapor transmission through a film, but will ultimately depend on the conditions of which the product is stored.

Water vapor is measured in a similar manner as OTR, with the film being analyzed while, and after, exposing it to water vapor. The water content in the product can also be analyzed by weighing the product before and after placing it in an oven at a set temperature and time (ISO 1994).

2.3.7 **Material overview**

The characteristics of the materials in section *2.3.1*-*2.3.5* are compiled in table 2. For SiO_x, the OTR and WVTR when coated on PET are presented. The material's effect on the laminate is presented in the right column.

Table 2 . The characteristics of the different polymers and what feature they contribute with to a laminate. Sources: Permeabilities PE-EVOH: Lange and Wyser 2003, pp. 150. Densities and features: Singh 2017, p. 5. SiO_x: Bobst 2019.

Material	*Oxygen permeability*	*Water permeability*	*Density*	*Feature in laminate*
	23°C, 50% RH [cm^3·mm/ (m^2·day·atm)]	*23°C, 85% RH [g·mm/(m^2·day)]*	*[kg/m^3]*	
PE	50-200	0.5-2	910-925[c]	Water barrier, good sealing properties
PET	1-5	0.5-2	1380-1410	Water barrier, stiffness
PP	50-100	0.2-0.4	900-915	Water barrier, stiffness
EVOH	0.001-0.01 (dry)	1-3	1140-1210	Gas barrier
SiO_x	0.3-0.5[a]	2[b]	-	Gas barrier

a. OTR when coated on PET. b. WVTR when coated on PET. c. Density of LDPE.

2.4 Environmental aspects

The largest use of plastic in the EU is related to packaging. Plastic can be produced by fossil fuels or by renewable sources, often referred to as biobased plastic. Over 99% of the global production of plastic is fossil based, which contribute to significant climate effects (Fråne 2022, p. 24). The production and incineration of plastic is cause for 5-10% of Sweden's greenhouse gas emissions (Almasi 2021, p. 3). Another issue is that in many cases, production of plastic from fossil fuels is cheaper than using recycled plastic (Fråne 2022, p. 24). This creates a linear system where the product produced is considered to be waste and is discarded after the intended use. EU is striving towards circular economy, which focuses on circulating products by recycling and reusing them (EU 2023; Ellen MacArthur Foundation 2023).

2.4.1 **Packaging waste**

Waste is defined by the European Union as "any substance or object which the holder disposes of or is required to dispose" (Eurostat 2019). The handling of waste is regulated according to EU law and follows the Waste Framework Directive on how waste should be handled without risking people or the environment (Swedish Environmental Protection Agency, 2023a). The Waste Framework Directive is based on the *Waste hierarchy* (fig. 13) that originated in a report in 1989 – a way to rank the different methods of handling waste. Although the waste hierarchy is not scientifically based in the sense that none of the categories have been measured and compared to one another, it can be used as a base to evaluate the production process of material that will eventually become waste. In the waste hierarchy, the most favored option is to prevent waste; followed by being reused and thereafter recycled. If none of these can be applied, the material should be handled by incineration where energy can be recovered. Lastly, the least favored option is for the waste to end up on a landfill (European Commission 2023; Robertson 2013, pp. 645-648).

Figure 13. The Waste hierarchy. Source: European Commission 2023

Prevention does not only imply to exclude the material entirely, but also to reduce the amount used. Lighter packages cost less to transport since less energy is used and the overall use of material is also reduced. However, reducing the material must be done with the product quality in mind to not compromise the safety and function of the packaging.

According to evaluations from 2016-2017, the plastic waste in Sweden is estimated to 1 705 000 tons yearly. The largest category of plastic on the market is packages, with approximately 350 000-500 000 tons distributed in Sweden every year. Consumers are obliged by law to sort their waste in Sweden, there amongst packages such as food packages (FTI 2023b, p. 19). However, majority of the residual waste consists of packages, soft packages reaching half of the waste and hard plastic a third of it (Swedish Environmental Protection Agency, 2021).

77% of the plastic waste is handled by incineration for energy recovery and fuel. (Swedish Environmental Protection Agency 2021a, p. 47). According to FTI, only 15.4% of the plastic collected by them was recycled in 2020 (FTI 2023a). The incineration of plastic contributes to fossil greenhouse gas emissions (Fråne et al. 2022, p. 24).

2.4.2 **Recyclability**

The general recommendation for coffee packaging is to recycle it. Zoégas packages informs the consumer to recycle the outer layer as paper package and the inner layer as soft plastic (Zoégas 2023).

As mentioned in *2.4.1. Packaging waste*, majority of the plastic waste in Sweden is incinerated for energy recovery while only a smaller fraction is recycled. In Sweden, FTI and TMR are the two companies responsible for collecting packages. All plastic waste collected by FTI is sent to Swedish Plastic Recycling in Motala, Sweden, where it is sorted. At the facility, the soft and hard plastic are separated through air streams. Thereafter the materials are identified by a light from a near infrared unit, a NIR unit. When the material is radiated with infrared light, some wavelengths will be absorbed by the material. Each material absorbs different wavelengths which makes it possible for the NIR to identify and separate them. Monomaterials will be melted and reshaped to pellets which can be used to produce new products (FTI 2023b, p. 25). The process of melting plastic and reshaping it is called mechanical recycling (Swedish Environmental Protection Agency 2021a, p. 65). The plastic waste collected by TMR is sent to their facility in Ängelholm, Omni Polymers, where it is sorted and recycled. At Omni Polymers, multimaterials are mechanically recycled and reshaped to pellets (Omni Polymers, 2023).

According to the Swedish Environmental Protection Agency, the hindrances for recycling can be divided into two categories. The first issue is that the design of some plastic packaging is complex. This refers to the labels on the packaging, colored plastic, and multilayer compositions. Plastic that is colored darker pigments can be more difficult to identify. Carbon black is a common pigment used in darker shades of plastic packaging that absorbs all light from the NIR-unit, causing the identification process to be disturbed. Pigmentation in general reduces the value in the recycling process and prevents the material to be recycled several times compared to an unpigmented or lighter plastic. Similarly, the labeling of a plastic material can pose an issue with the NIR unit if it is directly printed on the package and is either dark and/or covers majority of the surface. The preferable option is to use labels made of PE or PP that are easy to separate from the package and does not affect the sorting process. The adhesive should be water soluble and therefore possible to wash away. (FTI 2023b, pp. 28-35; Swedish Environmental Protection Agency 2021a, pp. 78-79; Fråne et al. 2022, p. 69).

Monomaterial films, with or without barrier layers, are recycled mechanically as mentioned above. At Swedish Plastic Recycling, monomaterial film based on PE can be recycled, and PP will be possible to recycle in the near future. Use of barrier materials that follow the guidelines of FTI will be recycled together with the rest of the material, since it has a negligible effect on the final material and can be seen as a contamination in the same way as pigmentation, prints and labels will be. However, it will reduce the quality of the final product. Laminates that are composed of less than 5 weight% EVOH or uses a barrier such as SiO_x or AlO_x are recyclable (FTI 2023b, pp. 23, 36-37). At Swedish Plastic Recycling, the laminates that are possible to recycle only include one type of polymer (i.e. PE or PP) along with a barrier material. Multimaterial films composed of both PE and PP such as the laminate in this thesis cannot be separated and therefore not sorted for material recycling at Swedish Plastic Recycling (Ahlström 2023).

However, the Swedish Environmental Protection Agency also points out that the lack of plastic recycling is both due to the complexity of the design, as well as the format of the current recycling processes. Today, Swedish Plastic Recycling categorizes and recycles PP, PE and transparent PET (Fråne et al. 2022, p. 69; FTI 2023b, p. 23). Laminates are as mentioned only recycled if they consist of a PE monomaterial. The packages that are not possible to identify are considered as rejects and are in most cases incinerated for energy recovery. Omni polymers is a recycling site in Ängelholm, Sweden, that focuses on mechanically recycling multimaterials and create a product of PE and PP which means that films based on these materials, such as the future laminate in this thesis, can be recycled instead of incinerated. Omni started in 2022 and aims to produce 12 000 tons of this type of granulate each year (Fråne et al. 2022, p. 73; Omni Polymers, 2023).

There are two other recycling techniques that are less common than mechanical recycling: physical and chemical recycling. Physical recycling separates different polymers with the aid of solvents. The new material can be damaged or provide a lower quality than intended. Chemical recycling includes a variety of techniques which all result in a breakdown of the polymers to monomers. Chemical recycling requires considerably higher amounts of energy than mechanical engineering. On the other hand, it causes less emissions than incineration. Since the final result of chemical recycling is monomers, it has the possibility of replacing the original feedstock which is fossil-based (Távora de Mello Soares et al. 2022, section 1.1; Swedish Environmental Protection Agency 2021b).

Mechanically recycled plastic is not allowed to be used in food products or cosmetics due to legislative reasons as there is no traceability of the material. The recycled material can be used for several other applications, such as car components, laundry detergent bottles or furniture. On the other hand, recycled plastic is not a product that is highly requested since prices of newly produced plastic can be lower than that of recycled plastic. It can be difficult to ensure the appropriate mechanical properties for recycled plastic since it can consist of other plastic types or contain color, while the producer is able to regulate newly produced plastic more efficiently (Fråne et al. 2022. pp. 166-168).

