CHARACTERIZATION OF THERMOFORMED AND HEAT-SEALED FIBRE-BASED MATERIALS: FUNCTIONALITY AND STORAGE BEHAVIOUR ANALYSIS

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ABSTRACT

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Characterization of Thermoformed and Heat-Sealed Fibre-Based Materials: Functionality and Storage Behaviour Analysis

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This study examined the storage behaviour of thermoformed and heat-sealed fibre-based packaging materials, which are environmentally friendly. The study primarily evaluated the impact of humidity and temperature on the occurrence of curls in plastic-coated paperboard packages. The results showed that humidity has a more significant effect on curling than temperature, with higher humidity resulting in more curls. Skin-sealed packages experienced less curling than MAP-sealed packages, and the hanging hole in packages was found to be a significant factor in package deformation. The study recommended modifications to the mould geometry used for tray production, such as the presence of grooves and avoiding great corner radius, to reduce package deformation. Additionally, the study found that material properties, such as grammage and tensile stiffness, are key factors in package deformation. The findings can help improve the quality and longevity of fibre-based packaging materials and guide the design of sustainable packaging solutions.

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ABBREVIATIONS

FEA	Finite Element Analysis
ISO	International Organization for Standardization
MAP	Modified Atmosphere Packaging
PE	Polyethylene
PET	Polyethylene Terephthalate
RH	Relative Humidity
VSP	Vacuum Skin Packaging

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1 Introduction

Recently, the packaging industry has been increasingly turning to sustainable and recyclable materials to produce more environmentally friendly products. This shift is in recognition of the significance of environmental sustainability and the urgent need to reduce global plastic consumption, which is a petroleum-derived, non-biodegradable substance, and focus resources towards more sustainable alternatives. (Afshariantorghabeh & Kärki & Leminen 2022, p. 1-2.) As food and beverages account for almost 70 % of all packaging, it is essential to focus on this area to protect food from external impacts and damages while meeting the needs of customers and the industry and reducing harmful impacts on the environment. (Marsh & Bugusu 2007, p. 39-40.)

Among the various materials for packaging, paper and paperboard-based materials were widely used in food packaging (Deshwal & Panjagari & Alam 2019, p. 4391). Paper and paperboard materials were distinguished in packaging based on their performance properties and have been used in various forms and cost-effective structures (Kirwan 2008, p. 4). However, there are various factors that can affect the properties of fibre-based material packages, such as formability, heat sealability, and barrier properties, including oxygen, oil, and water barriers. (Deshwal & Panjagari & Alam 2019, p. 4391-4393.)

One of the most crucial factors that needs to be considered when using paperboard for packaging is moisture absorption in high humidity conditions or when in contact with high-moisture foods. This feature can lead to a significant loss in mechanical qualities of the paperboard beyond a specific threshold of moisture content (Robertson 2005, p. 114.) Additionally, the moisture content level of a material plays a crucial role in the forming process and deformation of the package after forming and storing (Niini & Berthold & Müller & Tanninen & Majschak & Varis & Leminen 2022, p. 4-14).

Therefore, the focus of this study is to investigate the influence of various environmental conditions, such as different temperatures and relative humidity (RH), on the properties of paper-based packaging materials. The study aims to contribute to the ongoing efforts towards achieving sustainable packaging solutions that are not only environmentally friendly but also meet the necessary performance requirements for effective food packaging.

1.1 Background

The packaging process is an essential aspect of the food industry as it ensures that product quality is maintained during storage, on shelves, and during transportation from the manufacturer to the end consumer (Hanlon & Kelsey 1998, p. 1-2). The concept of packaging was changed over time. It was used not only as limited to the transportation and storage of the packed product but also to ensure the product quality, information of legal right from the manufacturer, providing information on marketing strategies and product. (Bratovčić & Odobašić & Ćatić & Šestan 2015, p. 86-88.) Every food item will be packed several times with various reasons in order to meet the containment, protection and utility functionalities (Hughes 2019, p. 718).

Berger (2003, p. 1-5) showed that food packaging technology has advanced along with changes in the human lifestyle and has experienced significant growth through various factors. First and foremost, people's demands and concerns have played a crucial role in driving the growth of the industry. Customers are increasingly looking for packaging solutions that are not only functional but also environmentally friendly. Unexpected occurrences such as war and natural disasters as well as marketing competition are other factors that have driven the growth of the packaging industry. At early ages, people used natural materials such as shells or leaves to have food packaging. Little by little as time went by, various processes and chemical components were discovered by people, and materials like metals, glasses, plastics, and paper became more common for packaging foods. (Berger 2003, p. 1-5.)

Metal cans were produced to provide a superior level of protection for food products. They are known to be an excellent barrier, ensuring that moisture is retained within the product while preventing contaminants and external factors from penetrating the packaging. This is crucial in maintaining the quality, texture, and flavor of food items for extended periods, even during transportation and storage. (Risch 2009, p. 8089.) Plastic packaging has been one of the most popular packaging after the word war II and considered to develop an affordable process and provide proper plastic materials for different applications (Emblem 2012, p. 8).

Plastic packaging can be source of thermoset polymers and thermoplastic polymers (non-biodegradable) which contains toxic elements causes negative influence on the landfills, ocean, river, etc. (Emblem 2012, p. 9). According to Jones and Comfort (2017, p. 1-2), paper and paperboards play a significant role in the packaging industry, accounting for 31% of the global market. They are widely utilized in food packaging to securely contain and safeguard food products. Additionally, they provide convenience in terms of storage and consumption, while also serving as a means to communicate relevant information to consumers, including marketing messages. (Jones & Comfort 2017, p. 1-2.) It was reported that in the year 2000, approximately 47% of the total paper and paperboard production was dedicated to packaging purposes (James & Jewitt & Matussek & Moohan & Potter 2002, p. 2).

Today's food packaging is focused on the paper and paperboard more than plastics. Plain paper is insufficient for food products due to poor barrier properties, low heat seal ability and strength. Therefore, paper-kind material is covered with some additive, laminated or coated with plastic material to improve its functional properties. (Deshwal et al. 2019, p. 4391-4392.) To seal the paper and paperboard materials properly, heat sealing, wetting and adhesion method is required (Vähä-Nissi & Rintanen & Savolainen 1999, p. 63-72). Despite its less formability and attractiveness, paper material is of valuable as compared to plastic owing to recyclability, renewability, and biodegradability (Vishtal & Hauptmann & Zelm & Majschak & Retulainen 2014, p. 677).

1.2 Motivation

As global concerns continue to shift towards eco-friendliness and recyclability, research and studies in this field are increasing at a rapid pace. Each breakthrough in this field provides a new opportunity to delve deeper into this science and technology, thereby inspiring further research, and knowledge-seeking among individuals. The packaging industry plays a pivotal role in developing sustainable solutions that can minimize the impact on the environment and reduce the global carbon footprint. By adopting innovative and eco-friendly practices, such as utilizing biodegradable and fibre-based materials and reducing packaging waste, the industry can significantly contribute towards the fight against climate change.

Furthermore, the packaging industry has a critical role to play in educating consumers about the significance of responsible consumption and recycling. By implementing conscientious design and labelling strategies, manufacturers can help consumers make informed decisions regarding the products they purchase and the environmental consequences that may arise from using them. Overall, the packaging industry has the potential to drive significant positive change in the fight against climate change. By prioritizing sustainability and responsible practices, it can become a key contributor to a more environmentally conscious future. The mentioned factors led the packaging industry to pay more attention to the fibre-based materials.

The behaviour of paper and paperboard materials can vary significantly with changes in temperature and moisture, and understanding these fundamental principles is crucial for developing high-quality, reliable packaging solutions. By examining the behaviour of these materials, better understand on how they will perform under different conditions can be gained and their properties can be optimized accordingly. In addition, the processing method can have a significant impact on the behaviour of packages made from these materials. By perception how the process affects the behaviour of paper and paperboard materials, the quality and consistency can be improved. Moreover, improving their storage behaviour can help reduce waste and support more eco-friendly practices across various sectors.

1.3 Objectives

The purpose of this study is to explore and examine the functional properties and the storage behaviour of plastic-coated heat-sealed and thermoformed paperboard under varying humidity conditions. To achieve this objective, the thermoform process was utilized to manufacture trays, while heat sealing was employed to affix film onto the trays and produce the packages.

This research aims to advance fibre-based materials by investigating their storage behaviour. The primary objective is to identify ways to enhance the properties and performance of these materials, which will lead to the production of more environmentally friendly products. To achieve this, the study will explore specific factors that contribute to the storage behaviour of fibre-based materials, including temperature and humidity. Therefore, the three selected conditions for this study are constant temperature of 6 °C and relative humidity (RH) of 50 %, 75 %, and 90 %.

To achieve the objective of accurately comparing different materials, it is important to develop reliable and quantitative methods for measuring their behaviour. In this research curling, twisting and deformation of packages were chosen as indicator of storage behaviour of materials under varying humidity conditions.

1.4 Research problems and questions

The primary focus of this research study is to explore the storage behaviour of fibre-based materials post thermoforming and heat sealing, along with the effect of varying humidity conditions, such as moisture and temperature, on packaging behaviour. In order to achieve this, the following research questions have been formulated:

The main research questions are:

- What is the storage behaviour of fibre-based materials after thermoforming and heat sealing?
- What is the effect of different possible humidity conditions (e.g., moisture, temperature) on the packaging behavior?

The sub-questions are:

- Is there any influence of the package geometry on the storage performance of packages?
- What is the effect of material properties in storage behavior of packages?
- What methods should be used to quantitively measure the storage behavior of packages?
- What is the effect of varnishing on the material surface and the behavior of materials during forming, sealing, and storing?

Undertaking this research is anticipated to pose various challenges since there is a lack of relevant literature on storage behaviour of packaging made by fibre-based material and effect of hanging hole, which is used to hang the package in stores, in various humidity conditions. Consequently, by addressing these research questions the theoretical foundation of this research experiment will be based on existing literature and knowledge on this subject. The results of this study could have significant implications for the development of more effective packaging solutions that are durable and functional.

1.5 Scope

The study focuses on examining the characteristics and properties of four specific types of fibre-based materials. To ensure a comprehensive understanding of these materials, the experiments will be conducted in three distinct humidity conditions, ranging from low to high humidity levels with constant temperature. By analysing how the materials react and behave under varying humidity conditions, the study aims to identify the effect of material properties on behaviour of packages. It should be noted that the scope of this study is limited to these four specific fibre-based materials and the three humidity conditions chosen for experimentation. Other fibre-based materials and humidity conditions may exhibit different properties and reactions. Nonetheless, the insights gained from this study will provide valuable information for the development and improvement of fibre-based products.

2 Literature Review

The literature review will primarily concentrate on explaining the core principles of the thermoforming packaging machine, heat sealing section and in general the whole process of producing a filled package. Additionally, the effective factors on the storage behaviour of the produced packages under humid conditions will be explained clearly.

2.1 Thermoforming packaging machine

Thermoforming packaging machines which are typically integrated as thermoform-fill-seal machines play a critical role in the creation of customized packaging solutions for various industries. By choosing the appropriate type of thermoforming machine based on the specific needs of the product and packaging design, manufacturers can ensure that they are producing high-quality packaging efficiently and cost-effectively. These machines are used to create customized packaging solutions for a wide range of products, including food and beverages, pharmaceuticals, and consumer goods. To meet the specific needs of different products and packaging designs, various types of thermoforming machines are available. (Engelmann 2012, p. 8.)

The thermoforming machines provides automatically pack a variety of products, including food and non-food items, into either flexible or rigid packages. They are made of stainless steel, due to the properties of this material in terms of long-lasting and resistant to residue build up. One of the controllers can be used in these machines is the programmable logic controller (PLC), which can help to store different programs and enables easy customization of the machine settings. Furthermore, the die is easily replaceable, allowing to produce trays in different shapes and sizes. The sealing plate is also designed to facilitate easy opening of the tray, making it convenient for customers to access the product. The machine also features vacuum, MAP (Modified Atmosphere Package) and VSP (Vacuum Skin Packaging) capabilities, which help to extend the shelf life of the packed products. (ZY Automation NA.)

Sheet-Processing Machines are utilized in diverse situations, ranging from processing small- to medium-sized batches, enabling rapid colour changes, to manufacturing large-scale products. These machines are particularly useful in shaping and forming various components, including the interiors of refrigerators and automobiles, as well as body parts for vehicles. By leveraging the capabilities of sheet-processing machines, manufacturers can streamline the production process and achieve greater precision, consistency, and efficiency in their operations. (Engelmann 2012, p. 5.)

Roll-fed machines are designed to process materials that are supplied in rolls as can be seen in Figure 1. These machines can be coupled with an extruder, located upstream of the thermoforming line, which enables the production of large quantities of products. Depending on the application and specific machine, roll-fed machines can also produce medium to high quantities of parts. These machines are typically used to create a range of products, including yogurt cups, drinking cups, and cookie trays. By leveraging the capabilities of roll-fed machines, manufacturers can streamline their production processes and achieve greater efficiency and consistency in their operations. Roll-fed machines offer several advantages over other types of machines, including the ability to process materials in roll form, which reduces the need for frequent material changes and increases productivity. Additionally, these machines can handle a wide range of materials, including plastics, paper, and aluminium. Therefore, roll-fed machines are a versatile and efficient option for manufacturers looking to produce high-quality products in large quantities. By leveraging these machines, manufacturers can reduce material waste, increase productivity, and achieve consistent and reliable results. (Engelmann 2012, p. 5.)

Figure 1. One example of roll-fed thermoforming machine (Spalding & Chatterjee 2017, p. 586).

Skin and blister machines are used for packaging various products. In the skin method, a heated film is placed over the product to be packaged, creating a seal around it. Unlike the blister method, this process does not require the use of a forming tool. (Engelmann 2012, p. 5.) In blister machine which is shown in Figure 2, the forming web which is mostly plastic is extracted from the reel and placed into the machine at first step. Subsequently, heating the material and thermoforming it into blister cavities to have series of blisters. The thermoformed blisters are filled by product. this process can be manual or fully automatically. Finally, at the sealing station, a lidding film is introduced over the blisters and heat sealed to create the packages. (Pilchik 2000, p. 68.) The examples of blister packaging can be seen in Figure 3.

Skin and blister machines offer a range of benefits, including increased product visibility, improved product protection, and reduced packaging waste. These machines can be employed for a variety of products and are an excellent option for manufacturers looking to optimize their packaging processes. (Engelmann 2012, p. 5.) These machines are known as high-quality machines in terms of handling automated loading, filling, and continuous feeding. The pharmaceutical industry mostly uses blister packaging machines for packing capsules and tablets. The packing process would be changed based on the shape of product or used material from linear feeder to brush box feeder. (Das & Saha & Das 2018, p. 19.)

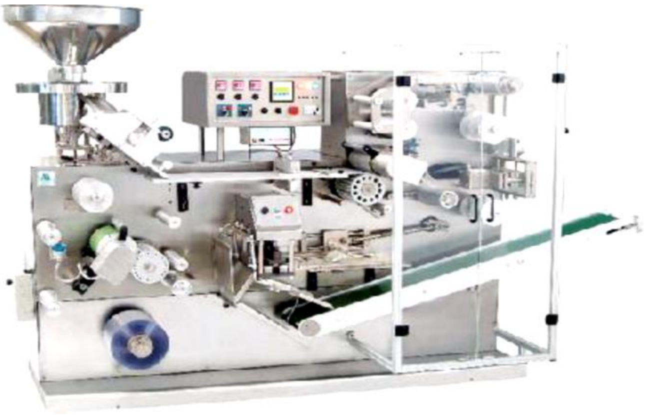
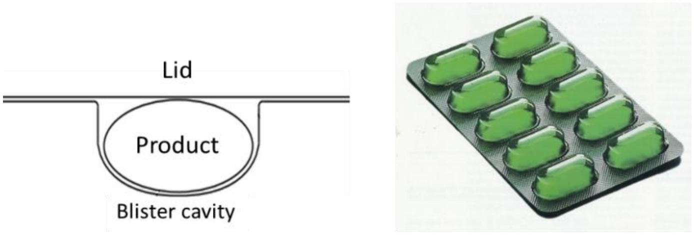


Figure 2. Blister machine (Das et al. 2018, p. 19).



(a) (b)

Figure 3. (a) Sample of a blister package (Müller & Weygand 2016, p. 1). (b) Thermoforming blister pack (Lamonte & McNally 2001, p. 36).