2.4.3 **Food waste**

Food production accounts for a third of the human climate impact (Wikström and Williams 2023, p.1). At the same time, the amount of food waste in the EU reaches 59 million tons yearly. The Food and Agriculture Organization of the United Nations (FAO) estimates that a third of the food produced in the world is wasted. Out of the food produced, 14% is lost during harvest, production, processing, and distribution while 17% is wasted at retail and consumer level (FAO 2023).

According to EU, the causes for food waste are several, there amongst misunderstandings about the meaning of “best before” and “use by” – where best before means that it is usually safe to consume after the set date as well. Food packages, many of which are made of plastic, were developed to keep the product safe and prolong its shelf life. Packaging contributes to reduced food waste, and it is of importance not to compromise the product by opting for cheaper and worse-performing materials (Wikström and Williams 2023).

The major waste from coffee comes from used coffee grounds, or already brewed coffee. Coffee ground is categorized as inevitable food waste, while brewed coffee or R&G coffee that is thrown away is categorized as evitable food waste since it could have been drunk (Swedish Environmental Protection Agency 2023b). Both coffee grounds that have been used or not can be collected as compost and can be converted to biogas or bio-fertilizer (Sysav 2023).

2.4.4 **Different coffee packaging methods on the market**

Zoégas packaging consists of two easily separable units. The laminate can remain clear, as all information is printed on the paper instead. The paper also offers the product needed shield from light. The paper can be recycled by itself, and the plastic film is collected as plastic waste. (Zoégas 2023). Since it is constructed of both PE and PP, it cannot be sorted for recycling at Swedish Plastic Recycling, but there are optional techniques for handling of the laminate. Omni Polymers are owned by TMR and the PE/PP plastic laminates that are collected by them are recycled (Fråne et al. 2022, p. 73; Omni Polymers, 2023). Unlike Zoégas, there are several brands on the market that use a dark colored plastic laminate to protect the product from light as well as a base for printing information.

Materials used for coffee packaging include glass and aluminum, but it has become more common to use plastic laminates. Aluminum was used in some laminates since it has good barrier properties, which has now been exchanged for a metallized layer (Robertson 2013, p. 587; Farah 2019, p. 265). Aluminum oxide, AlO_x, is accepted as a barrier according to FTI's packaging manual, as long as it does not disturb the identification process of the material (FTI 2023b, p. 37).

In February 2023, Löfbergs announced their new coffee packaging, a monomaterial made of PE. (Wallteg 2023). Packages with PE or PP are allowed to contain up to 5 weight% of EVOH to still be able to claim to be monomaterials (FTI, 2023c). The idea behind using a monomaterial is the possibility to recycle it according to FTI's and Swedish Plastic Recycling's standards.

Arvid Nordquist is a Swedish coffee brand whose coffee packaging is produced with Finnish pine oil, which is a rest product from the forest industry. This reduces the carbon dioxide emissions compared to fossil oil produced plastic (Arvid Nordquist, 2023). There is no difference in the breakdown of biobased and oil-based plastic, but the climate impact of the production phase is lower (Almasi 2021, pp. 12, 23).

For roast and ground coffee, the plastic laminates are dominating. A newer way to consume coffee that has grown more popular in recent years is capsules. The capsules contain one cup worth of coffee and is specifically customized for a certain machine, or machine brand. The capsules can be made of aluminum or a mix of plastic and aluminum components. Each brand has different methods for recycling, where aluminum capsules can be recycled with metal recycling, which is a material that is infinitely recyclable with no material loss. Mixed component capsules are recommended by the companies to be sent to an external recycling company that separates the components and recycles them (Nespresso 2023b, Petersson 2019, FTI 2023d).

3 Materials and methods

3.1 Experimental overview

The setup of the project was to compare experimental values of different packaging material properties with theoretically calculated values and examine how similar they were. The aim of the setup was to examine the difference between the current and the future packaging materials and how the theoretical values could be applied in the production and development of coffee packaging material in the future.

The two main focuses when comparing theoretical values to experimental were the examination of oxygen transmission rate, OTR, and water vapor transmission rate, WVTR. The OTR measurements were done in collaboration with Tetra Pak through permeability testing of the laminate. The WVTR was analyzed through measuring the moisture content of the coffee. Color analyses were also conducted. The color of the coffee does not reflect on the shelf life but is important to determine the quality of the product and was therefore compared between the current and future packaging.

3.2 Materials

The tests conducted for this project were continuously conducted by comparing the current and future packaging. The current laminate consists of PET/SiO_x/PE and the future laminate consists of OPP/EVOH/PE. The coffee packages used for OTR measurements were produced and packaged in January 2023 and have a best before date of January 2024. The measurements related to WVTR and color were compared not only between current and future laminate, but also between different storing times to observe changes over time.

In the OTR measurements, the laminate itself was tested by removing it from the coffee. In the moisture and color calculations, the coffee from newly opened packages was used. The theoretical calculations were be done by using Norner Barrier Calculator (Norner Barrier Calculator 2023).

3.3 Analyzes

The analyses performed are summarized in table 3. OTR measurements and Norner calculations are performed by testing the laminate, meanwhile the moisture and color are performed directly on the coffee.

Table 3. The analyses conducted along with which component (laminate or coffee) it is performed on. The right column contains the comparisons that are aimed to make with the obtained information.

Analysis	*Component*	*Comparison*
OTR	Laminate	Current vs. future laminate Experimental vs. theoretical
Moisture content	Coffee	Current vs. future laminate Experimental vs. theoretical
Color	Coffee	Current vs. future laminate
Norner barrier calculator	Laminate	Theoretical vs. experimental results Shelf life period of current and future packaging

3.3.1 **Oxygen measurements**

The oxygen transmission rate, OTR, of the laminate was measured at Tetra Pak with an oxygen permeability analyzer from Ametek Mocon and used the iso-static steady state method. The principle behind the measurements is to attach a piece of the laminate in the middle of two chambers. Each chamber has a flow of a gas, one side with test gas and one side with carrier gas. The test gas in this case is oxygen gas and the carrier gas is nitrogen gas with 1% of hydrogen gas. There is an abundance of hydrogen gas compared to the amount of oxygen gas that is expected to pass through the laminate. There is a catalysator that enables a chemical reaction between oxygen and hydrogen. As each oxygen gas molecule contains four atoms that are released, this will create a small current. The current is transferred through a sensor that measures it and thereafter a computer converts it to the amount of oxygen that has passed through the laminate.

The laminate was measured by itself, meaning that it was cut off from the coffee package. The area of measurement was 50 cm^2 and the material was cut out with a template to fit into the machine and have excess material to be able to attach it. High vacuum grease was applied to the machine to ensure that there was no gap between the laminate and the chamber. After attaching the test material to the machine, the gas flow was adjusted on the machine and the measuring settings through a computer connected to it. The machine contains two cells, meaning that two laminates were tested at the same time.

The flow of the gases was set to 10 ml/minute. For the first period of time, nitrogen gas flowed on both sides to ensure that there was no residue oxygen from the outside environment affecting the test results. When both sides had been flushed, an “individual zero” was obtained. The value obtained comes from the instrument and was deducted from the measurements. Thereafter, the machine switched to an oxygen flow on one of the sides. It took roughly 2 days for it to reach the individual zero, which was then followed by 7-10 days of the measurements that resulted in an OTR-value once the system had reached steady state. The computer alternated between measuring the two cells with an interval of 40 minutes per side (Gunnarsson 2023).

The tests were made on two replicates from the current laminates, and two from the future laminate, leading to a total of four tests. The replicates were made to ensure that the values were reliable. If one value would be significantly higher it can be disregarded, as it is likely a result of an unsuccessful measurement (Halldén Björklund 2023). The tests were conducted on the packages produced in January 2023.

3.3.2 **Moisture measurements**

The moisture measurements were based on ISO 11294 (1994) to determine moisture content through the loss of mass at 103°C. One aspect was to observe the difference between the current and future laminate. Double samples from four batches with the current laminate as well as four double samples from the future laminate were taken and analyzed. Double samples were taken from each package that was tested to ensure the reliability of the result. The test batches had a production date of March 2022, July 2022, November 2022, and January 2023. During these production occasions, the current and future laminate were tested right after each other to contain the same batch of coffee. A total of 8 tests were conducted for this comparison.

To observe the change of moisture during the shelf life, several batches of coffee using the current laminate where tested. Double sample tests were conducted on coffee produced with roughly one-month intervals between 03.2022 and 03.2023.

Prior to setting up the samples, the oven was turned on to heat up to 103°C. This took roughly an hour. Each sample was then prepared by opening a new package of coffee, stirring it, and thereafter adding approximately 5 grams of coffee into a metal container that has been weighed beforehand. The sample was weighed and thereafter covered with a lid and placed in the oven. The oven held four samples at once, meaning that two double tests could be performed at once. The samples were taken out from the oven after two hours and are left to cool down for one hour. Thereafter each sample was weighed again and compared to its starting weight.