Forming, Filling, and Sealing Machines that have various component such as forming, filling, sealing, and punching stations. Engelmann (2012, p. 5) describes these machines as comprehensive packaging systems employed in the thermoforming process. The process involves shaping the material, which is promptly filled with the desired product and then sealed using a lid film. Finally, the package is punched out to its final form. These machines find applications in various scenarios, including multipacks for items such as yogurt, cheese, meat, cold-cuts, single-portion packs, toothbrushes, and batteries. (Engelmann 2012, p. 5.)

In general, it can be mentioned that thermoforming lines can consist of the following parts: sheet-handling system, method of rigidly clamping sheet, oven(s), forming press, pneumatic or mechanical pre-stretching (optional), load/unload elements, vacuum box, pressurization system (optional), condition monitors and process control, safety elements, and method of trimming the product from the web which is presented in Figure 4. (Throne 2011, p. 351-352.)

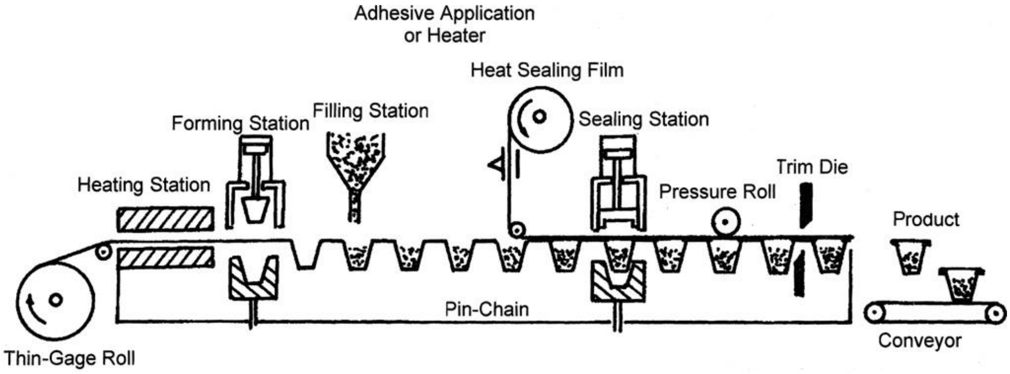
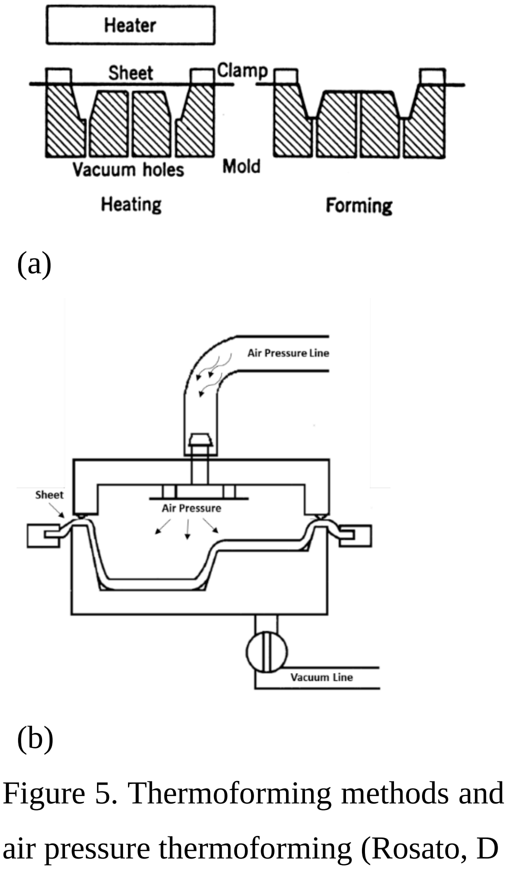


Figure 4. Forming, Filling, and Sealing Machines (Throne 2011, p. 351).

2.1.1 Thermoforming process

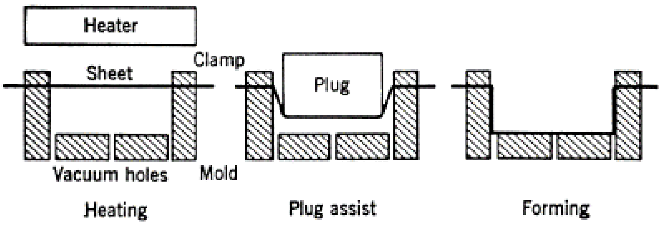
Thermoforming is a common method of forming where a material is heated until it reaches its softening point, and then pressure or mechanical forces are applied to shape it into the desired form. There are three different thermoforming process in terms of vacuum thermoforming, involved applying vacuum pressure to the material to create a mould shape; air-pressure thermoforming by applying air pressure to the material. Combination of vacuum and air-pressure thermoforming involved applying both vacuum and air-pressure to create the mould shape. (Afshariantorghabeh et al. 2022, p. 4-5.) The last process is the plug assisted thermoforming which leads the material to get the shape of mould by applying the preheated mechanical plug (Martin & Duncan 2007, p. 804). By examining the mentioned processes, the researchers were able to compare the effectiveness of each and identify any benefits or drawbacks associated with them. A detailed illustration of the techniques of vacuum thermoforming, the combination of vacuum and air-pressure thermoforming, and plug assisted thermoforming in Figure 5 can be observed.



(a)

(b)

Figure 5. Thermoforming methods and tools. (a) Vacuum thermoforming. (b) Vacuum and air pressure thermoforming (Rosato, D & Schott & Rosato, M 2001, p. 1142-1198).



(c)

Figure 5 continues. Thermoforming methods and tools. (c) Plug assisted thermoforming (Rosato, D & Schott & Rosato, M 2001, p. 1143).

Thermoforming process results in the production of a stable plastic or fibre-based material part through a series of steps. Initially, the roll of raw material, which is fed to the machine, is heated until it reaches a viscous-flexible phase. It is then stretched and induced to reproduce the mould shape via applying pressure difference or mechanical forces. The formed part is cooled within the tooling and subsequently removed from the mould. The molecular chains of the material remain stretched due to the cooling process, which enables the part to maintain its shape. If the part needs to be reformed specially in thermoplastic materials, it can be heated again, allowing the molecular chains to recover their original state. Thermoforming offers several economic advantages compared to other methods, particularly in relation to forming tool costs. This method allows for the production of complex shapes at a relatively low cost, making it a popular choice in a variety of industries. Therefore, thermoforming is a versatile and cost-effective method for producing plastic parts with a stable form. The process can be used for a variety of materials and shapes, making it an ideal choice for manufacturers looking to optimize their production processes. When it comes to the advantages of the manufacturing of packaging parts by forming, the shorter cycle times, high outputs, possibility of printed product processing, and possibility of multi-layered semifinished product can be mentioned. In addition to all the benefits, it also has its own drawbacks in terms of less scope for design (undercuts), non-uniform distribution of wall thickness, difficult temperature control, and having no influence over the formulation of the film for the manufacturer, if dealing with purchased film. (Engelmann 2012, p. 5.)

2.1.2 Heat sealing process

Heat sealing is utilized as an important part in form-fill-seal machines (Theller 1989, p. 66). It is a technique used to join two thermoplastic materials by using heat to melt their surfaces and then cooling them down to create a strong bond. The heat is transferred to the surface of the films to be bonded, and the temperature is carefully controlled to ensure that it is sufficient to create a secure seal. After heating, the surfaces are pressed together and cooled down rapidly to complete the bonding process. (Hishinuma 2009, p. 2.) To ensure that the results meet necessary requirements in terms of strength and do not leak, it is crucial to carefully regulate the temperature, duration of contact, and pressure applied during the process. This must be done according to the specific properties of each type of laminate film being used. (Yuan & Hassan 2007, p. 773.) The impact of the heat-sealing temperature on the sealing process is apparent, but optimizing the parameters depends on the material combinations employed (Leminen & Kainusalmi & Tanninen & Lohtander & Varis 2012, p. 77). Generally, the film sticks together through thermal adhesion when it reaches a certain temperature. The strength of the seal indicates the quality of the bonding. It is also important to understand the way the material fails during thermal bonding in order to assess its performance and determine how it separates into two layers. When there is sufficient molecular interaction between the layers, the seal is of good quality, resulting in a new, uniform layer and ensuring the integrity of package. (Suh & Ock & Park, G & Lee & Park, H 2020, p. 3.)

There are different types of heat sealing in terms of hot bar sealing (jaw bar sealing) and impulse sealing which are mostly used in food packaging industry (Troughton 2008, p. 121). The heat-sealing system that utilizes a jaw-bar involves pressure cylinders and a heating block bar. The heating block bar is composed of a heater, a temperature sensor, and a heating pipe that distributes heat through conduction to bond two films together upon contact. To prevent fluctuations between the set temperature and the actual temperature of the hot bar, the temperature sensor monitors and regulates the temperature continuously. However, there may be delays in the surface temperature due to variations in the heating bar temperature. (Hishinuma 2009, p. 31-32.) In the process described by Leminen (2016, p. 29) a tray composed of paperboard coated with polymer is placed between the sealing tools. The lower tool lifts the tray by its flange, and then the sealing chamber is closed. Subsequently, the sealing tools are brought together with a defined force. During this step, the tray and the lidding film are joined and maintained in contact for a predetermined duration, leading to the creation of a seal. (Leminen 2016, p. 29.)

Regarding the sealing parameters, seal bar temperature has a strong influence on seal strength as shown in Figure 6, while dwell time has a relatively small influence (Figure 7 (a)). Increasing dwell time only slightly increases seal strength, while increasing platen temperature significantly increases seal strength. Moreover, pressure has an ineffective impact on seal strength compared to seal bar temperature which can be seen in Figure 7 (b). However, a small amount of pressure is required to bring the surfaces into contact.

In addition, accurate control of the sealing temperature interface is necessary to melt the adhesive layer and ensure effective sealing in thermoplastic films. (Meka & Stehling 1994, p. 97-100.) Also, Yuan et al. (2007, p. 777) has proved this claim by doing experiments and discovered that seal bar temperature and dwell time are key factors in comparison with pressure for determining the strength of heat seals. Achieving minimum required temperature to activate sealing at the interface is essential and longer dwell times ensure sufficient heat transfer while increasing pressure has no significant effect on heat seal strength. (Yuan et al. 2007, p. 777.) The research of Merabtene (2022, p. 225) indicates that this fact also applies to paper-based materials. The study reveals that the sealing strength of paper-based materials is not dependent on the amount of pressure applied, and that the effectiveness of the seal is influenced by factors such as the material's thickness, as well as the time and temperature at which the sealing is performed. (Merabtene & Tanninen & varis & Leminen 2022, p. 225.)

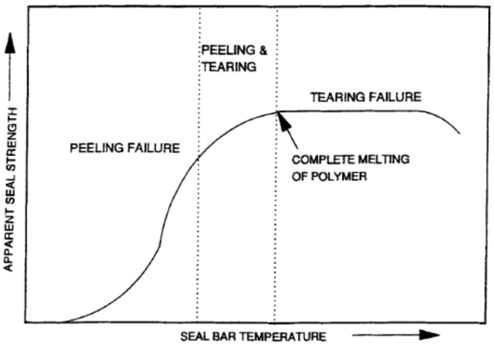
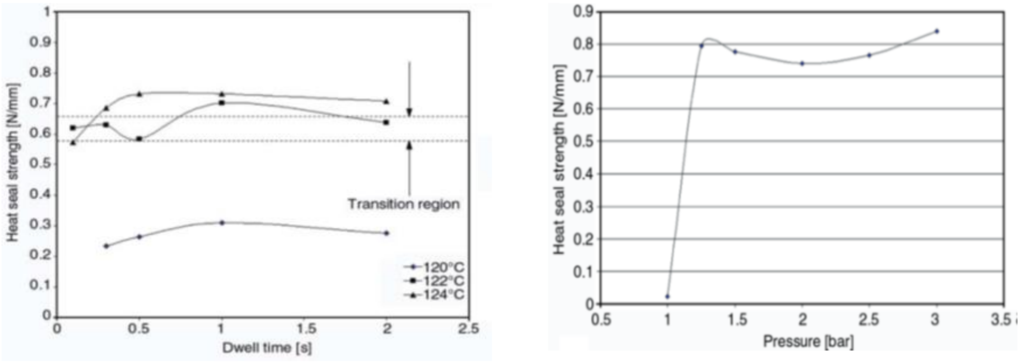


Figure 6. Relation between seal strength and temperature (Meka et al. 1994, p. 97-100).



(a) (b)

Figure 7. Relation between seal strength and (a) Dwell time and (b) Pressure (Yuan et al. 2007, p. 777).

2.2 Plastic-coated paperboard packaging materials

The fundamental structure of paper is composed of cellulose fibres, which contain numerous pores. Porosity of paper-kind material may cause challenges in applications where liquids or moisture are present. (Sjöström & Alén 1998, p. 269.) In other words, regular paper is not proper for food products due to its inadequate ability to prevent liquids and moisture from passing through, its limited capacity to be sealed with heat, and its low durability. Therefore, paper-based products are treated with an additive or covered with plastic in order to enhance its functional properties (Deshwal et al. 2019, p. 4391). Fibre-based packaging materials are often coated with plastics such as polyethylene (PE) or polyethylene terephthalate (PET) using extrusion and subjected to surface treatment. This coating process was found to be highly effective for a wide range of applications, as the plastic coatings provide a physical barrier against oils, while the fluorocompounds help to prevent the wetting of the fibres. (Leminen & Ovaska & Tanninen & Varis 2015, p. 92.)

When paper-based packaging is exposed to high levels of humidity or comes into contact with liquids, it can quickly lose its structural integrity and barrier properties (Khwaldia & Arab-Tehrany & Desobry 2010, p. 82). Preserving the barrier properties of paper or paperboard through the whole process of converting the material to package is essential and should be considered. The key reason is during the folding of the sheet, the formation of pinholes and cracks can occur, and this is causing a reduction or loss of any barrier properties in terms of gass, moisture, or oxygen in the coating. (Tanninen & Lindell & Saukkonen & Backfolk 2014, p. 354.)

Typically, in packaging applications, fibre-based materials are coated with a polymer layer to provide sufficient protection against substances like water, oxygen, and grease. The polymer coating has a significant impact on the barrier properties of the fibre-based material, including its oxygen transmission rate and its ability to resist oil and grease permeation. (Franke & Leminen & Groche & Varis 2021, p. 1-2.) Moreover, polymers like polyethylene and polyethylene terephthalate do not alter their barrier resistance upon exposure to moisture. This is because hydrophobic polymers do not absorb sufficient water to soften the polymer chains and increase gas permeability. (Zhang & Britt & Tung 2001, p. 1866.)

2.3 Heat sealing of plastic-coated paperboard with MAP and skin films

The principle of heat sealing is to bond two thermoplastic materials by applying heat, pressure, and dwell time (Hishinuma 2009, p. 21-23). Heat sealing is a highly efficient, cost-effective, and common technique used to seal plastic-coated paperboard with Modified Atmosphere Packaging (MAP) and skin sealing methods. This process involves the use of heat to melt the plastic coating, which then forms a bond with the film, creating a tight seal that helps to preserve the freshness and quality of the packaged product. This process can be customized to suit the specific needs of different products, allowing for a high degree of flexibility in terms of packaging design and functionality. (Engelmann 2012, p. 200.)

Overall, heat sealing is an important technique for creating effective packaging solutions for a wide range of food products. By using this method in combination with plastic-coated paperboard and MAP or skin films, manufacturers can create packaging that is both functional and attractive, while also helping to preserve the freshness and quality of the product.

2.3.1 Skin film

Vacuum packaging refers to the process of removing the air from the package and sealing the sides of the package (Seideman & Durland 1983, p. 29-31). To achieve skin vacuum packaging, the process involves placing the food in a tray and covering it with a lid. The vacuum packaging machine then utilizes a heated upper film to wrap tightly around the food, while a tray is placed in the vacuum chamber. By utilizing this method, the food's presentation is improved, and its value is enhanced, resulting in an overall increase in display effect. (Yamaguchi 1990, p. 279-280.) One example of a vacuum packaging is shown in Figure 8.

When the packaging material is in close contact with the product surface, it prevents air from entering and spoiling the product. Therefore, the contact between the product surface and the packaging material plays a critical role in creating an airtight seal necessary for effective vacuum packages. (Toldra 2017, p. 305-307.) Oxygen is necessary for the growth of spoilage agents such as aerobic bacteria and oxidative reactions. When oxygen is unavailable, spoilage is inhibited, leading to improved quality and storage life. (Church & Parsons 1995, p. 143.)

Moreover, vacuum packaging significantly reduces the chemical and biological degradation of food within its packaging. Vacuum packing protects packaged food from potential external elements such as insects, humidity, and dirt. It also provides excellent protection over freezer burn, which can develop after long periods of freezer storage. While vacuum packing provides greater sealing, it is also more expensive than conventional packaging solutions. However, there are certain disadvantages to vacuum packing, such as difficulty opening and the possibility of injuring particularly delicate items, such as soft cheese. (Priyadarshi & Deeba & Negi 2020, p. 266.)

Figure 8. Vacuum skin protruding packaging (Toldra 2017, p. 307).

2.3.2 MAP film

Modified Atmosphere Packaging (MAP) is a popular packaging technique to extend the shelf-life and improve the quality of products (Figure 9). The basic idea is to substitute the air inside a package with a predetermined combination of gases. When it comes to the MAP of food products, the three main gases utilized are oxygen (O_2) because of decreasing the chances of harmful bacterial growth, nitrogen (N_2) due to being tasteless and insolubility in fat and water, and carbon dioxide (CO_2) because of its ability to inhibit the growth of bacteria and fungi. Typically, a specific combination of two or three of these gases is employed to cater to the requirements of a particular food item (Ohlsson & Bengtsson 2002, p. 61-80). Table 1 shows the mixture of oxygen, nitrogen, and carbon dioxide for special products and how the MAP can affect on shelf life of the product. (Engelmann 2012, p. 201.)

Table 1. Gas mixture and its effect on shelf life of food products (Engelmann 2012, p. 201).

	Gas mixture (%)		
Product	CO_2	N_2	O_2
Poultry	50	50	0
Meat	30(25)	0(5)	70
Bakery products	100	0	0
Ready to eat dishes	30	70	0

	Shelf life (Days)	
Product	Exposed to air	MAP
Poultry	6	18
Beef	4	12
Bread	7	21
Prepared foods	7	28

MAP has many advantages. One of the primary benefits of MAP is that it maintains the original shape and consistency of the product. Moreover, MAP helps to preserve the vitamins, taste, and natural colour of the products. This is especially important for delicate foods that tend to spoil quickly, such as fresh fruits and vegetables, dairy products, and meats. With MAP, these items can be kept fresh for longer periods of time. The longer shelf life also results in a reduction of commercial loss, as products are less likely to spoil or become unsellable. (Engelmann 2012, p. 201.) MAP has been utilized in food packaging industry in order to extend the shelf life of the product and decrease the microbiological development at the same time. Therefore, it should mention that high tightness sealing process needs to prevent the water or oil leakage in MAP. (Leminen et al. 2012, p. 28-30.)

Figure 9. Modified atmosphere packaging (Toldra 2017, p. 308).

2.4 Paperboard storage behaviour in various humidity conditions

The usage of fibre-based materials has become increasingly widespread due to its cost-effectiveness, waste reduction benefits, and decreased demand for virgin wood fibres. Despite the fact that paperboard provides excellent stiffness and strength while utilizing less material, its mechanical properties and structural performance degrade when subjected to temperature and relative humidity fluctuations (Singh, J & Olsen & Singh, S & Manley & Wallace 2008, p. 227-229).

Moisture can be one of the factors affect maintaining the quality of plastic packaging. It affects several key properties of the material, including its thermo-mechanical behaviour, gas barrier performance, adhesion capability, and dielectric properties. Therefore, it is crucial to comprehend the moisture-water sorption capacity of materials to determine the storage behaviour of the packages. (Sapalidis & Katsaros & Romanos & Kakizis & Kanellopoulos 2007, p. 398-401.)

The moisture content of fibre-based materials has a significant impact on their mechanical properties because the lignin matrix between cellulose microfibrils softens as moisture content increases. This can cause fibre delamination, which weakens the bonding between fibres and reduces the stiffness of individual fibres. Moreover, an increase in relative humidity leads to a decrease in the compressive strength and modulus of elasticity of paperboard as well as decrease in the tensile strength. (Navaranjan & Dickson & Paltakari & Ilmonen 2013, p. 967.)

Fadiji's (2019, p. 135) study demonstrated that both temperature and humidity significantly influence the creep behaviour of packaging, with higher levels of both factors leading to more pronounced creep deformation. Additionally, the study revealed that the design of the packaging has a substantial impact on its deformation under different conditions, particularly in relation to variations in relative humidity. (Fadiji & Coetzee & Opara 2019, p. 135.) Vishtal and Retulainen (2012, p. 4435) emphasized the importance of moisture in achieving the desired deformation of a paperboard material. Their study showed that while moisture in paperboard can lead to curled blanks, it plays a critical role in facilitating plastic deformation and increasing material elongation during three-dimensional forming processes (Vishtal & Retulainen 2012, p. 4435.) Additionally, further research of Vishtal (2015, p. 452) on the role of moisture in the formability of paperboard has investigated that when the forming temperature is low, the influence of moisture on the paperboard's formability becomes more pronounced (Vishtal & Retulainen & Khakalo & Rojas 2015, p. 452). However, a high moisture content was previously considered necessary for successful three-dimensional forming, but it resulted in a loss of dimensional stability as well as curls and deformation on the paperboard packaging (Ovaska & Tanninen & Saukkonen & Backfolk 2018, p. 348-349).

The rate of moisture sorption, which is closely related to the rate of dimensional change, is considerably affected by the coupling between the paper and the surrounding air, which refers to the exchange of heat and moisture (Leisen & Hojjatie & Coffin & Lavrykov & Ramarao & Beckham 2002, p. 6555). One common method of examining the dimensional change is through the investigation of balance hygroexpansion. This process involves observing the alteration of the shape of a sheet when exposed to moist air until it reaches a new equilibrium at a different humidity level from its initial state, where it was in equilibrium at a specific atmospheric relative humidity. (Larsson & Wågberg 2008, p. 515-517.) Moreover, Niini (2021, p. 517) investigation indicated that high humidity has a negative effect on the dimensional stability, durability, and quality of paper-based packages as humidity can change the properties of the materials (Niini & Leminen & Tanninen & Varis 2021, p. 517).

2.5 Effect of presence of hanging hole in the paperboard package

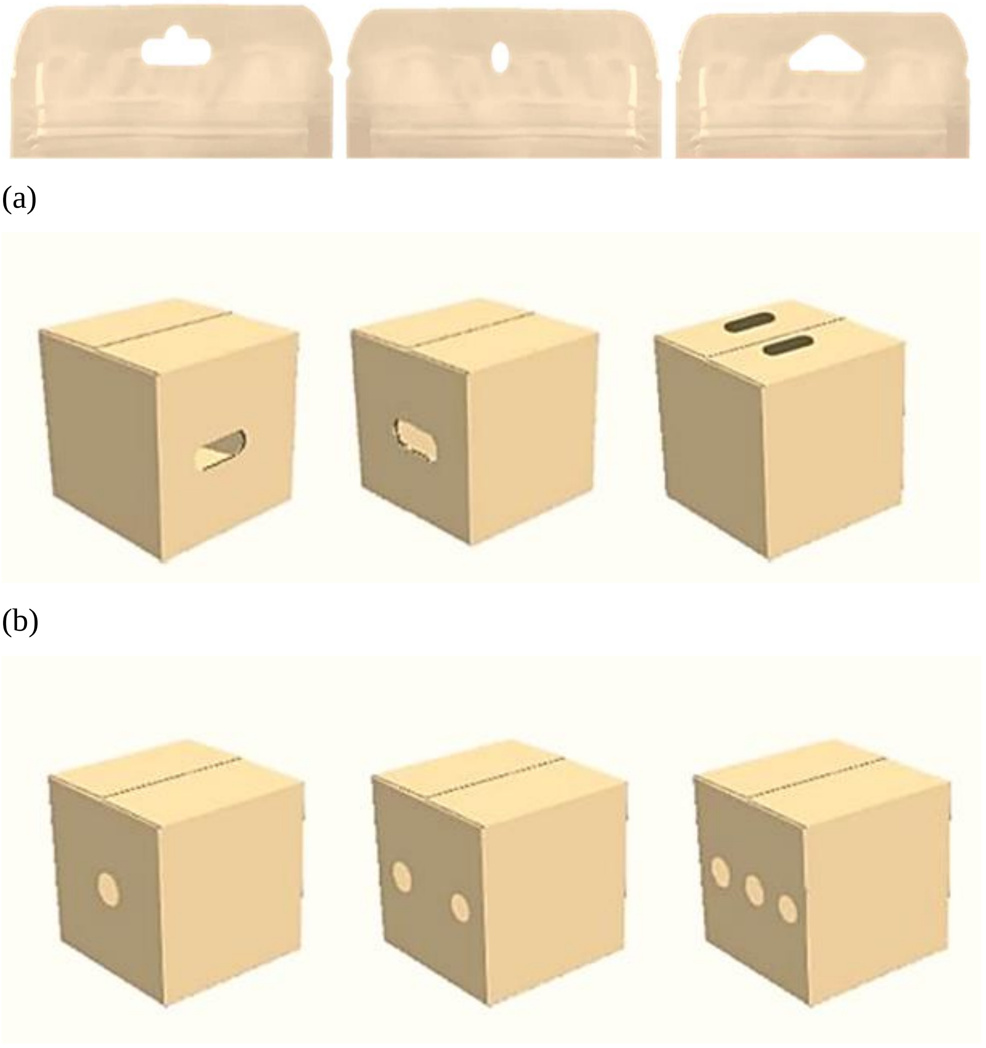
A variety of holes can be incorporated in the design of packages. These holes which can be seen in Figure 10 are hanging holes for suspension, hand holes intended to facilitate manual handling of the package, and ventilation holes designed to promote air circulation within the package. Consequently, several studies were conducted to investigate the effects of ventilation and hand holes on paperboard and paperboard carton packaging.

According to the study conducted by Singh (2008, p. 237), the impact of ventilation and hand holes were examined on the compression strength of paperboard cartons. The study revealed that the presence of ventilation and hand holes in the cartons can lead to a significant reduction in their compression strength, ranging from 20 % to 50 %. Moreover, this study showed that the shape of the hole played a critical role in the loss of compression strength. (Singh et al. 2008, p. 237.)

Effective package design requires consideration of not only the total vent and hole area but also the geometrical configurations of vent holes, including size, shape, and location, in order to achieve optimal mechanical strength and minimize the risk of product damage during shipping and handling. Therefore, a holistic approach to package design is needed in which considers the environmental conditions and product. (Pathare & Opara & Vigneault & Delele & Al-Said 2012, p. 2042.) In certain applications where holes are incorporated in packaging for the purposes of handling or air flow, paperboard packages with hand holes may experience reduced compression strength when exposed to high moisture environments. This can increase the risk of damage or failure during storage and transportation. (Fadiji & Coetzee & Opara 2016, p. 244-245.)

Han and Park (2007, p. 47) conducted a study where they utilized finite element analysis (FEA) to predict the compression strength reduction resulting from vent and hand holes. The study used double-walled corrugated boxes and the surface area occupied by the holes constituted roughly 2 % of the total surface area of the vertical box faces. According to the findings of the study, both FEA and experimental data showed a compression strength reduction of less than 10 %. (Han & park 2007, p. 47.)

The conducted literature review indicates an absence of research concerning hanging holes in packaging designed for storage and suspension. Consequently, this study aims to investigate the influence of hanging holes on the deformation of stored packages under diverse conditions, including varying relative humidity and temperature levels.



(a)

(b)

(c)

Figure 10. Different types of holes in packages. (a) Hanging hole (Pouch, NA). (b) Hand hole. (c) Ventilation hole (Archaviboonyobul & Chaveesuk & Singh & Jinkarn 2020, p. 173).

3 Materials and Methods

The objective of this thesis is to investigate the functionality and storage behaviour of fibre-based materials after thermoforming and heat sealing with MAP and skin film. In this chapter, a comprehensive summary of the testing procedure will be presented, which includes detailed descriptions of the materials and equipment used, as well as the processing parameters and data analysing method involved. The goal is to provide a clear understanding testing process and obtain accurate and reliable results. To begin with, the materials used over the testing process are thoroughly outlined with details of their properties and characteristics. This includes information on the type, quality, and quantity of materials used, as well as specific techniques used, such as the duration of the testing process, the temperature and humidity conditions required, and the other relevant factors that may impact the accuracy and reliability of the results.

3.1 Overview of experimental procedure

To gain an understanding of the experimental process, the initial steps have been visually represented in the Figure 11. This figure provides an overview of the essential steps involved in the experiment, enabling a clear and concise understanding of the process and the methodology of experiments.

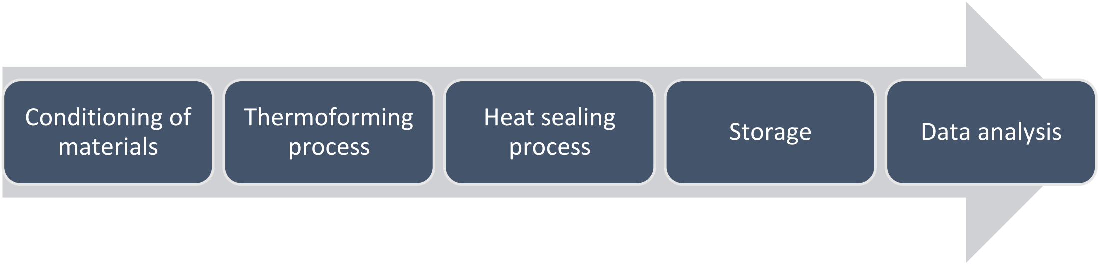


Figure 11. Experimental procedure.

The experiment process was done using the available equipment of LUT's Laboratory of Packaging Technology. Additionally, the collected experimented data was statistically analyzed which is a quantitative method in order to show the results of correlations or cause-and-effect relationships between the materials, their properties and the various storage conditions.

3.2 Experimental materials

One of the purposes of this study was to investigate the impact of material properties on the thermoforming process, heat sealing, and storage behaviour under various conditions. There are six distinct coated paperboard that are utilized in roll format for this particular purpose. Among these materials, four were considered as primary materials, while the remaining two were excluded after undergoing pre-tests owing to their similar performance to one paperboard selected for main experiments. Since these three materials exhibited nearly the same behaviour, paperboard 1 was chosen for the primary tests in order to reduce the number of samples.

Moreover, it should be noted that the basic material and coating of the paperboard 3 and paperboard 4 were the same just paperboard 4 had an extra layer of varnish. All the experimental paperboard materials were provided by Stora Enso. To ensure accurate and reliable results, materials were stored under controlled conditions with 80 % relative humidity and 23°C and standard condition of 50 % relative humidity and 23°C, in accordance with the manufacturer's instructions. All the materials have one layer of polyethylene (PE) or polyethylene terephthalate (PET) as coating to have sufficient barrier in packaging.

3.2.1 Properties of material

LUT laboratory of Packaging technology well-equipped with a range of instruments designed to measure the mechanical properties of materials. These instruments are capable of measuring properties such as thickness, grammage, tensile properties (in both machine and cross direction), and moisture content. These measurements provide valuable information and wider view about their functionalities in various applications. The properties of four main materials and coating are presented in the Table 2 andTable 3.

Table 2. Properties of main experimental paperboard materials.

Material	Grammage (g/m^2)	Thickness (µm)	Tensile stiffness MD (kN/m)	Tensile stiffness CD (kN/m)	Elongation MD (mm)	Elongation CD (mm)	Tensile strength MD (kN/m)	Tensile strength CD (kN/m)	Tensile index MD (kNm/g)	Tensile index CD (kNm/g)	E Modulus MD (Gpa)	E Modulus CD (Gpa)
Paperboard 1	390	475	2623.4	1213.3	7.5	7.8	29.96	14.2	6.64	3.07	5.535	2.56
Paperboard 2	249	396	1143.4	1007.9	10.7	9.78	30.88	14.79	4.58	4.04	0.577	0.509
Paperboard 3	216	286	1712.9	855.2	2.02	6.14	17.83	12.29	7.93	3.96	5.989	2.99
Paperboard 4	221	288	1754.3	869.1	2.03	6.36	18.26	12.75	1.05	2.35	6.091	3.018

Table 3. Grammage of used coating on the experimental paperboard materials.

Material	Coating type	Coating Grammage (g/m^2)
Paperboard 1	Polyethylene terephthalate (PET)	40
Paperboard 2	Polyethylene (PE)	55
Paperboard 3	Polyethylene (PE)	20
Paperboard 4	Polyethylene (PE)	20

The determination of the grammage of a material is a crucial aspect of the packaging, pulp, and paper industry. Grammage is defined as the mass of a unit area of paper or board and is expressed in grams per square metre (g/m^2). This measurement is obtained through a specific method of testing ISO 536. The process involves determining the area and mass of the samples, which is then used to calculate the grammage.