The moisture loss is expressed as a percentage which was calculated according to equation 1.

$$\frac{(m_1 - m_2) \cdot 100}{(m_1 - m_0)} \quad (1)$$

m_0 is the mass of the dish and lid, m_1 is the mass of the dish containing the sample before drying and m_2 is the mass of the dish containing the sample after drying.

3.3.3 **Color measurements**

The color analysis was mainly conducted to compare the coffee in the current and in the future laminate. The color analyzer used was Neuhaus Neotec Colortest II. Roughly 40 grams of coffee was poured to fill a metal container. It was thereafter passed through a blade that evened the product out in the container and removed the excess. The container was thereafter placed on the surface in the analyzer which provided a value after 2 seconds. The Colortest II illuminates the sample and determines the reflection which is shown as a three-digit number, referred to as CTN. Depending on the type of coffee and its roasting, the values can differ. Each company will set their own standard limits of values for the different products. In this experiment, the values were compared between the different samples and packaging types to observe if there were any values sticking out and if there was any different between the current and future packaging.

3.3.4 **Theoretical calculations**

The theoretical calculations were done with Norner Barrier Calculator, which can be seen in figure 14. The input factors are geometry of the package or film and its size, the materials, and their thickness as well as the surrounding environment, including number of days tested. In this case, the environment will be calculated for 365 days in 23°C, 50% relative humidity and an oxygen level of 21%. The output is permeability, transmission rate and total oxygen transmission for the time period entered. A graph was also presented with the total oxygen transmission or water vapor transmission for each day during the set time.

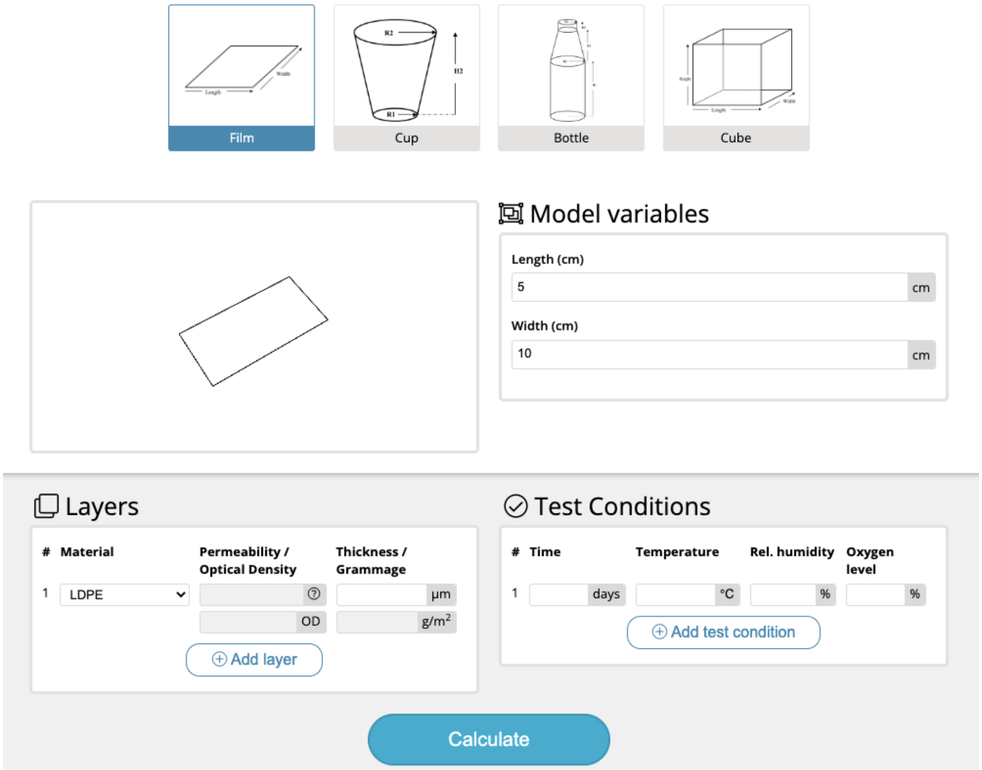

Figure 14. The Norner Barrier Calculator for oxygen transmission rate. The geometry for the material is chosen, and thereafter the material of the layers which can be chosen from a list. The thickness of each component is inserted as well as the test conditions. For WVTR calculations the relative humidity and oxygen level will be exchanged for relative humidity inside package and relative humidity outside package. Source: Norner Barrier Calculator (2023).

3.3.5 **Statistical evaluation**

3.3.5.1 ANOVA

A one-way analysis of variance, ANOVA, was conducted to examine the difference between the current and the future laminate. The null hypothesis, H_0, suggests that there is no significant difference at a 95% confidence level. If the obtained value of F > Fcrit, the null hypothesis is disregarded, and a difference can be established at a significance level of 95%. ANOVA can be conducted as two-way if there are more variants that are affecting the result.

3.3.5.2 Mann-Kendall

A Mann-Kendall test was used to investigate if there was an increasing or decreasing trend for the moisture content during the storing time of one year.

4 Results

The results obtained will be presented below. Each category; oxygen transmission rate, moisture, and color, will first be statistically compared between the current material and the future material of the coffee package to examine if there are any changes between the two. For oxygen and moisture, the results will additionally be compared to the ones obtained from the theoretical calculation tool.

4.1 Oxygen transmission rate

The OTR measurements were performed on the current and future laminates to examine how they perform as oxygen barriers and if there is any significant difference between them. It has thereafter been compared to the theoretically calculated values obtained through Norner Barrier Calculator.

The OTR measurements are plotted in a graph against the time. Two measurements of each laminate have been conducted and are presented below in figure 15-18. The y-axis represents the oxygen transmission rate with the unit of cc/(m^2·day) which is equal to cm^3/(m^2·day). The x-axis represents the time passed in hours, and the measurements have been conducted every 40 minutes until the system reaches steady state. The OTR is the value obtained at steady state. The first section of the measurement is deducted from the final OTR value since it represents the contribution from the system.

The first test for the current laminate showed an oxygen transmission rate of 0.929478 cm^3/(m^2·day). The second test for the current laminate resulted in an oxygen transmission rate of 1.136062 cm^3/(m^2·day). The mean value for oxygen transmission rate of the current material is 1.03277 with a standard deviation of 0.1033.

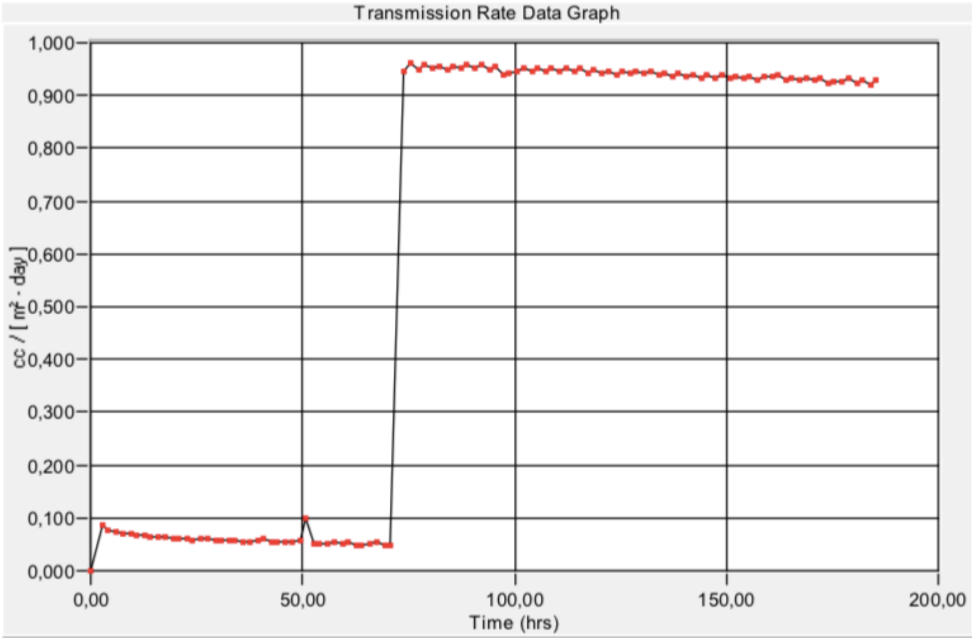

Figure 15. OTR measurement of the current coffee packaging laminate, replicate one out of two replicates. The oxygen transmission rate is plotted against time until the system reaches a steady state. The first section with lower values represents the contribution from the system.