Firstly, it is recommended to take three samples for weighing and repeat the measurement six times. This means that a total of eighteen samples are required to obtain reliable results. Each sample should have a size of 140 x 140 mm, as determined by the laboratory standards. After cutting the sheets, it is essential to condition the samples to reach a consistent moisture content equilibrium with the standard conditions of temperature and humidity. These standard conditions are 23 °C ± 1 °C and (50 + 2) % RH. This process is necessary to ensure that the samples have a consistent moisture content, which can affect the accuracy of the grammage measurement.

The utilized device for grammage measurement is Analytical balance ALS (Kern, Germany) as shown in Figure 12. It is important to calibrate the device to ensure accurate measurements. The weighing of every three samples must be conducted under the same conditioned environment, and this process should be repeated six times to obtain consistent and reliable results. Once the weighing process is completed, the grammage of every group of samples can be calculated using the following equation:

$$g_i = \frac{\text{Weight of group}_i \text{ of samples}}{\text{Number of samples} \times \text{Area of sample}} \tag{1}$$

Where the weight of the group of samples is determined by the weighing process, the area of the sample is the product of the length and width of the sample. By calculating the average of g_i, the grammage of the material can be calculated. By following this protocol, accurate and reliable measurements of the grammage of a material can be obtained, which is essential for various applications in the industry.

Figure 12. Analytical balance ALS (Kern, Germany).

Thickness refers to the distance between two parallel surfaces of an object, material, or structure. It is typically measured in millimetre (mm) or inches (in) and can be determined using various methods, such as callipers, micrometres, or thickness gauges (ISO 534). The paper thickness plays a significant role in assessing the stiffness, strength, and durability of the material. Furthermore, performance of the material in various applications is crucial. The International Organization for Standardization (ISO) 534 standard outlines a specific method for determining the single sheet thickness and bulking thickness of paper and paperboard.

For the used material in this research, micrometres method and bulking thickness measurement were utilized. The standard defines the apparent bulk density in g/cm3, which is the mass per unit volume calculated using the bulking thickness measurement. The device that used for this process is Digital Micrometre for Thick Materials Model 49-56 (TMI, Netherland) which can be seen in Figure 13. To carry out the measurement, samples must be prepared by cutting stance-cut sheets at LUT Pulp and Paper Laboratory in a size of 140 x 140 mm and conditioned at the standard condition of 23 ℃ ± 1 ℃ and (50 + 2) % RH. It is essential to avoid using folded or damaged samples as they can negatively impact the accuracy of the results. Four packs of samples, each containing five samples, are required for the measurement process, resulting in the preparation of 20 separate samples. Next, five points on each sample pack are measured, and the process is repeated for all four sample packs. The results are presented with three significant figures, including the minimum, maximum, and standard deviation values, and the accuracy of the mean is shown at a 95 % confidence level. Following the ISO 534 standard makes it possible to obtain accurate and reliable measurements of paper and paperboard thickness, enabling effective utilization and assessment of materials in various applications.

Figure 13. Digital Micrometre for Thick Materials Model 49-56 (TMI, Netherland).

Tensile properties refer to the mechanical behaviour of a material when subjected to tensile stress or tension. This involves pulling the material apart to determine its resistance to deformation and ultimate breaking point. Understanding the tensile properties of a material is crucial for determining its suitability for different applications. According to the standard ISO 1924-3, measurement of tensile properties of the material can be calculated. The utilize device for this process was L&W Tensile Tester from (Lorentzen & Wettre, Sweden) as shown in Figure 14.

This method will give the various properties of tensile such as Tensile stiffness, tensile strength, tensile energy absorption (TEA), elastic modulus, elongation, and stain at break. To evaluate the strength of a material, a specific procedure must be followed. This involves applying a tensile force to a sample of the material until it reaches the point of failure. The test must be conducted at a speed of 100 mm/min, while also measuring the tensile force and elongation that occurs. Additionally, certain parameters will be determined automatically. To prepare for this test, the test pieces must be conditioned in the same way as previous tests.

The test requires 20 successful samples, with ten pieces cut in the machine direction (MD) and ten in the cross direction (CD). These samples should have a width of 15 ± 1 mm, and they can be cut from the same samples used in previous tests to measure thickness and grammage. The test pieces should be secured between the clamps on the machine, and the clamp force must be adjustable to prevent damage or slippage of the sample. If the test piece breaks too close to either clamp, within a distance of 2 mm, the result should be discarded.

Figure 14. L&W Tensile Tester (Lorentzen & Wettre, Sweden).

Accurately measuring the moisture levels in fibre-based materials is essential for ensuring their quality. Typically, this is accomplished by utilizing moisture analysers that employ the Loss of Drying (LOD) technique. The Adams Equipment PMB 53 Moisture Analyser (ADAM, UK) which is shown in Figure 15 is a gravimetric moisture analyser that is utilized to measure the moisture content of materials. A small sample is placed within the analyser, and its weight is measured to establish its initial moisture content. The analyser then heats the material to completely evaporate all of the moisture, and its weight is measured once again. The difference between the initial and final weights is used to calculate the final moisture content of the material. The PMB moisture analyser is capable of handling up to 50 grams of material, and the moisture content is reported in units of % M.

Figure 15. PMB 53 moisture analyser (ADAM, UK).

3.2.2 Moisture and Temperature conditions

Various conditions were considered to analyse the storage behaviour of the packages made of six different materials. At the first trials three conditions in terms of refrigerator 8 ℃ and humidity, 23 ℃ and 50 % RH, and 38 ℃ and 90 % RH. These conditions were used to evaluate the effect of temperature and humidity on the storage behaviour of the packages and materials. Following the pre-test trials, the conditions were modified to consist of a constant temperature of 6 ℃ and three different relative humidity levels of 50 % RH, 75 % RH, and 90 % RH. These conditions were selected to further investigate the impact of humidity on the storage behaviour of the packages and materials.

3.3 Methods

The production and storage of packages is a complex process that requires deep understanding of the different stages of package production. In this section, a comprehensive overview has been presented regarding the forming process, storage of packages, and analysis methods as well as measuring their curls and deformation. Firstly, a detailed explanation was provided for the thermoforming process and the equipment involved. Subsequently, the heat-sealing process utilized for lid placement on the filled packages was carefully defined. Lastly, the analytical technique for measuring package curls and deformation was thoroughly examined. These steps are required to ensure that the packages produced are of high quality and meet the necessary standards.

3.3.1 Thermoforming Process

To carrying out the experimental tests the horizontal form-fill-seal machine, thermoforming line called VARIOVAC Primus from (Zarrentin, Germany) was utilized (Figure 16). This particular machine is designed to be supplied with materials in the form of rolls, specifically with a width of 423 mm, which is used as the package material. The material should be fitted between the clamps that are located both side of the machine. In the next step the material is transferred in to preheating stage. Following the preheating process, the paperboard is transferred and positioned within the moulding chamber. Utilizing vacuum and/or compressed air or plug assisted, the preheated paperboard is pulled downwards and moulded into the desired geometry and then cooled down to take the shape of a forming plate. The formed material is then transferred for further processing such as filling, sealing, and cutting.

In vacuum thermoforming, the preheated material, formed into female mould via aplying vacuum. During the vacuum and air-pressure thermoforming, in addition to vacuuming the material into mould, the pressure is applied from above the material. The forming pressure inside the forming chamber is controlled by the air pressure valve directly. Forming chamber consist of fixed upper part and movable bottom part as shown in Figure 17.

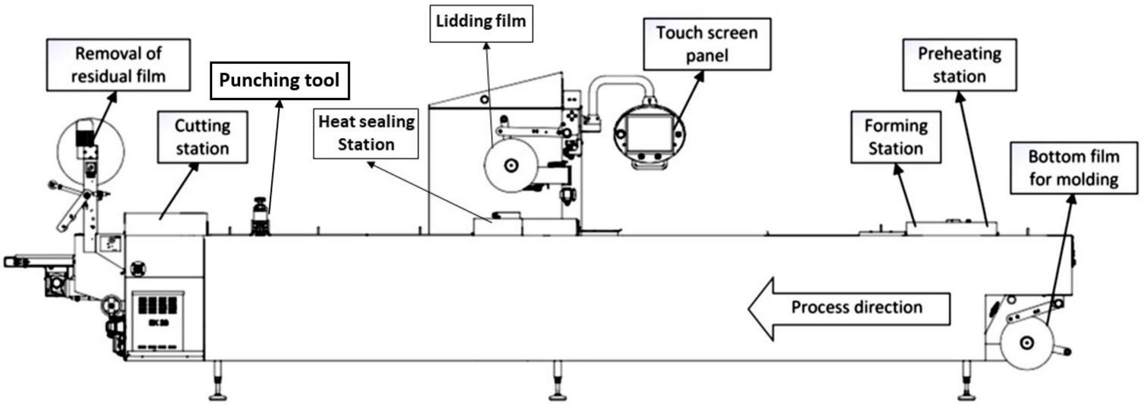


Figure 16. The schematics of utilize thermoforming line (Afshariantorghabeh, Kärki, & Leminen, 2022, p. 4).

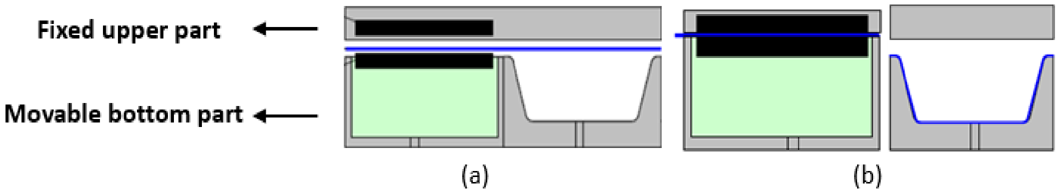


Figure 17. Forming station. a) Pre-heating stage. b) Forming stage.

The main mould used for experiments is Mould 1 as shown in Figure 18. To further investigate the effect of geometry on package deformation two additional moulds (Mould 2 and 3) were used in some of the experiments.

Figure 18. Used moulds in thermoforming.

Forming parameters applied to the materials are defined in Table 4. It should be noted that according to the formability and properties of the material, forming parameters may be different. As a result of the rupture of Paperboard 3 and 4 within the thermoforming section, adjustments to the parameters were necessary in order to reach the optimal parameters.

Table 4. Forming parameters for experimental paperboards.

Material	Temperature (°C)	Heating time (s)	Forming time (s)	Pressure (bar)
Paperboard 1	100	3	3	1
Paperboard 2	100	3	3	1
Paperboard 3	100	3	3	0.2
Paperboard 4	100	1.5	1.5	0.2

3.3.2 Heat Sealing Process

The heat-sealing process involves the application of heat and pressure to the lid and the package, which melts the plastic layers and creates a strong bond between the two surfaces. It is crucial that this process is carried out correctly to ensure that the packages are of high quality and meet the necessary standards.

Following the thermoforming stage, the lidding film is applied to the product. It is crucial to take into account the coating of the material or paperboard used when selecting the appropriate lidding film for the package. The paperboard tray is positioned in the sealing equipment, where the lower sealing tool raises the tray from its bottom. The sealing chamber is then closed, and the sealing tools affix the lidding film to the tray, using predetermined time and temperature settings.

The sealing tool consists of an upper and lower sealing tool. The top sealing tool is comprised of a sealing plate and a sealing film, while the bottom sealing tool consists of a silicone sealant, a sealing frame, and filling plates. As the lower and uPper sealing tools come together, the upper film and the tray surface film are compressed between them. Depending on the machinery used, air is either removed from the package (skin lidding) or removed and replaced with the appropriate gas (MAP lidding).

After this process, the sealing plate pushes the sealing film down, and the upper and lower films are sealed together. The filling plates provide support to the packaging and decrease its volume. The quality of the seal depends on various parameters, such as time, temperature, and pressure. Figure 19 displays the sealing tool.

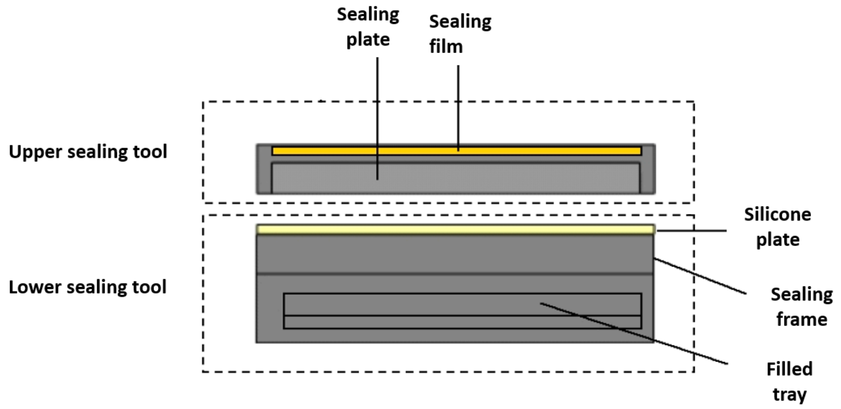


Figure 19. Heat sealing tool.

Heat sealing parameters utilized in this study are indicated in Table 5 and Table 6 for skin sealing and MAP sealing respectively. Due to different coating of the materials, the temperature of the heat sealing for MAP sealing is different. Paperboard 1 unlike other paperboards which are coated with PE, is coated with PET and it needs higher temperature to seal. The commercial materials utilized as lidding film were Buergofol OPET/T900RC for paperboard 1 and Ambar F310/838 BA5 TS for paperboard 2 to 4 for MAP sealing and SkinFilm 100 for skin sealing. The other factor which effects on changing the sealing parameter is final vacuum in order to prevent rupture of packages during MAP sealing.

Table 5. Heat sealing parameters for skin sealing.

Material	Temperature (°C)	Sealing time (s)	Vacuum time (s)	Final vacuum (mbar)
All of the materials	150	2	2	8

Table 6. Heat sealing parameters for MAP sealing.

Material	Temperature (°C)	Sealing time (s)	Final vacuum (mbar)	Gass pressure (mbar)
Paperboard 1	210	2	10	600
Paperboard 2	140	2	10	600
Paperboard 3	140	2	100	600
Paperboard 4	140	2	100	600

3.3.3 Cutting process

Once the heat-sealing process is completed, the sealed package moved forward to the cutting stage. Initially, for simulating the real environment to analyse the storage behaviour of packages, hanging hole was created in the package. The creation of a hanging hole provides convenience to sellers to store and hang the product. The hole is created using a punching tool as shown in Figure 20, which is set to the required size and shape. Also, corners of the package are punched to prevent sharp corners at the same time. Once the hole is made, the package moves onto the cutting stage.

Figure 20. Punching tool.

At the cutting stage, the sealed package is cut along its edges to separate it from the rest of the material. The cutting tools are designed to cut through the material precisely and cleanly, resulting in a professional-looking finish. The cutting stage is also critical in ensuring that the packaging is consistent in size and shape, as any errors in this stage could result in an inconsistent appearance or a poorly functioning package. After the cutting stage, the sealed package is released from the machine and is ready for the storage. Stored packages were conditioned in diverse conditions and analysed for their potential deformation and curling. Ready packages which were stored are shown in Figure 21.

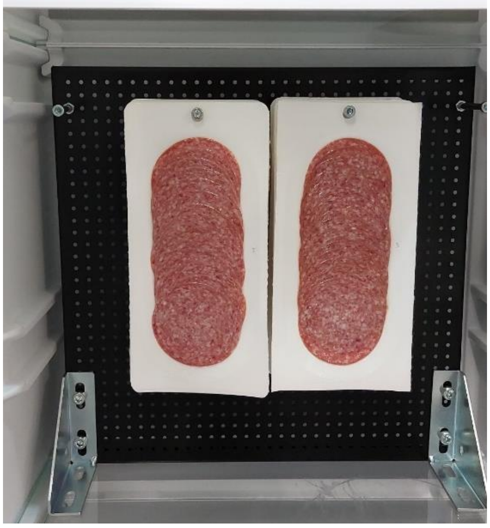


Figure 21. An example of stored packages with hanging hole.

3.4 Analysis Methods

The primary purpose of this research is to evaluate and analysis the storage behaviour of packages made from different materials under varying storage conditions. It is crucial to ensure that the method used to conduct this research is reliable and accurate to achieve optimal results. For this purpose, two L shape sheets and one flat sheet were used to hold the package on the even surface. To draw curls, paper was attached to the sheets using adhesive, and a marker was used to draw the curls of every edge of the package (Figure 22) on the paper. The Figure 23 provides a visual representation of this setup and steps to identify the curls on the paper for further analysis.

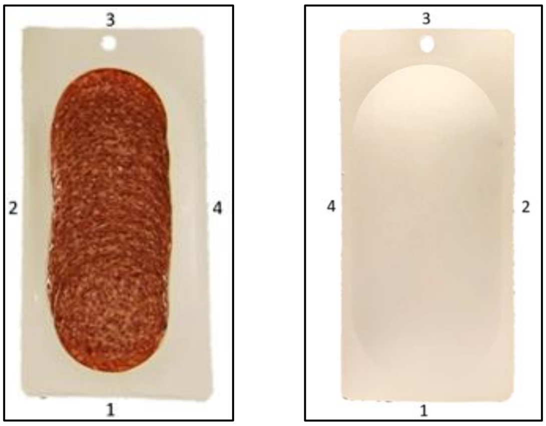


Figure 22. Numbering the edges of the package.

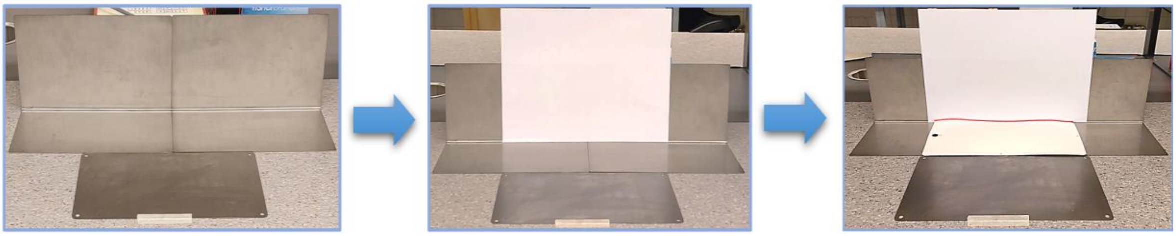
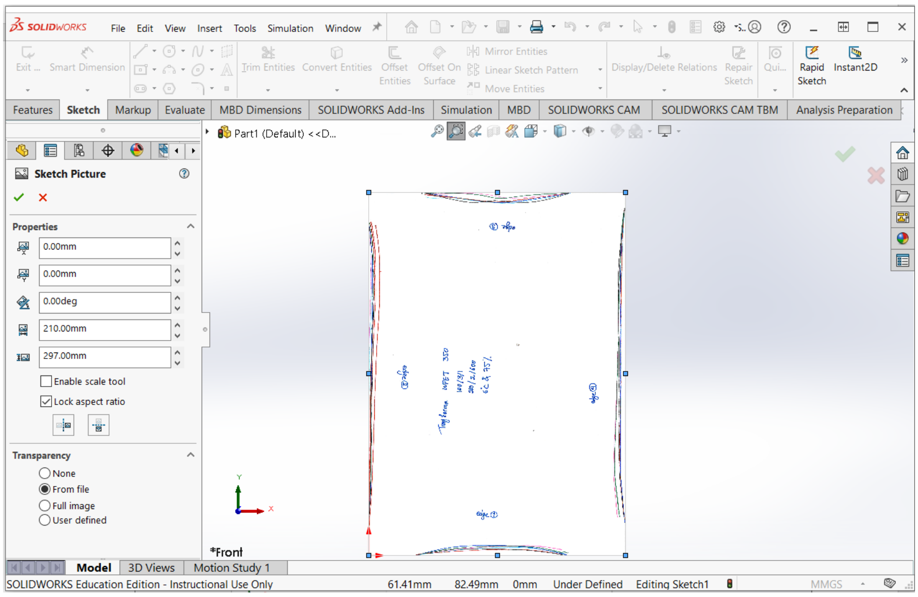


Figure 23. Set up for measuring curls of the packages.

In the next step, the paper contains the curls pattern was scanned and imported into in the SolidWorks as a sketch. As it can be seen in Figure 24, the size of the paper was chosen from the left sidebar the same as real size of the A4 paper and then by using the smart measurement feature, curls were measured. This method helps to model the pattern of the curls for every edge of the package and visualize a deformed package for more understanding and analysis.



Sketch Picture

Properties

0.00mm

0.00mm

0.00deg

210.00mm

297.00mm

☐ Enable scale tool

☑ Lock aspect ratio

Transparency

○ None

● From file

○ Full image

○ User defined

SOLIDWORKS Education Edition - Instructional Use Only 61.41mm 82.49mm 0mm Under Defined Editing Sketch1 MMGS

Figure 24. Imported paper as a sketch in SolidWorks.

In this study, eighteen packages were produced from each material and stored under defined conditions for seven days. For every condition six samples were produced and stored. This approach was to allow investigating whether the packages exhibit similar patterns of curling and deformation and enhance the precision of the measurements. Furthermore, to facilitate a proper comparison of the deformation and curling of the samples, measuring them under the same temperature and relative humidity (RH) conditions is essential. Finally, the packages were collected after seven days of storage and transferred to a standard climate room with a temperature of 23 °C ± 1 °C and (50 ± 2) % RH. The recommended approach to measuring curls involves depicting the curl pattern with reference to the ground. This technique provides information not only about the quantity of curls but also about their extent of deformation and specific location. By depicting the curls with respect to the ground, a comprehensive overview of the curl pattern was obtained, which is not possible with other measurement methods. Therefore, it is essential to use this method for accurate assessment of curls. For proving the accuracy of defined method, the curls were measured by calliper as well as shown in Figure 25.

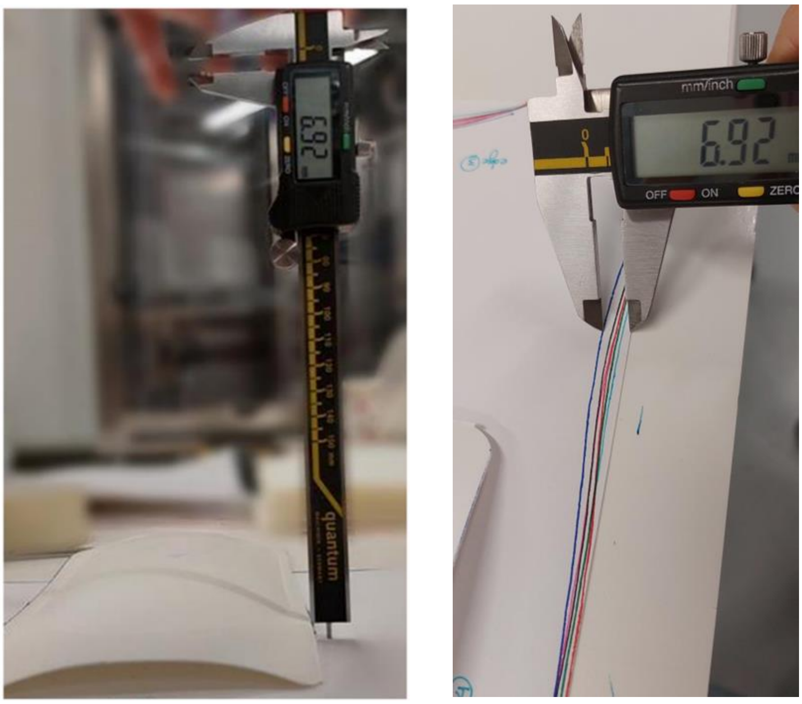
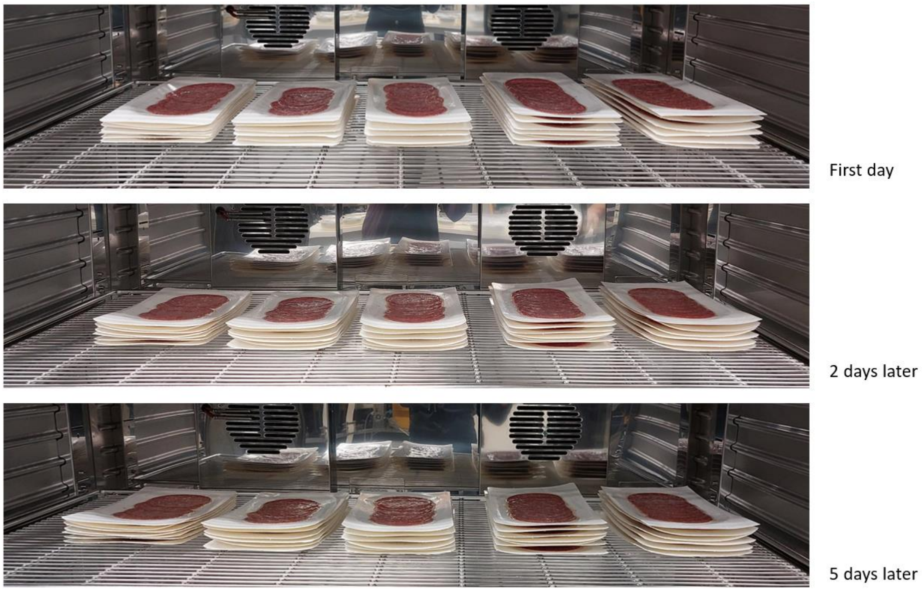


Figure 25. Validation of accuracy of the method.

Prior to conducting the primary test, several pre-tests were conducted to determine the key factors that influence the curls of packages. It was found that several factors, such as grammage of the product contained within the package, the temperature and relative humidity of the storage conditions, and the selection of appropriate materials, should be taken into account.

Initially, the experiments commenced by determining the weight of the contents inside the packaging. Consequently, five distinct weights of the actual product, such as ham, were chosen and kept in an environment with a high temperature and relative humidity of 38 ℃ and 90 % RH. After five days, it was observed that there were no significant variations in the curls of packaging. This is apparent in Figure 26, where the product weights inside the packages, from left to right, are 43.8 gr, 50 gr, 57.7 gr, 65 gr, and 72.8 gr. According to the results of this test, it was determined that the primary test will be continued using the maximum weight of the product that can fit in a package, which was found to be 100 grams. This amount is equivalent to 14-15 pieces of ham.



First day

2 days later

5 days later

Figure 26. Effect of product grammage on package curls.

4 Results and Discussion

The findings of this study are presented in the results and discussion section, along with an analysis of them. Tables, graphs, and charts are used when appropriate to show the results in an understandable approach. Moreover, the implications of the results, their relevance, and how they connect to the study are explained. Overall, this part offers insights into the study issue and offers a complete analysis of the data.

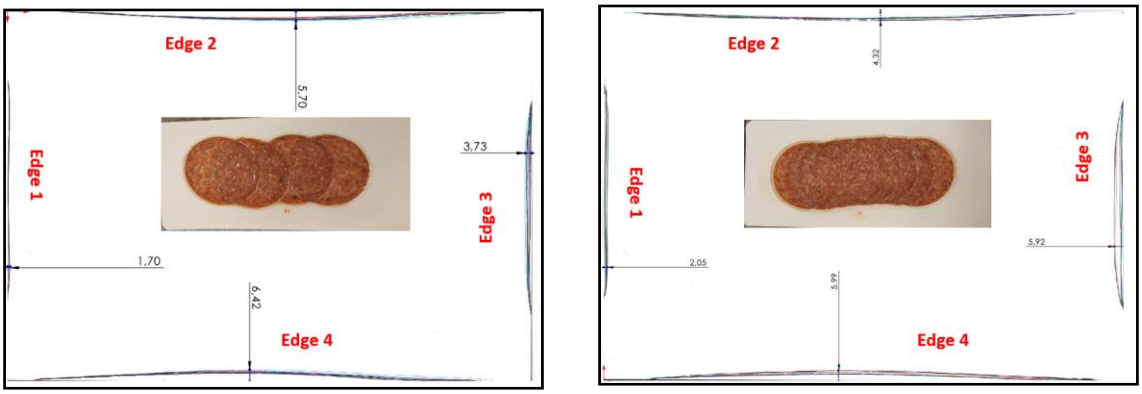
4.1 Evaluation of storage behaviour of studied material

The storage behaviour of the packages made by plastic-coated paperboard materials was assessed. In this section the obtained results according to the pre-tests and main tests is explained clearly.

4.1.1 Pre-tests

This section provides brief results of pre-tests on which the actual testing parameters were selected. The impact of various features on the curls of the packages produced by various materials are presented. These factors are grammage of the product contained within the package, skin and MAP sealing, the temperature and relative humidity of the storage conditions, and the selection of appropriate material.

To begin with, the ham was stored in five different grammages under the conditions of 38 °C and 90 % RH, as depicted in Figure 26 in section 3.4 . The curls of packages containing the lowest (43.8 gr) and highest (72.8 gr) product were subsequently measured. Upon comparing the curls of each edge, it became apparent that the grammage of the product inside the package did not have a significant impact on its curls and deformations. Additionally, the Figure 27 demonstrates that the pattern of the curls in both packages remains the same, despite any variation in weight. It can be inferred that weight does not have any considerable impact on this this aspect as well. The data collected was graphically presented in Figure 28 to facilitate visual comparison. It is important to note that the curls of each edge should be compared against each other. Based on the results, the primary tests were carried out with maximum grammage can be contained in the package which is 100 gr of product.



(a)

(b)

Figure 27. Curls of the packages with (a) Minimum and (b) maximum grammage of product.

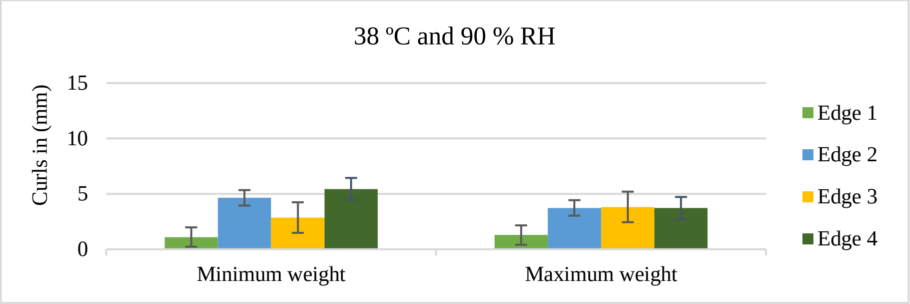


Figure 28. Comparison of packages curls with minimum and maximum weight of product.

In the subsequent phase of pre-testing, a hanging hole was incorporated into the packaging, following which the packages were subjected to storage under three distinct conditions: In a refrigerator at a temperature of 8 °C and humidity, standard condition with a temperature of 23 °C and 50 % RH, and high-humidity condition at a temperature of 38 °C and 90 % RH. Owing to the observed occurrence of grease leakage under the third condition, it was subsequently excluded from further investigation. Additionally, it was established that the optimal storage conditions for preserving the quality and integrity of a given product necessitate maintaining a low temperature. As such, the storage conditions were revised to maintain a constant temperature of 6 °C, with varying levels of humidity set at 50 %, 75 %, and 90 % RH to evaluate their impact on the product. This approach is intended to ensure that the product is maintained at an ideal temperature and humidity level, thereby minimizing the likelihood of degradation or spoilage.

4.1.2 Results in condition with 6 °C and 50 % RH

The present section investigates the effects of the temperature of the controlled environment of 6 °C and 50 % relative humidity for seven days on the behaviour of produced packages with paperboards 1 to 4. The quantity of curls and the patterns of the curls that formed during the storage were examined. Figure 29 to Figure 32 illustrate the extent of curl the packages have faced and storage behaviour of the skin-sealed and MAP-sealed packages.

According to the findings presented for Paperboard 1, the packages experienced a higher incidence of curls in width of the package in skin-sealed packages. Specifically, these curls were predominantly observed around the edge where the hanging hole was located. Packages produced using MAP sealing exhibited a fluctuating pattern of curls around the hanging hole, which differed from the curling patterns observed in other edge areas. Additionally, the incidence of curls was observed to be greater in MAP-sealed packages when compared to skin-sealed packages.

The analysis of packages produced by Paperboard 2 revealed the occurrence of curls in the corner of the edge where the hanging hole was located, consistent with the findings of Paperboard 1 except that the quantity of curls was almost four times greater. However, in contrast to paperboard 1, the results demonstrated that MAP-sealed packages produced using paperboard 2 exhibited fewer curls when compared to skin-sealed packages. Additionally, the pattern of the curls around the hanging hole in MAP-sealed packages using paperboard 2 was observed to be distinct from that observed in skin-sealed packages.

The investigation of the storage behaviour of packages produced using Paperboard 3 revealed that MAP-sealed packages experienced a greater incidence of curls and deformation when compared to skin-sealed packages. Furthermore, the length of the MAP-sealed packages exhibited a fluctuating pattern, as evidenced in Figure 31. The pattern of deformation in skin-sealed packages are almost the same as paperboard 1.