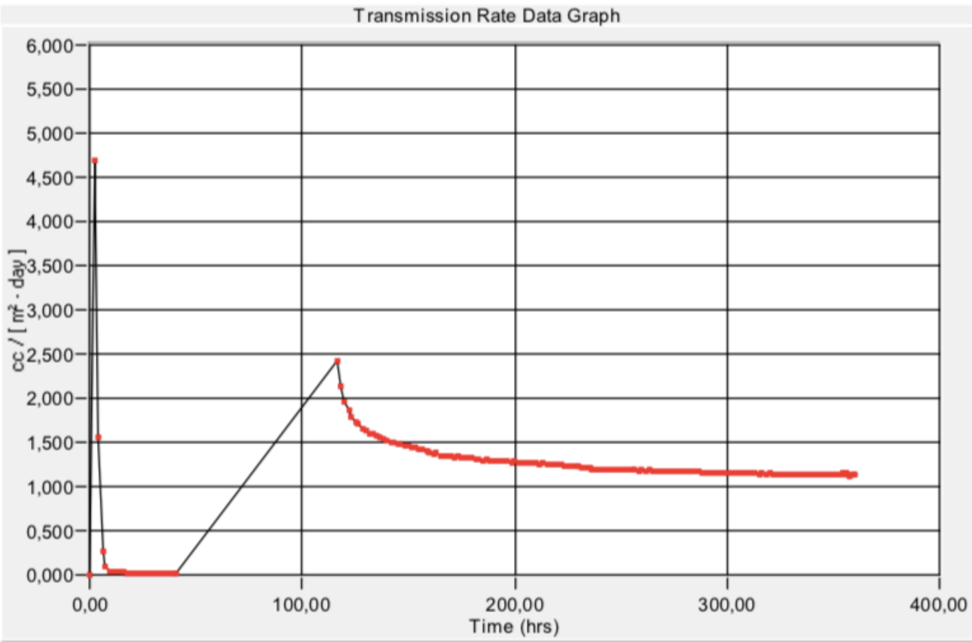

Figure 16. OTR measurement of the current coffee packaging laminate, replicate two out of two replicates. The oxygen transmission rate is plotted against time until

the system reaches a steady state, with the first section representing the contribution from the system.

The first test for the future laminate resulted in a transmission rate of 0.761879 $cm^3/(m^2 \cdot day)$. The second test for the future laminate resulted in a transmission rate of 0.773480 $cm^3/(m^2 \cdot day)$. The mean value for oxygen transmission rate of the future material is 0.7676795 with a standard deviation of 0.0058.

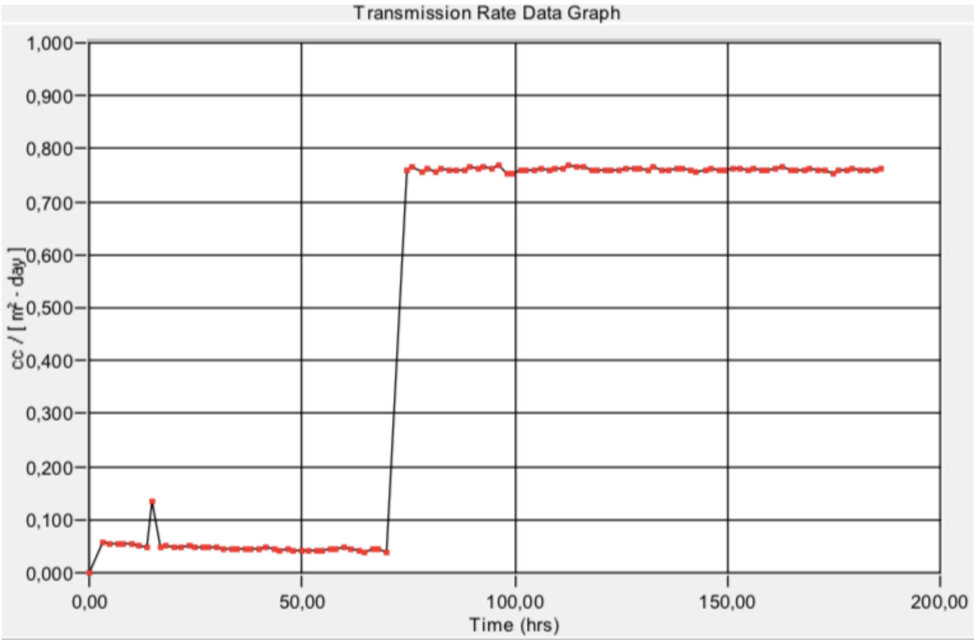

Figure 17. OTR measurement of the future coffee packaging laminate, replicate one out of two replicates. The oxygen transmission rate is plotted against time until the system reaches a steady state, with the first section representing the contribution of the system.

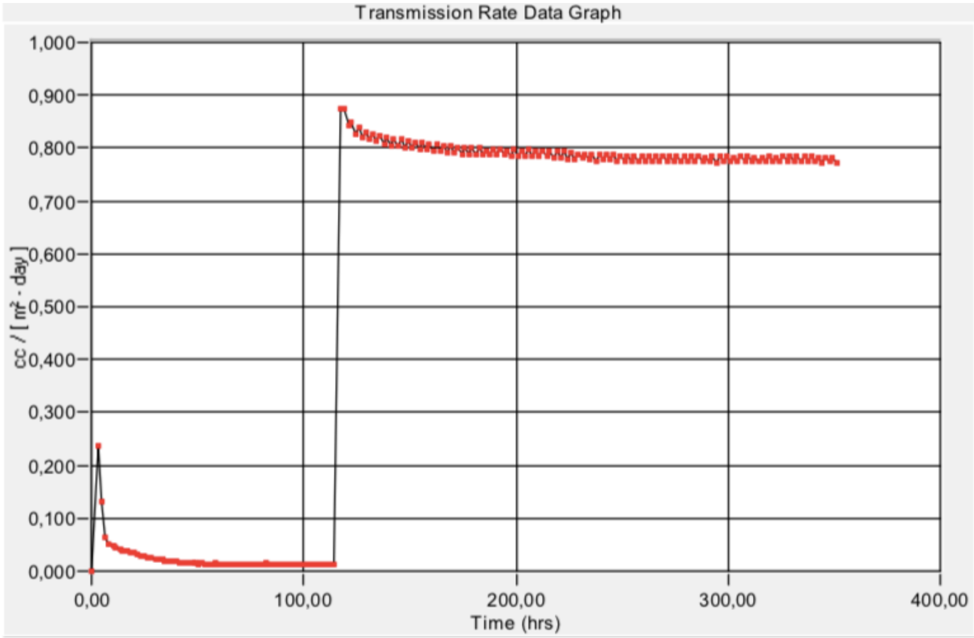

Figure 18. OTR measurement of the future coffee packaging laminate, replicate two out of two replicates. The oxygen transmission rate is plotted against time until the system reaches a steady state, with the first section representing the contribution of the system.

The results obtained from the OTR measurements have been compiled in table 4 along with their average value and standard deviation, as well as the theoretical values for the current and future laminate.

Table 4. Results from OTR measurements conducted at Tetra Pak as well as the average and standard deviation. All values are expressed in $cm^3/(m^2 \cdot day)$. The right column contains the theoretical values of the OTR. For the current laminate and thereby SiO_x, the value is based on Roberts et al. (2002). For the future laminate the theoretical value has been calculated with the Norner Barrier Calculator (2023).

Material	*Test 1*	*Test 2*	*Average OTR*	*Standard deviation*	*Theoretical value*
Current	0.929478	1.136062	1.03277	0.1033	0.3-0.5
Future	0.761879	0.773480	0.7676705	0.0058	0.776

The confidence interval for the current laminate is [0.8896 1.1759] and [0.7596 0.7757] for the future laminate with a significance level of 95%. As there is no overlap between the two, the difference between the current and future laminate can be concluded to be significant. However, a one-way ANOVA-test indicates that there is no significant difference on a 95% confidence level. At least three values are needed to obtain a statistically representative result. Although the results can be used as an indication, it can be considered to be inconclusive from a statistical point of view.

To determine the finer settings needed for the testing of a laminate, a rougher test is conducted. The results from these tests are called *benches*. Although they are normally not used, they can be included for the performed measurements to obtain a more statistically representative result. The results from the benches are 1.184273 $cm^3/(m^2 \cdot day)$ for the current laminate and 0.54404 $cm^3/(m^2 \cdot day)$ for the future laminate. If these are included, a one-way ANOVA-test with the benches and experimental results will indicate a significant difference between the two laminates at a 95% confidence level. The different results of the ANOVA-tests are most likely due to the low number of replicates. A statistical analysis consisting of a small sample size leads to low statistical power, which means that the chance of detecting a significant finding is reduced.

Test 1 of the current material has been tested parallel to test 1 of the future material, and test 2 of the current material has been tested against test 2 of the future material. In test 2 of current and future, the cell containing the current material reached an individual zero at 41 hours 45 minutes, while the cell containing the future material reached the individual zero at 114 hours 27 minutes. When one of the cells has reached an individual zero it does not take any more measurements until the test gas is introduced. There is therefore a visibly larger gap between two points of measurements in test 2 of the current laminate (fig 16), as both oxygen measurements during test 2 start at 115 hours 37 minutes.

Test 1 and test 2 have been conducted at different machines. Although the same method is used, the sensors can differ in sensibility. When the system switches to oxygen, there can be residue nitrogen that results in different shapes of the graphs. The machines are calibrated to calculate the final transmission rate correctly, which means that different shapes will not affect the result (Gunnarsson 2023).