The findings presented in Paperboard 4 which was varnished demonstrate that skin-sealed packages exhibit deformations and curls in their width. The material used in these packages is characterized by low formability and low moisture content 4.54 %, even after undergoing conditioning at 23 ℃ and 80 % RH. Consequently, it was deemed unsuitable for use in thermoform-fill-seal lines and was consequently excluded from further testing.

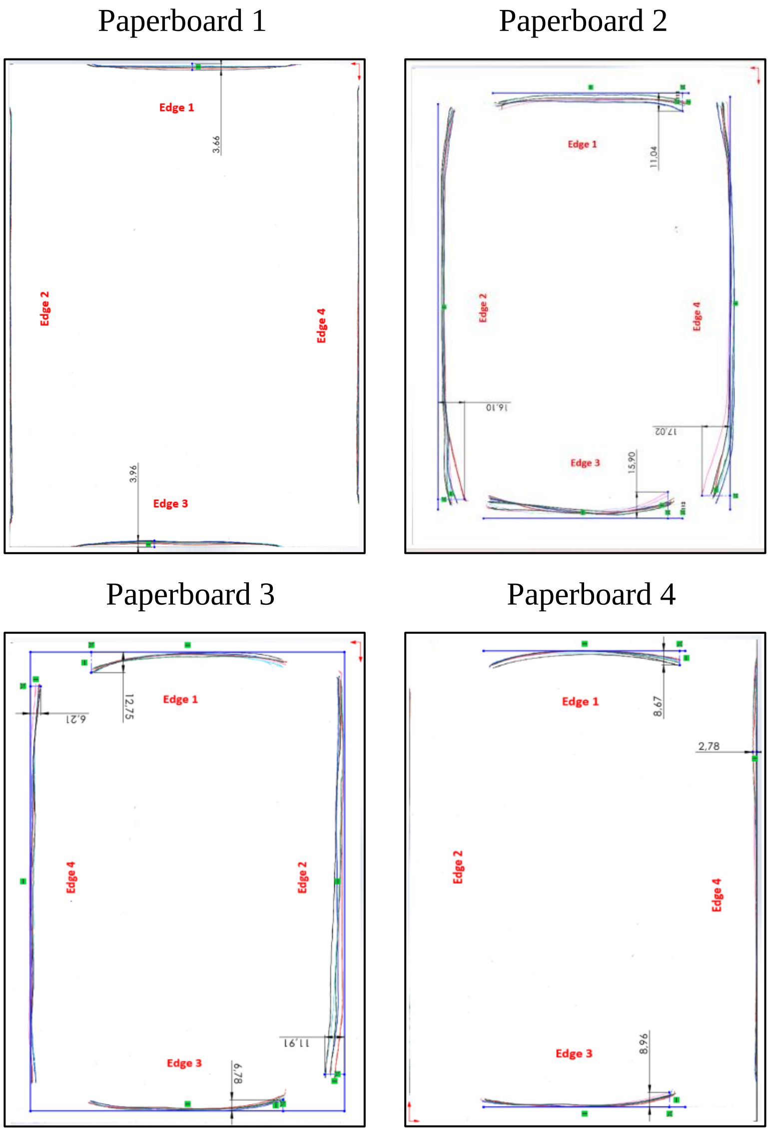


Figure 29. Curling profile of the skin-sealed packages stored in 6 ℃ and 50 % RH.

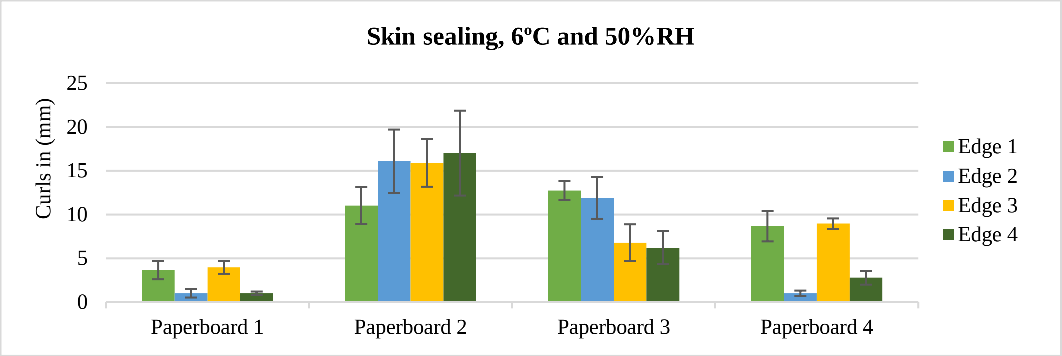
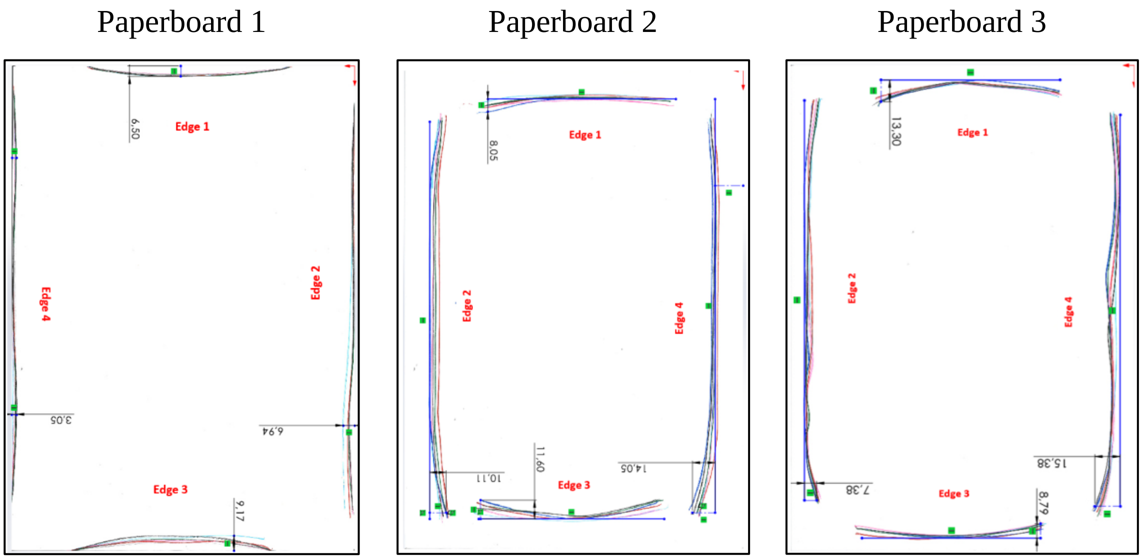


Figure 30. Curling analysis of the skin-sealed packages stored in 6 ºC and 50 % RH.


Paperboard 1

Paperboard 2

Paperboard 3

Figure 31. Curling profile of the MAP-sealed packages stored in 6 °C and 50 % RH.

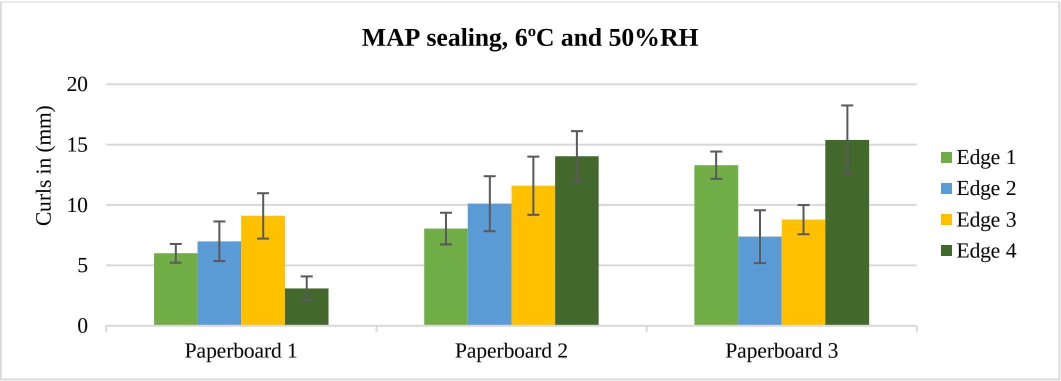


Figure 32. Curling analysis of the MAP-sealed packages stored in 6 ºC and 50 % RH.

4.1.3 Results in condition with 6 °C and 75 % RH

This section of the study involves an analysis of the storage characteristics of the packages, specifically their behaviour after being stored for a period of seven days in an environment with a temperature of 6 °C and a relative humidity of 75 %. Figure 33 Figure 35 present the pattern and Figure 34 and Figure 36 show the quantity of the curls in this condition.

Based on the results outlined in Paperboard 1, the observed trend of the curls and storage behaviour of the packages was almost similar to the storage behaviour in condition with 50 % RH. MAP-sealed packages demonstrated a varied pattern of curls around the hanging hole, distinct from the curling patterns detected in other edge areas. Furthermore, more curls have observed on the edge that hanging hole is located in comparison with the other edges in skin-sealed packages. By comparing the results with obtained outcome from condition with 50 % RH, it was observed that humidity can increase the curls and deformations of packages. The more humidity, the more curls.

After a thorough analysis of the packages produced by Paperboard 2, it was observed that the occurrence of curls follows the findings of Paperboard 2 in the condition where the RH is at 50 %. These curls were predominantly observed in the corner of the edge where the hanging hole was located. Furthermore, it was observed that an increase in humidity reduced the quantity of curls in skin-sealed packages. In contrast, MAP-sealed packages experienced a higher number of curls when compared to packages in the condition with 50 % RH. The results obtained from the analysis indicate that humidity directly affects MAP-sealed packages and inverse skin-sealed packages.

The results gathered from testing the storage performance of packaging produced by paperboard 3 demonstrated a similar trend to that observed in a 50 % relative humidity environment but with a greater quantity of curls. Packaging sealed MAP displayed more curling than those sealed with skin. Additionally, higher humidity levels caused an increase in curling for MAP-sealed packages, while skin-sealed packages experienced less curling. Also, the pattern of the curls on edge 2 and 4 are fluctuated and differs from curls on other edges in MAP-sealed packages as can be seen in Figure 35 Figure 36 for Paperboard 3.

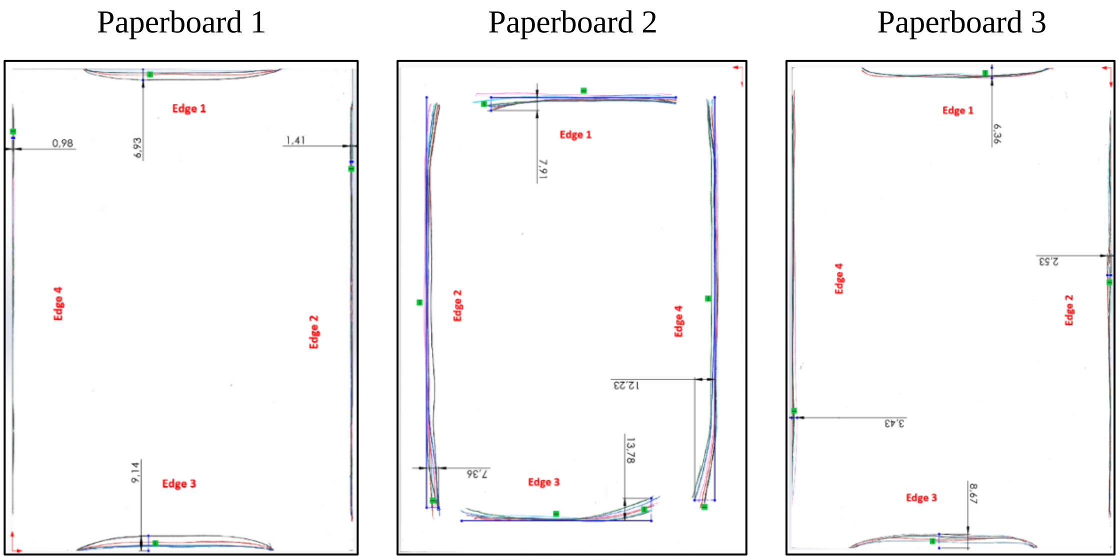


Figure 33. Curling profile of the skin-sealed packages stored in 6 °C and 75 % RH.

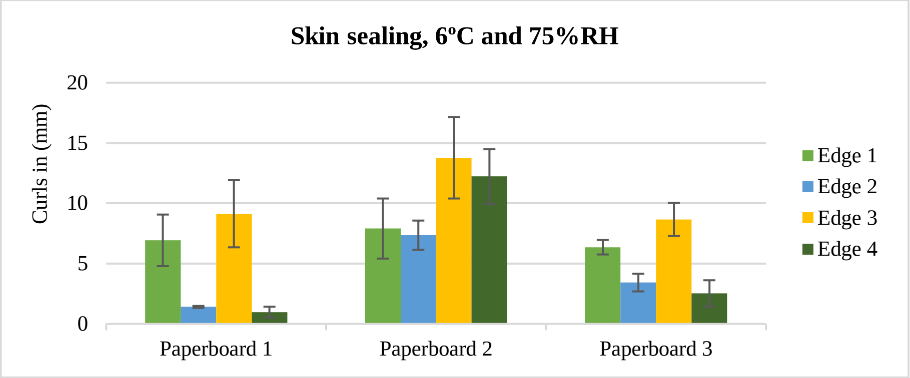


Figure 34. Curling analysis of the skin-sealed packages stored in 6 ºC and 75 % RH.

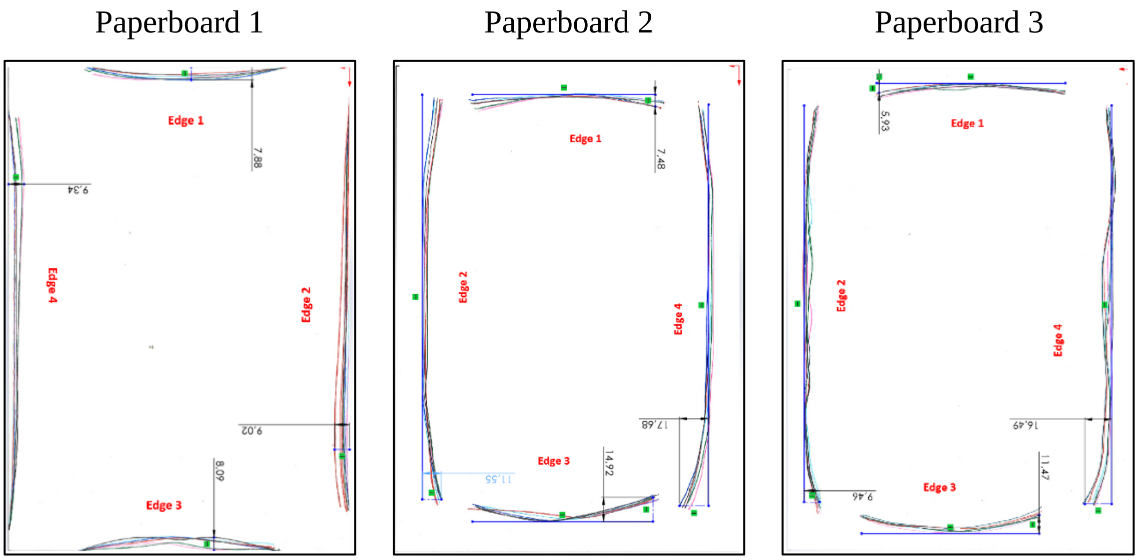


Figure 35. Curling profile of the MAP-sealed packages stored in 6 °C and 75 % RH.

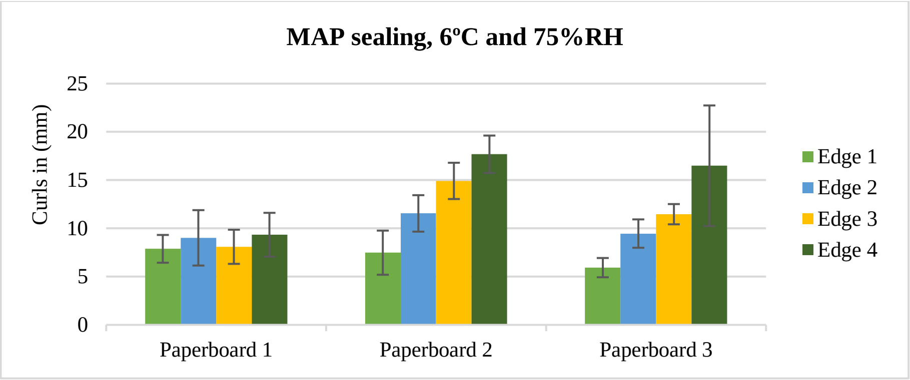


Figure 36. Curling analysis of the MAP-sealed packages stored in 6 ºC and 75 % RH.