Theoretical calculations of the future laminate were made using the Norner OTR calculator, with conditions set at 23°C and 50% relative humidity to simulate the same conditions as the experimental measurements. This resulted in a transmission rate of 0.776 $cm^3/(m^2 \cdot day)$ when the EVOH is set at 3,2 weight%. The values obtained from Norner barrier calculator fits within the experimental interval of the OTR measurements, leading to a highly comparable result between the experimental and theoretical values. An OTR of 0.776 $cm^3/(m^2 \cdot day)$ would lead to a total oxygen transmission of 16.938 ml/package over the year. Using the experimental OTR of current package the total oxygen transmission would be 22.547 ml/package during the same period. This is a decrease of 24.9% of oxygen entering a coffee package during its set shelf life. To obtain a total oxygen transmission of 22.547 ml/(package·year) like the current package, the future laminate thickness could be reduced with 46.8% according to Norner barrier calculator. This would lead to reducing the thickness of the OPP and PE almost in half, while the EVOH would be reduced with 24.8%.

4.2 Moisture measurements

Moisture measurements were conducted on the coffee to examine the difference of moisture content in current and future packaging material. These have been plotted and statistically compared to each other and are presented in figure 19.

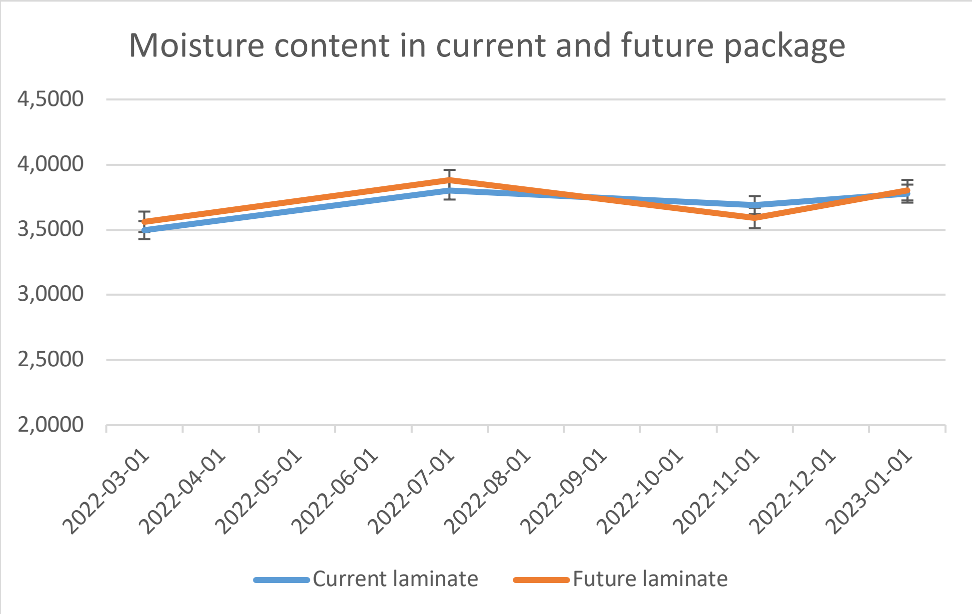

Figure 19. The moisture content in percentage of the coffee in the current and future laminate compared to each other.

A one-way ANOVA-test with 95% confidence interval indicates that there is no significant difference between the moisture levels of the coffee packaged in the current laminate and the future laminate. The coffee in the batches that have been compared to each other have been packed consecutively to contain the same coffee during the same conditions. However – if one batch of current laminate is packed, followed by one batch of future laminate, the second batch to be packed will be exposed to the surrounding conditions for a while longer. During this time, it can absorb moisture from the surrounding air, leading to a higher moisture value.

To obtain a more general view of the moisture in coffee packages, the moisture content of several batches with different storing times were tested. They were conducted on packages with the current laminate. Figure 20 demonstrates the moisture content of coffee after different times of storing compared to its moisture content at the time of roasting. Each value represents the difference between start and final moisture content.

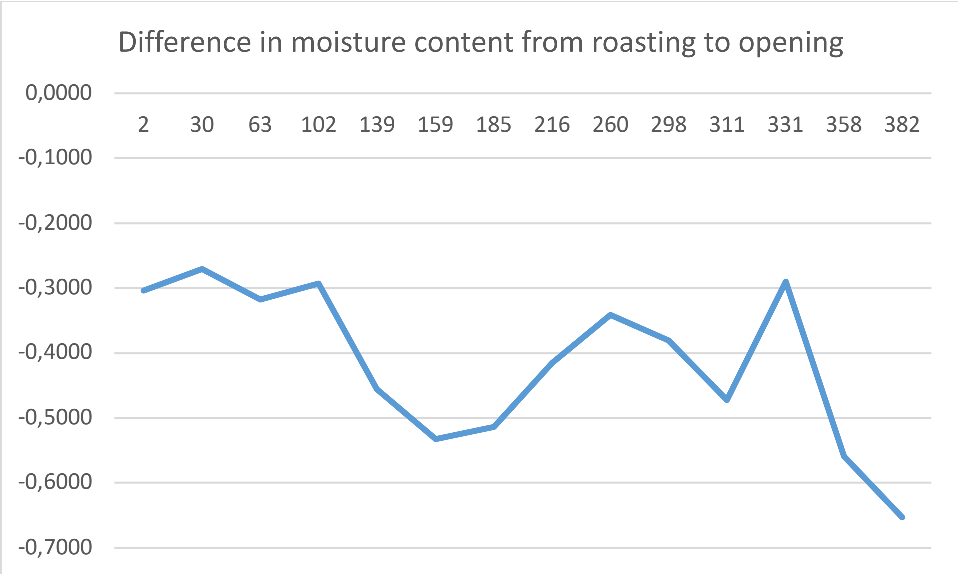

Figure 20. The difference in moisture content from the day it was roasted until it was tested. The y-axis represents the difference in value and the x-axis represents days since roasting. The trend is decreasing with a significance level of 95%.

According to a Mann-Kendall test there is a decreasing trend with a significance level of 95%. This indicates that the moisture content of coffee declines during its storing time and thus that the relative humidity is higher inside the coffee package than the relative humidity of the storage conditions, consequently leading to a loss of moisture.

The package that had been stored for a year had a moisture reduction of 0.65% which equals a loss of 2.939 g/(package·year). With this information, the Norner barrier calculator can be used in "reverse". As all input values are known except the RH inside a coffee package, and one of the outputs is known, the relative humidity on the inside can be identified. At an outer RH of 50%, this leads to an internal RH of 63%. Based on this knowledge, the calculator can be used to examine how the package would perform in different climates. In a desert climate like in the Sahara, with an average relative humidity of 38% over the year, the moisture content of the coffee after one year would be 2.9%. In a tropical climate such as in Costa Rica, with an average relative humidity of 92%, the moisture content would be 5.6% after a year (Pearce and Smith, 2000). These calculations neglect the temperatures in these climates, which have been set to 23°C, and the actual temperatures would most probably increase rate of moisture loss or rise.

4.3 Color analysis

A color analysis was conducted on the coffee to examine the difference in values between the current and future packaging material. These values obtained have been plotted and statistically compared to each other and are presented in figure 21.

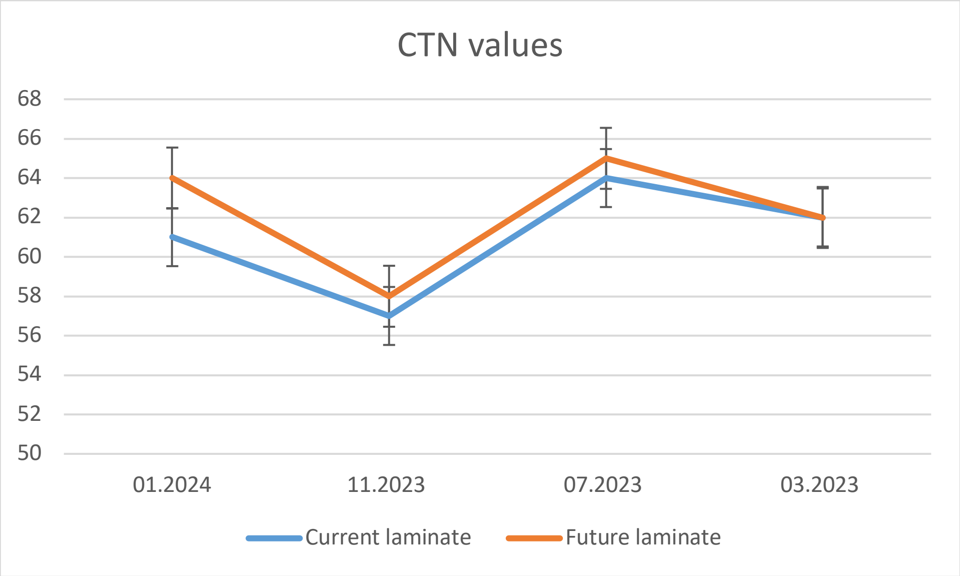

Figure 21. The CTN values measured for the current and future laminate

A one-way ANOVA-test with 95% confidence interval indicates that there is no significant difference between the CTN values of the current and future laminate. The values range from 57 to 65.