4.1.4 Results in condition with 6 °C and 90 % RH

According to previous observations of the storage behaviour of Paperboard 1, it was anticipated that it would exhibit more significant deformation in the current condition of 90 % RH. The results monitored and presented in Figure 38 and Figure 40 confirmed this hypothesis, indicating that high humidity conditions led to increased deformation and curls. Furthermore, while the magnitude of the curls was expected to be greater in this condition, the observed trend and pattern of the curls were similar to those seen in conditions of 50 % and 75 % RH, as illustrated in Figure 37 and Figure 39.

With respect to the curls and deformations exhibited by the packages produced by Paperboard 2, a comparable pattern to that of prior conditions was observed. While the quantity of curls in skin-sealed packages in this particular condition have similarities with that of the 75 % relative humidity condition, MAP-sealed packages demonstrate greater levels of curling when compared to other conditions.

The analysis of Paperboard 3 behaviour revealed that, similar to other materials, high humidity stimulates curling. In skin-sealed packages, the observed amount of curling was lower than in packages with 75 % relative humidity (RH); however, it remained higher than detected curls in the first condition with 50 % RH. Furthermore, MAP-sealed packages followed the same trend and exhibited higher levels of curling compared to packages in other conditions.

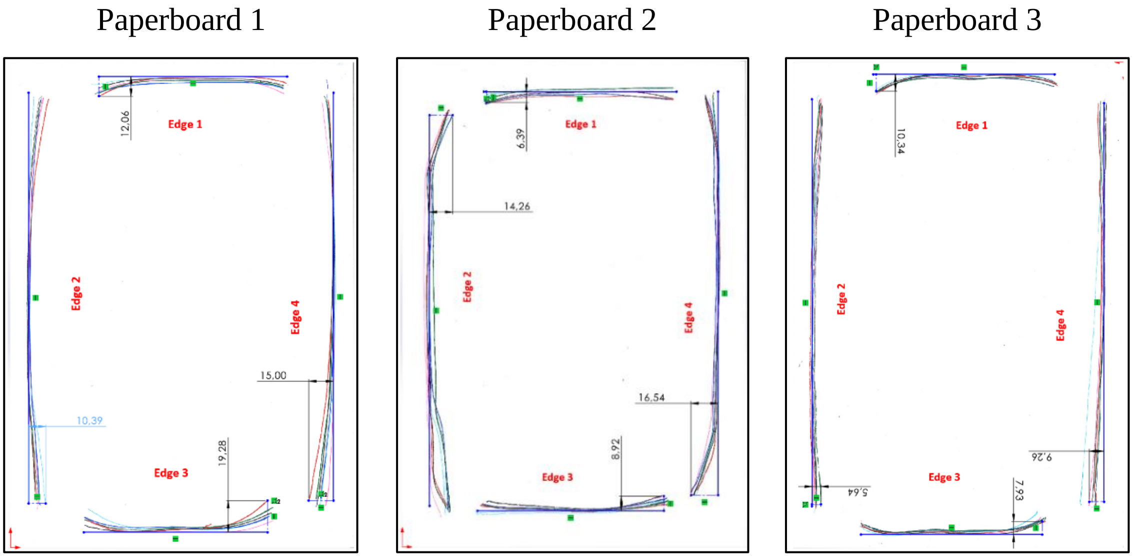

Paperboard 1 Paperboard 2 Paperboard 3

Figure 37. Curling profile of the skin-sealed packages stored in 6 °C and 90 % RH.

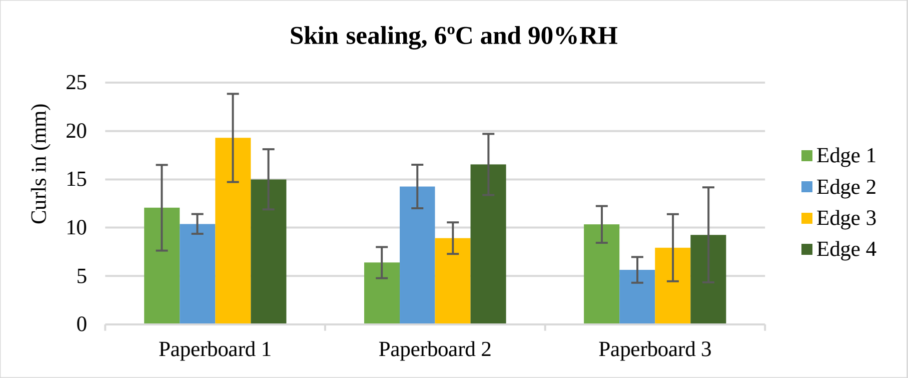


Figure 38. Curling analysis of the skin-sealed packages stored in 6 ºC and 90 % RH.

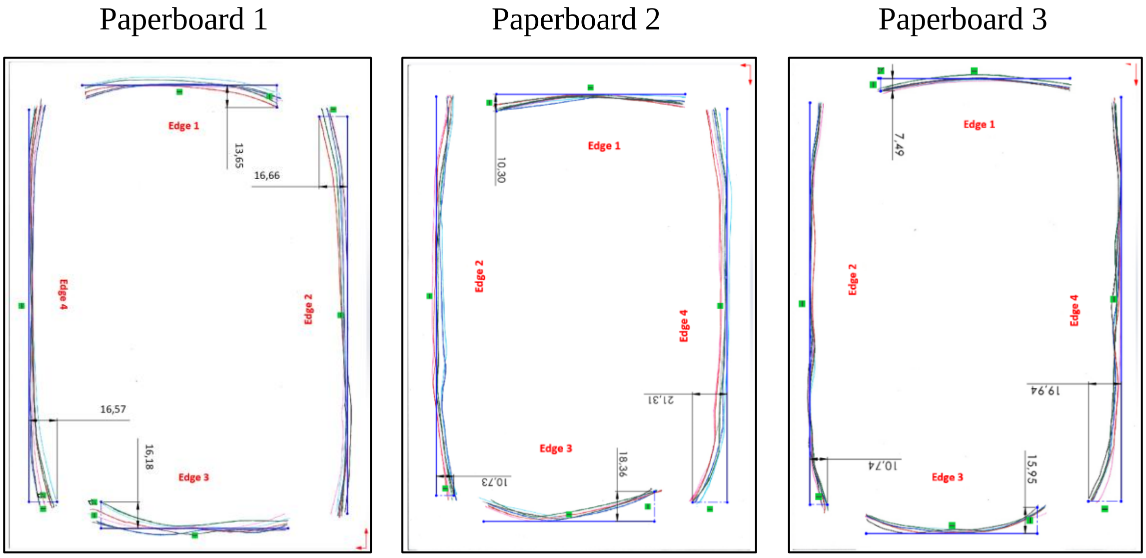


Figure 39. Curling profile of the MAP-sealed packages stored in 6 °C and 90 % RH.

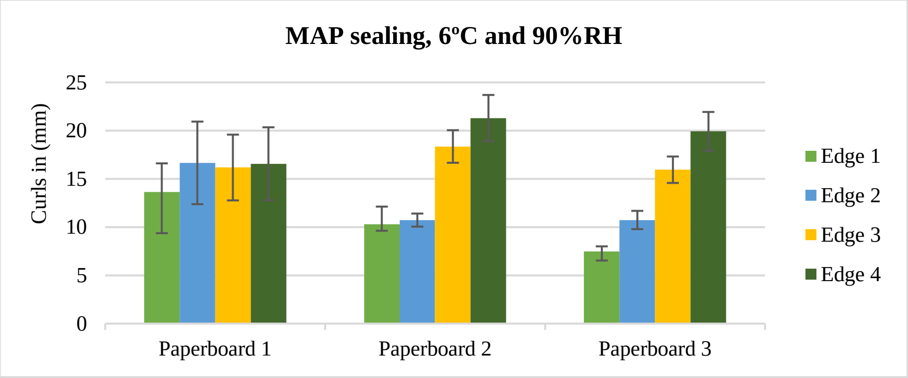


Figure 40. Curling analysis of the MAP-sealed packages stored in 6 ºC and 90 % RH.

4.2 Evaluation of tool geometry effect on storage behaviour of studied material

In this section, the influence of geometry on the curling and deformation of packages was analysed. The goal is to investigate whether the extent of curling can be further controlled by optimizing the geometry of the package. To achieve this, three different moulds were selected, as depicted in Figure 18. For a clear observation, the condition and material which have had most curls were chosen. Therefore, Paperboard 2 was utilized as the test material under the conditions of 6 ºC and 90 % relative humidity.

The results obtained from the experiments demonstrate the feasibility of reducing the curls and deformations of thermoformed trays by modifying the geometry of moulds. Mould 1 was employed throughout the experiments, and Figure 41 and Figure 42 illustrates that by replacing it with a grooved-shape mould (Mould 2) and stair-shaped mould (Mould 3), the curls can be decreased by almost two-fold. However, the pattern of the curls is similar in three different moulds.

The trays produced from Mould 1 showed the highest degree of curls, while Mould 3 produced the least amount of curls. Mould 2 produced a combination of rounded and grooved shapes and presented moderate levels of curls. The observed differences in the degree of curls between the trays can be attributed to the geometry of the moulds. Mould 1 had a larger radius than Mould 2, which could be a possible reason for the higher degree of curls observed. Furthermore, the absence of great corner radius in Mould 3 confirms the claim that the groove or stair-shape can increase the stiffness of the tray, thereby reducing curls. Comparison between Mould 2 and 3 showed that the fully grooved mould presented less curling than the combination of round shape and grooved mould.

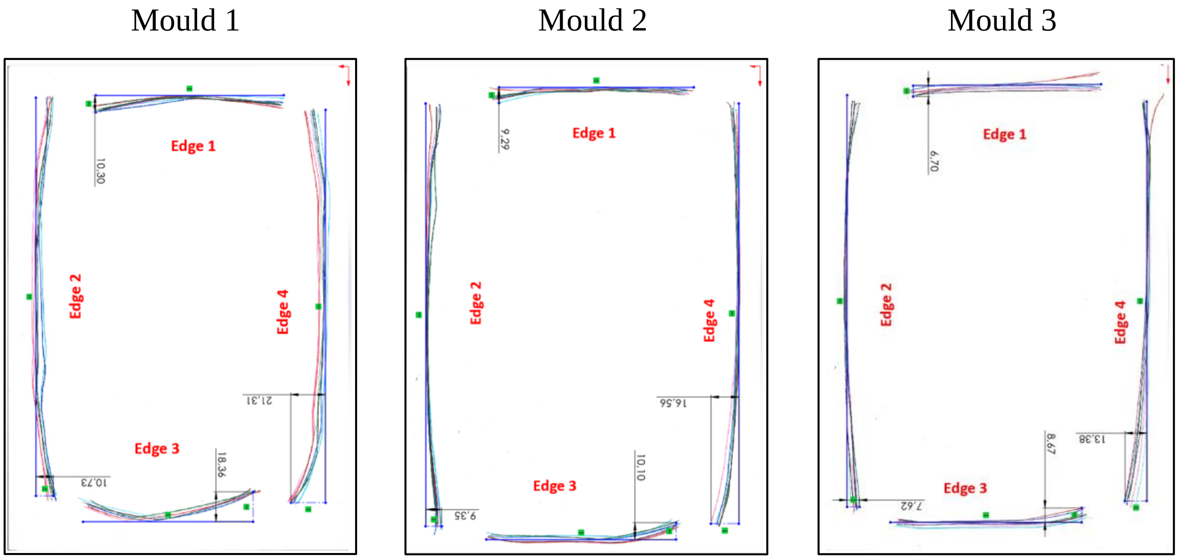


Figure 41. Curl profile of stored packages with paperboard 2 in 6 ºC and 90 % RH.

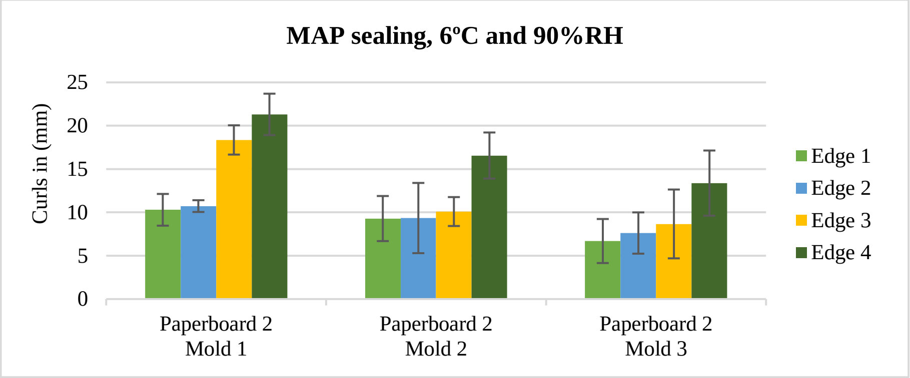


Figure 42. Curling analysis of the MAP-sealed packages stored in 6 ºC and 90 % RH.

4.3 Statistical analysis

To have a statistical analysis of the obtained data from the experiments, data analysis tool in Excel was utilized. Data analysis involves exploring, cleaning, transforming, and modelling data to extract useful information from it. Correlation, on the other hand, is a statistical technique used to measure the strength and direction of the relationship between two variables. The correlation coefficient is a number between -1 and 1 that represents the strength of the correlation, with 0 indicating no correlation, -1 indicating a perfect negative correlation, and 1 indicating a perfect positive correlation. To obtain the correlation coefficient in Excel, the CORREL function can be used. This function takes two arrays of data as input and returns the correlation coefficient between them.

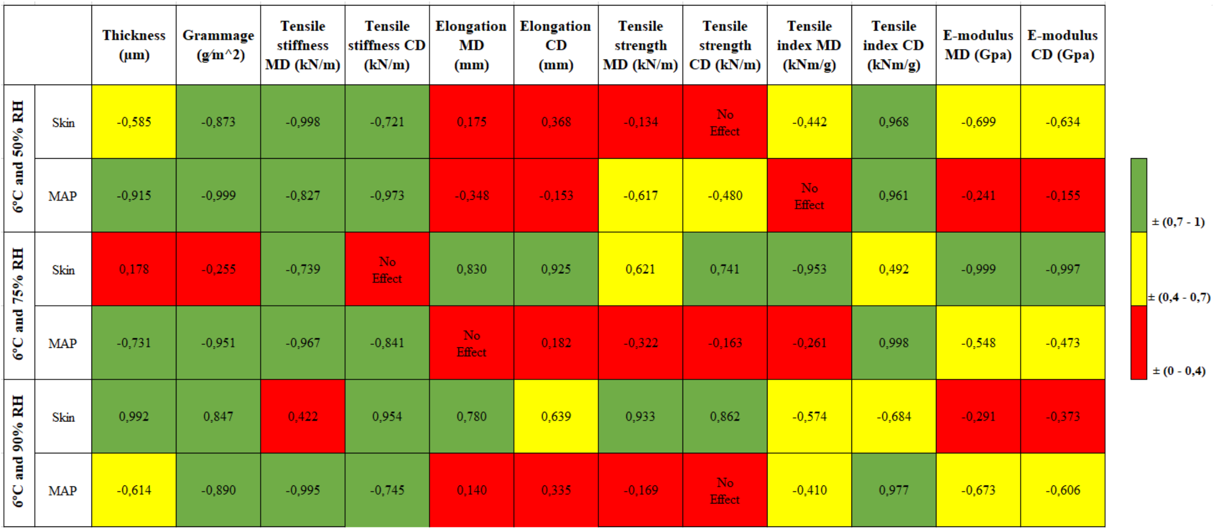
According to the collected experimental, the correlation between material properties and the curls and deformation of packages was evaluated. Thickness, grammage, and tensile properties of the materials have been conducted to this statistical analysis. Table 7 visually presents the correlations and effects of material properties on the highest observed curl of each material in each specific condition. It provides a clear and concise representation of the data, making it easily accessible for a comprehensive overview of the observed trends.

The findings from the experiments conducted indicate a clear and strong correlation between the grammage and tensile stiffness, in both the machine direction (MD) and cross direction (CD), and the formation of curls in the produced packages despite the used condition. This implies that the weight of materials and its ability to resist deformation under tension play a significant role in the curling of the packages. Furthermore, the experiments showed that the tensile strength and E-modulus of the packaging materials has only a minor effect on the curls formed in the packages. Therefore, it can be inferred that the deformation of the packages is not solely dependent on the tensile strength of the material, but also on the tensile stiffness and grammage of the materials. Also, by considering these factors it is possible to predict curls for both skin and MAP-sealed packages produced by Paperboard 1 to 3.