5 Discussion

The aim of the experiments that have been conducted for this report is mainly to compare the current and future packaging material regarding their barrier properties. In the following section each category of experiment, oxygen transmission, moisture, and color, will be further discussed from a quality point of view, with regard to the materials being used. The theoretical tool and the obtained values will be compared to examine the future use of such tools. To attain a broader perspective on the packaging material, the specific needs of coffee products will be reviewed concerning the product quality and environment. Lastly, the challenges encountered will be discussed, as well as possible further work.

5.1 Oxygen transmission

According to FTI, PET used in flexible films is not possible to recycle, which means that a transition to PP is favorable from an environmental perspective. Since there are companies that specifically handle the PE/PP combination, the material will go from 100% incineration to the possibility of being recycled. When considering the confidence intervals and the ANOVA-test with larger sample size of three values rather than two, the OTR measurements indicate that there is a significant difference between the current and future laminate. The future laminate has reduced its OTR with 25% compared to the current material. From a quality perspective, this is a positive transition since the product will be better protected from oxygen.

Although SiO_x is a preferable barrier material according to the FTI plastic packaging manual, SiO_x combined with OPP would most likely perform worse as an oxygen barrier (Mount and Wagner 2001, 223). Considering that oxygen is the most important factor in the shelf life of coffee (Cardelli and Labuza 2001, pp.276-277, this combination could lead to a deterioration of the product quality, which means that EVOH at a presence lower than 5% will be favorable to prevent spoilage of the product. EVOH at a low presence is still possible to recycle, but the recycled material will obtain a weakened material quality. However, worsened material quality can be set in contrast to the worsened quality of the product and the shortening of the shelf life if the packaging material does not correspond to the barrier needs of the product.

The current laminate could not be theoretically calculated with the Norner barrier calculator since the calculator does not contain the characteristics for SiO_x. The theoretical data is therefore based on literature which is found to be 0.3-0.5 $cm^3/(m^2 \cdot day)$. Although PET and PE are present as thicker layers than SiO_x, their OTR is significantly higher based on their high oxygen permeability. When several polymers are used in a laminate, the OTR for the laminate is based on the material with the lowest OTR, since this will be the main barrier for the oxygen. Compared with theoretically obtained values, the oxygen transmission rate for the current laminate is roughly twice as high as theoretical data. This could be a result of its glass-like structure that easily obtains structural dagames when being stretched. The higher difference in OTR measurements for the material containing SiO_x is therefore also be argued to be in line with the theory, as different parts of the surface can have been exposed to different treatment and therefore vary in the structural damage.

When using the Norner barrier calculator for the future laminate, it results in 0.776 $cm^3/(m^2 \cdot day)$ which is included in the confidence interval for the future laminate, which makes the Norner calculator highly comparable to the experimental results. Compared to SiO_x, EVOH is a sturdier material that is not affected by structural damages as easily, and the results obtained are therefore more similar to each other, both experimental replicates as well as theoretical calculations. To be certain of the accuracy of Norner barrier calculator to real polymers and laminates, more experimental tests in the lab would have to be done before drawing a conclusion. The calculator contains the characteristics of a limited amount of polymers, which only makes it relevant if it matches the ones the user wants to investigate. It will also be dependent on the sensibility of the material. SiO_x is an example of a material that can have impaired barrier depending on how it is handled. However, a great accuracy between the theoretical calculations with the actual values of a packaging material can also be used to test future variations of laminates and to do accelerated shelf-life tests.

When comparing the total oxygen transmission of the package during a year, the current transmission is 22.547 ml oxygen/(package·year) while the future has a total transmission of 16.938 ml/(package·year). If the main factor of product deterioration and shelf-life limitations is fully based on the oxygen levels and the critical value is 22.547 ml/package, this could mean that the shelf life of the new product would be 485 days instead of 365 which would extend the shelf life from 12 months to 16 months. However, there could be other factors that are relevant, such as aromas and taste after brewing, which means that the coffee would need to be tested by an expert panel before determining a new shelf-life period. The Norner barrier calculator can also be used to test what changes could be done to the laminate while obtaining certain barrier properties and results. When reducing the thickness of the future laminate with a total of 46.8% the same OTR is obtained. However, the WVTR would become twice as high. Several factors need to be considered when making changes to a laminate, but Norner can be used as a tool to test potential changes beforehand.

One important factor when using Norner in comparison to a packaging material is also to consider the whole packaging including sealings and how the material is being bent around the product. Both the experimental values as well as the theoretical calculations have been made on a section of the package material. There could therefore be additional oxygen transmission through the sealings and where it has been bent.

5.2 Moisture

The moisture measurements indicate that there is no significant difference of moisture content in the current and future material. The small differences can be a result of the time between the roasting and the packaging. When conducting comparative tests between current and future laminate, the same batch of coffee has been used. The difference in the moisture measured in the package with current and future laminate varies between 0.02% and 0.1% which can be a result of how long they have waited between the roasting and packaging, as well as the conditions during the day of packaging and the day of testing. In general, the moisture content during the roasting is higher than the moisture content after packing and storing. This is due to that the coffee will continue to degas and release moisture after the roasting, for example during the grinding, until it is packed and sealed. On a winter day with low relative humidity in the surrounding air, the coffee could release more moisture to the surrounding air compared to a humid summer day.

None of the materials present a moisture content higher than 3,9% during its shelf life, which is lower than the maximum moisture content of 5.5% determined through the calculations in section *1.3.2. Water activity*. This indicates that the packaging material chosen for the product is suitable to obtain the expected shelf life and quality standards throughout this. Although PP has a lower water vapor permeability, it is PE that provides the lowest WVTR since it is present as a thicker layer and can therefore be seen as the most important water vapor barrier.

When testing the moisture content of more batches of coffee, we can see a trend of a decreasing moisture content over the storing time. In this case, the Norner calculator is used to find the RH of the coffee package. When obtaining this, the coffee package can be tested against different climate conditions. It can be observed that a coffee package would dry out fast in the desert, taking about 6 months to reach the same moisture content as a year in Sweden. On the other hand, it can be observed that a coffee package of this kind would not perform well in tropical climate. The coffee would exceed 5.5% moisture content, which was determined to be the critical value in *1.3.2 Water activity*. However, the coffee package can be established to be appropriate for a Swedish climate.

The required water vapor transmission for a coffee package is 0.61-1.1 g/(m²·day) at 23°C and 85% RH according to Singh (2017, 58). With the parameters mentioned, the WVTR would be 0.229 g/(m²·day) which is lower than the critical values, which can be beneficial to obtain a similar product characteristic during the shelf life. As this is based on a higher relative humidity on the outside of the package, the result obtained is not comparable to that of Swedish climate and further investigations would need to be done to obtain the optimal WVTR for coffee in temperate climates. When using conditions that are in line with the Scandinavian climate, a lower water vapor transmission rate is obtained which is favorable to obtain a good quality of the product.

5.3 Color

According to the ANOVA-test there is no significant difference between the color of the coffee packaged in the current and the future laminate. The differences of CTN values ranging from 57 to 65 can be explained by the difference in coffee beans harvested. Although the goal is to obtain similar appearances and compositions, the coffee beans will always have a slight variation depending on the climate and location of its growth, harvest, drying and processing.

The component of the packaging material that shields the product from light is primarily the paper wrapped around the laminate. This has remained the same during the laminate change which is why the result of the color measurements is expected to not change. The separate paper that shields it from light and therefore color variations is also beneficial from a recycling perspective since it is easily separated from the laminate and can be recycled on its own.

5.4 Difference between current and future packaging

From a quality perspective the future material provides a better OTR barrier while the moisture content and color of the coffee appears to be unaffected by the change. This indicates that the future coffee packaging will be favorable for the product and that the change that will be made is positive. From a recycling perspective the possibilities for material recycling are also increasing with the new package since the PET is excluded in the new laminate.

5.5 R&G coffee needs in relation to recycling

When producing a package for R&G coffee, the main focus is to provide a good gas and moisture barrier. This is fulfilled by using a barrier polymer for the oxygen, such as SiO_x and EVOH in this report. The moisture barrier is provided by the PE, PP and PET layers. PE is present in a layer that is 4 and 7 times thicker than the PP and PET respectively which makes it the most important water vapor barrier. However, the PET/PP contributes with a stiffness that helps the packaging keep its shape even after it is opened, and the vacuum treatment does not hold up its shape anymore. The need for a stiff laminate can be argued to be a consumer-friendly characteristic rather than necessary for the product quality. As PE is a tough material itself, and HDPE could provide the material with certain stiffness, there is a possibility to obtain similar characteristics of the future material even if it only contains PE and EVOH. According to Norner barrier calculator, the OTR would be identical to that of PE/PP and the WVTR would be reduced. Furthermore, it would increase the recyclability even further and make it a more environmentally friendly package material.

Compared to other types of packaging materials, the clear laminate of PE and PP is an acceptable packaging in terms of recyclability. However, FTI and Swedish Plastic Recycling which are responsible for majority of the plastic recycling does not recycle the PE/PP combination. The only company in Sweden to do so is Omni Polymers, and although the recycling process is beneficial, the method would probably need to spread further in Sweden to make a larger impact. When comparing different barrier solutions, metallization with AlO_x is similar to SiO_x, where the recycled material quality is still good. On the other hand, Bauer (2021, section 3) explains that the metallized layer causes the laminate to become grayer when it is recycled, which is not wanted in the recycling process as it shortens the number of times a material can be recycled. The optimal packaging from a recycling aspect would be a monolayer of PE, which is still considered to be a clear monolayer even with a EVOH-layer of maximum 5%, followed by a separate layer for printing and light shielding. Before considering this type of material change it is important to consider how the material would affect the product quality and its shelf life as well.

When aiming for a higher recyclability of plastic packaging in particular, the PET-system could be seen as a good example of how beverage brands work together using the same method and material for their bottles. PET in the form of bottles is highly recyclable and can be used over and over (Pantamera, 2023) in a way that might not be possible at all when the needs for oxygen barrier is as high as it is for coffee, but the collaboration between different brands and recycle companies can be beneficial. A standard can be set according to the recycling possibilities to increase the environmental effect of coffee products in general. On the other hand, it can be discussed whether the brands should adjust their product and consequently its quality to become more recyclable, or if the recycling methods should develop to be able to meet the material needed to obtain a good quality product. To battle the material loss due to lack of recycling, a combination of recycling development and coffee packaging material standards could be aspired for in the future. Furthermore, each producer uses different machinery which is compatible with their current material, and recently installed machines might still have several years of duration before it should be exchanged to reduce waste and excess production.

5.6 Challenges in methods

When determining whether a packaging change is positive several factors must be considered. The material itself needs to be tested to ensure that the expected barrier properties are attained. The OTR measurement of the material is a reliable method but would need further replicates to ensure a higher reliability from a statistical perspective. The method used measures the plain surfaces, and to obtain a result that is accurate to the actual product, the sealings also need to be included.

There was no possibility to conduct WVTR measurements, which would have been the preferred method to investigate the water vapor effect on the packaging material. However, the moisture content was still able to indicate the efficiency of the material. As mentioned earlier, the moisture levels did not exceed 5.5% which suggest that the material is meeting the needs of the product. Due to time limitations, different batches of coffee were tested. To obtain a more representative result of the water vapor transmission and how the moisture values vary over a year, it would be preferred to follow one single batch during its shelf life.

The results from the Norner barrier calculator have shown to correspond to the OTR value obtained experimentally. Since it could only be used for direct comparison of the future material and only for the OTR measurements, no conclusion can be drawn from the comparison. To obtain a more meaningful result, the material types in the calculator would need to correspond to the ones examined in this report, as well as being able to be compared to a WVTR experimental measurement for better understanding and use of the calculator.

5.7 Further work

To fully understand the effect of the changes between the materials, further tests and additional replicates would need to be conducted. The WVTR of the material could be tested experimentally to compare the current and the future material.

It could also be interesting to compare the OTR and WVTR of several types of coffee packages to gain a further understanding of how different materials affect R&G coffee and be a foundation for further development of packaging materials for oxygen sensitive products. This type of comparison could be compared to the recycling opportunities to determine the optimal coffee package both from a product perspective, as well as an environmental perspective.

Using Norner barrier calculator, the results of total transmissions in current and future packages can be compared to each other. With the results of the Norner barrier calculator indicating that the shelf life could be prolonged if based on the oxygen transmission, further sensory tests would need to be done to determine if the calculator can be a base for accelerated shelf-life testing. If the product quality with the future material after 16 months is comparable to the quality with the current material after 12 months, it could also indicate that oxygen is not only one of the major factors, but the solely most important factor in relation to the expected flavor.

The Norner barrier calculator provided indications of how the coffee package would perform in different climates and conditions. The effect of a package that dries out the product faster or that gains moisture would need complementary sensory tasting to determine the effects on the flavor. It could be of interest to store the coffee packages at different humidity levels and thereafter do a sensory analysis to see the exact effects on moisture on the coffee. This could be used as a base to investigate a more exact water barrier need for coffee.

6 Conclusion

The objective of this thesis has been to examine the difference between the current and the future laminate of Zoégas vacuum-packed coffee. Oxygen and moisture are the most important factors influencing the shelf-life of the product, and according to these it can be concluded that the future laminate is superior to the current one. Although no significant changes have been observed for effect on moisture content, the OTR has been decreased with 25%. There are possibilities to recycle the future laminate, which is not possible with the current, which makes it better from a recyclability perspective as well.

It can be established that a high barrier for both oxygen and moisture is needed to provide good quality throughout the shelf life. A monolayer of PE with an oxygen barrier such as SiO_x or EVOH would be a preferrable material choice from a barrier and recyclability perspective. However, other aspects such as material characteristics and consumer accessibility need to be considered as well before determining the optimal package material for coffee.

One of the objectives of this thesis was to examine theoretical tools to experimental data. Norner Barrier calculator was used, but due to a limitation in materials that could be tested, it could only be compared to one experimental value. On the other hand, the result was near identical to the experimentally obtained value and indicates high accuracy of the Norner barrier calculator, but further tries and comparisons would have to be done to confirm it. It was possible to use the calculator to investigate the material and product characteristics further if there were unknown factors. This makes the Norner barrier calculator an excellent tool to use as a guideline when examining packaging materials in relation to surrounding conditions.

Further work that would be of interest is to continue the development of packaging materials that are suitable for recycling, as well as developing recycling methods to meet the needs of the product.

This thesis has investigated and concluded following:

- The future packaging material of Zoégas vacuum-packed coffee is superior to the current one in terms of oxygen barrier properties, showing a 25% decrease in OTR compared to the current one.
- The future laminate can be recycled, unlike the current laminate. This makes the future laminate more favorable from a recyclability perspective.
- The shelf-life of coffee is highly dependent on a good oxygen and moisture barrier. PE with an oxygen barrier would be preferable from a recyclability perspective with current techniques.
- The Norner barrier calculator could only be compared to one set of experimental data, which resulted in near identical values. This indicates that the calculator can be a useful guideline for assessing packaging materials under different conditions.
- Further work should focus on developing packaging materials as well as recycling methods that meet the specific needs of the product.

References

Ahlström, E. (2023). FTI, Personal communication. 2023-04-19.

Almasi, A., Nellström, M., Ahlm, M., Berglund, R., Johannesson, C. (2021). *Hållbar plastanvändning - tips, verktyg och exempel*. Naturvårdsverket, Stockholm. ISBN 978-91-620-6963-6

Arvid Nordquist. (2023). *En kaffeförpackning baserad på nordisk tallolja*. https://www.arvidnordquist.se/kaffe/hallbarhet/forpackning/ (accessed 2023-04-19).

Bauer, A-S., Tacker, M., Uysal-Unalan, I., Cruz, R.M.S., Varzakas, T., Krauter, V. (2021). Recyclability and Redesign Challanges in Multilayer Flexible Food Packaging - A Review. *Foods,* 10(11), 2702.

https://doi.org/10.3390/foods10112702

Belitz, H.D., Grosch, W., Schieberle, P. (2009). Coffee, Tea, Cocoa. *Food chemistry*. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-69934-7

Bobst Manchester Ltd. (2019). *The future of sustainable barrier film is clear: BOBST's transparent, high barrier SiO_x solution is both robust and environmentally friendly*. 26 February 2019. https://media.bobst.com/esen/releases/detail/article/1551169922-the-future-of-sustainable-barrier-films-is-clear-bobsts-transparent-high-barrier-siox-solution-is-both-robust-and-environmentally-friendly/?no_cache=1&cHash=7a3a3894ad2c71dfe4a2b7feb216cb86 (accessed 2023-05-10)

Buchner, N., Weisser, H., Vogelpohl, H., Baner, A.L., Brandsch, R. and Piringer, O. (2003). Foods, 4. Food Packaging. In *Ullmann's Encyclopedia of Industrial Chemistry*, (Ed.). John Wiley & Sons, Ltd https://doi-org.ludwig.lub.lu.se/10.1002/14356007.a11_583.pub2

Buffo, R.A. & Cardelli-Freire, C. (2004) 'Coffee flavour: an overview', *Flavour & Fragrance Journal*, 19(2). https://doi-org.ludwig.lub.lu.se/10.1002/ffj.1325

Cardelli, C., Labuza, T.P. (2001). Application of Weibull Hazard Analysis to the Determination of the Shelf Life of Roasted and Ground Coffee. *LWT - Food Science and Technology*, volume 34, issue 5 https://doi.org/10.1006/fstl.2000.0732.https://doi.org/10.1006/fstl.2000.0732.

Dulsat-Serra, N., Quintanilla-Casas, B. and Vichi, S. (2016) 'Volatile thiols in coffee: A review on their formation, degradation, assessment and influence on coffee sensory quality', *Food Research International*, 89 (Part 2), pp. 982–988. https://doi.org/10.1016/j.foodres.2016.02.008

Eagle Flexible Packaging. (2023) *Types of packaging materials.* https://www.eagleflexible.com/products/laminate-structures/ (accessed 2023-05-09)

Ellen MacArthur Foundation. (2023). *Plastics and the circular economy – Deep dive*. https://ellenmacarthurfoundation.org/plastics-and-the-circular-economy-deep-dive (Accessed 2023-04-20).

European Comission. (2023). *Waste Framework Directive*. https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en (accessed 2023-04-20).

European Union. (2023). *Plastics strategy*. https://environment.ec.europa.eu/strategy/plastics-strategy_en (accessed 2023-04-20).

Eurostat. (2019). *Glossary: Waste*. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Waste (accessed 2023-04-06).

Fairtrade. (2023). *Kaffe.* https://fairtrade.se/om-fairtrade/det-har-ar-fairtrade/ravaror-och-produkter/kaffe/ (accessed 2023-05-11)

Farah, A. (2019) *Coffee*. Royal Society of Chemistry. https://doi-org.ludwig.lub.lu.se/10.1039/9781782622437

Food and Agriculture Organization of the United Nations. (2022). *Tackling food loss and waste: A triple win opportunity.* https://www.fao.org/newsroom/detail/FAO-UNEP-agriculture-environment-food-loss-waste-day-2022/en (accessed 2023-04-18).

FTI (2023a). "Varför återvinns så lite av de insamlade plastförpackningarna?", *Vanliga frågor*. https://fti.se/om-fti/vanliga-fragor (accessed 2023-05-11)

FTI. (2023b). *Plastförpackningar - En återvinningsmanual från FTI på uppdrag av Svensk Plaståtervinning*. Version 6.0. https://fti.se/foretag/design-av-forpackningar

FTI. (2023c). *Nya avgiftskriterier för plastförpackningar*. https://fti.se/om-fti/nyheter/nyheter-foretag/nya-avgiftskriterier-for-plastforpackningar

(Accessed 2023-04-19).

FTI. (2023d). *Metallförpackningar*. https://fti.se/privatperson/metallforpackningar (accessed 2023-04-209

Fråne, A., Anderson, S., Andersson, C., Boberg, N., Dahlbom, M., Miliute-Plepiene, J., Unsbo, H., Villner, M. och George, M. (2022). *Kartläggning av plastflöden i Sverige 2020*. Naturvårdsverket, Stockholm.

Gunnarsson, M. (2023). Tetra Pak, Personal communication. 2023-03-22.

Halldén Björklund, Å. (2023). Personal communication. 2023-01-25 – 2023-05-18.

International Organization for Standardization. (1994) *Roasted ground coffee – Determination of moisture content – Method by determination of loss in mass at 103ºC (Routine method)*. (ISO standard 11294:1994).

Lange, J. and Wyser, Y. (2003). Recent innovations in barrier technologies for plastic packaging—a review. *Packaging Technology and Science,* 16: 149-158. https://doi.org/10.1002/pts.621

Manzocco, L., Calligaris, S., Anese, M. Nicoli, M.C. (2016) '13 - The Stability and Shelf Life of Coffee Products', *The Stability and Shelf Life of Food*, pp. 375–398. doi:10.1016/B978-0-08-100435-7.00013-7.

Mount, E.M III and Wagner, J.R Jr. 2001. Aroma, Oxygen and Moisture Barrier Behaviour of Coated and Vacuum Coated OPP Films for Packaging. *Journal of Plastic Film & Sheeting.* 2001 17:3, 221-237. https://journals.sagepub.com/doi/epdf/10.1106/4062-X5AF-6N8D-JD0H

Nationalencyklopedin. (2023) *Kaffe*. https://www.ne.se/uppslagsverk/encyklopedi/l%C3%A5ng/kaffe (accessed 2023-05-11)

Nespresso. (2023a). *The ultimate coffee bean guide.* https://www.nespresso.com/au/en/news/blog-ultimate-coffee-bean-guide (accessed 2023-05-08)

Nespresso. (2023b). Återvinning av Nespresso-kapslar. https://www.nespresso.com/se/se/atervinning (accessed 2023-04-19).

Nicoli, M.C., Calligaris, S. and Manzocco, L. (2009) 'Shelf-Life Testing of Coffee and Related Products: Uncertainties, Pitfalls, and Perspectives', *Food Engineering Reviews*, 1(2), pp. 159–168. https://doi.org/10.1007/s12393-009-9010-8.

Norner Barrier Calculator. (2023). https://barrier.norner.no/

Omni Polymers. (2023). *Product.* https://www.omnipolymers.com/ (accessed 2023-04-14).

Pantamera. 2023. *Om pantsystemet.*https://pantamera.nu/sv/privatperson/fakta--statistik/om-pantsystemet/ (accessed 2023-05-04)

Pearce, E.A., and Smith, C.G. 2000. *The Hutchinson World Weather Guide.* New Edition. Oxford, Helicon Publishing Ltd. ISBN: 1-85986-342-6.

Petersson, Marcus. (2019). *Nescafé lanserar återvinningssystem för kaffekapslar. Packmarknaden.* https://www.packnet.se/article/view/642236/nescafe_lanserar_atervinningssystem_for_kaffekapslar (accessed 2023-04-19).

Piergiovanni, L., Limbo, S. 2016. *Food Packaging Materials*. 1st ed. 2016. Springer International Publishing (SpringerBriefs in Molecular Science). https://doi.org/10.1007/978-3-319-24732-8

Ramakrishna, A., Giridhar, P., & Jeszka-Skowron, M. (2022) *Coffee Science: Biotechnological advances, Economics, and Health Benefits*. (1st ed.) CRC Press https://doi-org.ludwig.lub.lu.se/10.1201/9781003043133

Roberts, A.P., Henry, B.M., Sutton, A.P., Grovenor, C.R.M., Briggs, G.A.D., Miyamoto, T., Kano, M., Tsukahara, Y., Yanaka M. 2002. Gas permeation in silicon-oxide/polymer (SiO_x/PET) barrier films: role of the oxide lattice, nano-defects and macro-defects. *Journal of Membrane Science* 208 (2002) 75–88.

Robertson, G. L. (2013). *Food Packaging: Principles and Practice*, Third Edition (3rd ed.). CRC Press. https://ebookcentral.proquest.com/lib/lund/reader.action?docID=1449617

Singh, P., Wani, A.A., Langowski, H-C. (2017) *Food Packaging Materials. Testing & Quality Assurance*. CRC Press https://search-ebscohost-com.ludwig.lub.lu.se/login.aspx?direct=true&AuthType=ip,uid&db=cat02271a&AN=atoz.ebs14037054e&site=eds-live&scope=site

SSNC (Swedish Society for Nature Conservation). (2022). *Plast och mikroplast*. 2022-08-17. https://www.naturskyddsforeningen.se/faktablad/plast-och-mikroplast/ (accessed 2023-05-11)

Swedish Environmental Protection Agency. (2023a). *Avfall.* https://www.naturvardsverket.se/amnesomraden/avfall/ (accessed 2023-04-06).

Swedish Environmental Protection Agency. (2023b). *Matavfall och matsvinn*. https://www.naturvardsverket.se/amnesomraden/avfall/avfallslag/matavfall-och-matsvinn/ (accessed 2023-04-21).

Swedish Environmental Protection Agency. (2021a). *Uppdrag att föreslå åtgärder för att materialåtervinningen av plast ska öka - Redovisning av ett regeringsuppdrag.* Naturvårdsverket, Stockholm.

Swedish Environmental Protection Agency. (2021b). *Kemisk återvinning - ingen universallösning för plast*. https://www.naturvardsverket.se/om-oss/aktuellt/nyheter-och-pressmeddelanden/kemisk-atervinning--ingen-universallosning-for-plast/ (accessed 2023-04-18).

Sysav. 2023. *Matavfall*. https://www.sysav.se/Privat/Sorteringsguiden-for-hushall/kategori/matavfall/#inneh%C3%A5ll (accessed 2023-05-09)

Távora de Mello Soares, C., Ek, M., Östmark, E., Gällstedt, M., Karlsson, S. (2022). Recycling of multi-material multilayer plastic packaging: Current trends and future scenarios. *Resources, Conservation and Recycling.* Volume 176, 105905, ISSN 0921-3449, https://doi.org/10.1016/j.resconrec.2021.105905.

Wallteg, Bo. (2023). Löfbergs kaffeförpackning en världsnyhet. *Livsmedelsnyheter*. 22 februari. https://livsmedelsnyheter.se/2023/02/22/lofbergs-kaffeforpackning-en-varldsnyhet/ (accessed 2023-02-27).

Wikström, F., & Williams, H. (2023). *Packaging design that reduces food waste and increases recycling*. Karlstad, Karlstad Universitet. http://urn.kb.se/resolve?urn=urn:nbn:se:kau:diva-93830

Wrede, A. (2007). *Kaffeförpackningar*. Norrbottens museum. https://norrbottensmuseum.se/bildarkiv-foeremaalssamlingar/ur-samlingarna/kaffefoerpackningar.aspx (accessed 2023-02-01).

Zoégas. (2023a). https://www.zoegas.se/ (2023).

Zoégas. (2023b). Personal communication. 2023-01-16 – 2023-05-24.