Based on a thorough examination and analysis of MAP-sealed packages, it was observed that these packages behave in a consistent manner in terms of the correlation between the properties of the materials used and the deformation of the packages. This means that the behaviour of the packages can be reliably predicted based on their material properties. Moreover, the analysis has also indicated that the thickness and tensile index CD of the materials used in the packages have a moderate influence on package deformation. The thickness of a material refers to the distance between its two surfaces, while the tensile index CD is a measure of the material's resistance to deformation in the cross-direction. These properties, while not as significant as tensile stiffness and grammage, can still impact the mechanical behaviour of the packages to some extent. The analysis has also revealed that the elongation and tensile strength in both directions have almost no effect on the curling of the packages. Elongation is the ability of a material to stretch without breaking, while tensile strength in both directions refers to the material's ability to withstand stretching in both the machine and cross-directions.

When it comes to skin-sealed packaging, the thickness of the material used has only a negligible impact on the curling of the packages. In fact, the relationship between thickness and curling is so slight that it can be considered insignificant. Similarly, in the case of MAP-sealed packages, tensile strength and elongation do not have any significant effect on the curling of the packages. This means that packaging manufacturers can use and optimize the forming of materials with varying levels of tensile strength and elongation without concerning the impact on the curling of the final product.

Table 7. Pearson correlation between curling and properties of materials.



		Thickness (µm)	Grammage (g/m^2)	Tensile stiffness MD (kN/m)	Tensile stiffness CD (kN/m)	Elongation MD (mm)	Elongation CD (mm)	Tensile strength MD (kN/m)	Tensile strength CD (kN/m)	Tensile index MD (kNm/g)	Tensile index CD (kNm/g)	E-modulus MD (Gpa)	E-modulus CD (Gpa)
6°C and 50% RH	Skin	-0,585	-0,873	-0,998	-0,721	0,175	0,368	-0,134	No Effect	-0,442	0,968	-0,699	-0,634
	MAP	-0,915	-0,999	-0,827	-0,973	-0,348	-0,153	-0,617	-0,480	No Effect	0,961	-0,241	-0,155
6°C and 75% RH	Skin	0,178	-0,255	-0,739	No Effect	0,830	0,925	0,621	0,741	-0,953	0,492	-0,999	-0,997
	MAP	-0,731	-0,951	-0,967	-0,841	No Effect	0,182	-0,322	-0,163	-0,261	0,998	-0,548	-0,473
6°C and 90% RH	Skin	0,992	0,847	0,422	0,954	0,780	0,639	0,933	0,862	-0,574	-0,684	-0,291	-0,373
	MAP	-0,614	-0,890	-0,995	-0,745	0,140	0,335	-0,169	No Effect	-0,410	0,977	-0,673	-0,606

🟩 ± (0,7 - 1)
🟨 ± (0,4 - 0,7)
🟥 ± (0 - 0,4)

5 Conclusions and Future work

This study investigated the storage behavior of thermoformed and heat-sealed fibre-based material. The performance of fibre-based packages can be affected by a variety of factors, including temperature and humidity. Therefore, understanding and optimizing their storage behaviour is of importance to ensure their optimal performance and functionality. The present study evaluated the storage behavior of obtained packages in three relative humidity conditions including 50 % ,75 %, 90 % at a constant temperature of 6°C. The packages were maintained in defined conditions for a period of seven days. Moreover, curling was chosen as an indicator to analysis deformation of the packages.

According to the results, the study shows that the level of humidity has a direct correlation with the occurrence of curls, with higher humidity resulting in more curls. Furthermore, it appears that humidity plays a significant role in curling of the package in comparison with temperature as evidenced by the test results. Moreover, the study reveals that skin-sealed packages exhibit slightly less curling than MAP-sealed packages. In skin-sealed packages, curls were observed primarily in the width of the package, whereas MAP-sealed packages were found to experience more curls in the length of the package. In addition. it observed that high moisture content before the thermoforming process was another important factor that increased the curls and deformation of the packages in the storage.

Upon analysis of the curl pattern presented in each edge of the package, it was observed that there were significant fluctuations and larger curls in the area of the hanging hole. This occurrence can be attributed to the reason that the hanging hole serves as a small support for the package, bearing the weight of both the package itself and the product contained within it. As the weight of the package and its contents bear down on the hanging hole, stress is generated in the surrounding material. This stress can result in greater deformation and curling, particularly in the areas closest to the hanging hole. Additionally, the hanging hole itself can create a discontinuity in the material, further contributing to the formation of curls. As the material is stretched and compressed around the hole, it can create variations in stress and strain, leading to the formation of curls and other deformations.

In order to reduce the occurrence of curls in thermoformed trays made of paperboard-based materials, modifications to the geometry of the moulds used for tray production can be made.

A study was conducted to investigate the effectiveness of different mould designs, and the results showed that the presence of grooves in the mould can be a useful method for reducing package deformation and improving tray stability. Moreover, another contributing factor to the reduction of curls is the absence of great corner radius in moulds. By implementing these modifications, the degree of curls can be significantly reduced, ultimately leading to improved package quality and reduced deformations. Despite the fact that the pattern of the curls may remain the same, the amount of curls can be significantly reduced by almost two-fold through the use of these modifications. These findings are useful for practitioners in the thermoforming industry who seek to minimize the degree of curling observed in their products.

Moreover, the study sought to examine the influence of material properties on the deformation of packages. The results indicate that the grammage and tensile stiffness of the material are key factors in the occurrence of package curls. Conversely, tensile strength was found to have a less significant impact on package deformation during storage. The finding suggests that careful consideration of material properties can greatly influence the quality and longevity of packaged products. By selecting materials with higher grammage and tensile stiffness, manufacturers can improve the structural integrity of their packages and reduce the occurrence of curls during storage.

Study findings showed that inclusion of a varnish layer adversely affected the formability of the material. A possible explanation for this is the low moisture content of the material despite conditioning at high humidity levels, indicating that the varnish serves as a barrier, preventing moisture absorption. In turn, this can affect thermoforming even when shallow forming parameters in terms of pressure and time are applied.

Overall, this thesis provided insights into the storage behavior of thermoformed and heat-sealed fibre-based materials and highlights the importance of proper storage conditions in maintaining their quality and functionality. Nevertheless, the study was limited to certain paperboard structures and storage conditions that should be taken into account when interpreting the findings. However, findings can help inform future research and development efforts in this field, as well as guide the design and implementation of sustainable and effective packaging solutions.

References

Afshariantorghabeh S, Kärki T, Leminen V. Three-dimensional forming of plastic-coated fibrebased materials using a thermoforming process. PackagTechnol Sci. 2022; Pp. 1-13. doi:10.1002/pts.2650.

Archaviboonyobul, T., Chaveesuk, R., Singh, J. and Jinkarn, T., 2020. An analysis of the influence of hand hole and ventilation hole design on compressive strength of corrugated fiberboard boxes by an artificial neural network model. Packaging Technology and Science, 33(4-5), Pp. 171-181.

Berger, Kenneth. (1969). A Brief History of Packaging. EDIS. 2003. 10.32473/edis-ae206-2002, Pp. 717-739.

Bratovčić, A., Odobašić, A., Ćatić, S. and Šestan, I., 2015. Application of polymer nanocomposite materials in food packaging. Croatian journal of food science and technology, 7(2), Pp. 86-94.

Church, I.J. and Parsons, A.L., 1995. Modified atmosphere packaging technology: a review. Journal of the Science of Food and Agriculture, 67(2), Pp. 143-152.

Das, P.S., Saha, P. and Das, R., 2018. Pharmaceutical packaging technology: a brief outline. Research Journal of Pharmaceutical Dosage Forms and Technology, 10(1), Pp. 23-28.

Deshwal, G.K., Panjagari, N.R. and Alam, T., 2019. An overview of paper and paper-based food packaging materials: Health safety and environmental concerns. Journal of food science and technology, 56, Pp. 4391-4403.

Emblem, A.N.N.E., 2012. Packaging and society. In Packaging Technology (Pp. 3-9). Woodhead Publishing.

Engelmann, S., 2012. Advanced Thermoforming: Methods, Machines and Materials, Applications and Automation (Vol. 8), Pp. 1-352. John Wiley & Sons. doi:10.1002/9781118207086.

Fadiji, T., Coetzee, C. and Opara, U.L., 2016. Compression strength of ventilated corrugated paperboard packages: Numerical modelling, experimental validation and effects of vent geometric design. Biosystems Engineering, 151, Pp. 231-247.

Fadiji, T., Coetzee, C.J. and Opara, U.L., 2019. Analysis of the creep behaviour of ventilated corrugated paperboard packaging for handling fresh produce—An experimental study. Food and Bioproducts Processing, 117, Pp. 126-137.

Franke, W., Leminen, V., Groche, P. and Varis, J., 2021. The effects of pretreatment and coating on the formability of extrusion-coated multilayer paperboard–plastic composites. Packaging Technology and Science, 34(2), Pp. 105-116.

Han, J. and Park, J.M., 2007. Finite element analysis of vent/hand hole designs for corrugated fibreboard boxes. Packaging Technology and Science: An International Journal, 20(1), Pp. 39-47.

Hanlon, J.F., Kelsey, R.J. and Forcinio, H.E., 1998. Handbook of package engineering. Handbook of package engineering. Pp. 1-700 (Ed. 3).

Hishinuma, K. (2009). Heat sealing technology and engineering for packaging. 1st ed. Pennsylvania: DEStech Publications Inc, Pp. 1-250.

Hughes, H. (2007). Food Packaging Machinery. Handbook of Farm, Dairy, and Food Machinery, Pp. 695-718.

James R, Jewitt M, Matussek H, Moohan M, Potter J (2002) Pulp and paper international facts and price book. Paperloop Publications, Brussels, Pp. 47, 166.

Jones P, Comfort D (2017) The forest, paper and packaging industry and sustainability. International Journal of Sales, Retailing and Marketing, 6 (1). Pp. 3-21.

Khwaldia, K., Arab-Tehrany, E. and Desobry, S., 2010. Biopolymer coatings on paper packaging materials. Comprehensive reviews in food science and food safety, 9(1), Pp. 82-91.

Kirwan, M.J., 2008. Paper and paperboard packaging technology, Pp. 1- 432. John Wiley & Sons.

Lamonte, R.R. and McNally, D., 2001. Cyclic olefin copolymers. Advanced Materials and Processes, 159(3), Pp. 33-36.

Larsson, P.A. and Wågberg, L., 2008. Influence of fibre–fibre joint properties on the dimensional stability of paper. Cellulose, 15, Pp. 515-525.

Leisen, J., Hojjatie, B., Coffin, D.W., Lavrykov, S.A., Ramarao, B.V. and Beckham, H.W., 2002. Through-plane diffusion of moisture in paper detected by magnetic resonance imaging. Industrial & engineering chemistry research, 41(25), Pp .6555-6565.

Leminen, V., 2016. Leak-proof heat sealing of press-formed paperboard trays, Pp. 1-73.

Leminen, V., Kainusalmi, M., Tanninen, P., Lohtander, M. and Varis, J., 2012. Effect of sealing temperature to required sealing time in heat sealing process of a paperboard tray. Journal of Applied Packaging Research, 6(2), Pp. 67-78.

Leminen, V., Ovaska, S.S.C., Tanninen, P. and Varis, J., 2015. Convertability and oil resistance of paperboard with hydroxypropyl-cellulose-based dispersion barrier coatings. Journal of Applied Packaging Research, 7(3), Pp. 91-100.

Marsh, K. and Bugusu, B., 2007. Food packaging—roles, materials, and environmental issues. Journal of food science, 72(3), Pp. R39-R55.

Martin, P.J. and Duncan, P., 2007. The role of plug design in determining wall thickness distribution in thermoforming. Polymer Engineering & Science, 47(6), Pp. 804-813.

Meka, P. and Stehling, F.C., 1994. Heat sealing of semicrystalline polymer films. I. Calculation and measurement of interfacial temperatures: Effect of process variables on seal properties. Journal of Applied Polymer Science, 51(1), Pp. 89-103.

Merabtene, M., Tanninen, P., Varis, J. and Leminen, V., 2022. Heat sealing evaluation and runnability issues of flexible paper materials in a vertical form fill seal packaging machine. BioResources, 17(1), p. 223-242.

Müller, S., and Weygand, S.M., 2016. Finite element simulation of stretch forming of aluminium-polymer laminate foils used for pharmaceutical packaging. In MATEC Web of Conferences (Vol. 80, Pp. 1-7). EDP Sciences.

Navaranjan, N., Dickson, A., Paltakari, J. and Ilmonen, K., 2013. Humidity effect on compressive deformation and failure of recycled and virgin layered corrugated paperboard structures. Composites Part B: Engineering, 45(1), Pp. 965-971.

Niini, A., Berthold, L., Müller, T., Tanninen, P., Majschak, J.P., Varis, J. and Leminen, V., 2022. Effect of Blank Moisture Content on Forming Behaviour and Mechanical Properties of Paperboard Tray Packages. Journal of Applied Packaging Research, 14(1), Pp. 1-18.

Niini, A., Leminen, V., Tanninen, P. and Varis, J., 2021. Humidity effect in heating and cooling of press-formed paperboard food packages: Comparison of storing and heating conditions. Packaging Technology and Science, 34(8), Pp. 517-522.

Ohlsson, T., Bengtsson, N., 2002. Modified atmosphere packaging in Minimal Processing Technologies in the Food Industries. Woodhead Publishing Series in Food Science, Technology and Nutrition, Pp. 61–86.

Ovaska, S.S., Tanninen, P., Saukkonen, E. and Backfolk, K., 2018. Effect of blank pre-conditioning humidity on the dimensional accuracy and rigidity of paperboard trays. Nordic Pulp & Paper Research Journal, 33(2), Pp. 348-357.

Pathare, P.B., Opara, U.L., Vigneault, C., Delele, M.A. and Al-Said, F.A.J., 2012. Design of packaging vents for cooling fresh horticultural produce. Food and Bioprocess Technology, 5, Pp. 2031-2045.

Pilchik, R., 2000. Pharmaceutical blister packaging, Part I. Pharmaceutical technology, 24(11), Pp. 68-68.

Priyadarshi, R., Deeba, F. and Negi, Y.S., 2020. Modified atmosphere packaging development. In Processing and development of polysaccharide-based biopolymers for packaging applications (Pp. 261-280). Elsevier.

Pouch, NA. Choosing the Right Hang Hole Bags for Your Product Packaging [Online]. Available at: < https://pouch.me/choosing-the-right-hang-hole-bags-for-your-product-packaging > [Accessed 4th June 2023].

Risch, S.J., 2009. Food packaging history and innovations. Journal of agricultural and food chemistry, 57(18), Pp. 8089-8092.

Robertson, G.L., 2005. Food Packaging-Principles and Practice (GL Robertson. CRC Press. https://doi. org/10, 1201(97814), Pp. 550.

Rosato, D.V., Schott, N.R. and Rosato, M.G. eds., 2001. Plastics Institute of America plastics engineering, manufacturing & data handbook (Vol. 2). Springer Science & Business Media.

Sapalidis AA, Katsaros FK, Romanos EG, Kakizis NK, Kanellopoulos NK. Preparation and characterization of novel poly-(vinyl alcohol)–Zostera flakes composites for packaging applications. Composites: Part B 2007; 38:398–404.

Seideman, S.C. and Durland, P.R., 1983. Vacuum packaging of fresh beef: A review. Journal of Food Quality, 6(1), Pp. 29-47.

Singh, J., Olsen, E., Singh, S.P., Manley, J. and Wallace, F., 2008. The effect of ventilation and hand holes on loss of compression strength in corrugated boxes. Journal of Applied Packaging Research, 2(4), Pp. 227.

Sjöström, E. and Alén, R. eds., 1998. Analytical methods in wood chemistry, pulping, and papermaking. Springer Science & Business Media, Pp. 1-328.

Spalding, M.A. and Chatterjee, A. eds., 2017. Handbook of industrial polyethylene and technology: Definitive guide to manufacturing, properties, processing, applications and markets set. John Wiley & Sons, Pp. 1381.

Suh, J.H., Ock, S.Y., Park, G.D., Lee, M.H. and Park, H.J., 2020. Effect of moisture content on the heat-sealing property of starch films from different botanical sources. *Polymer Testing*, *89*, Pp. 106612.

Tanninen, P., Lindell, H., Saukkonen, E. and Backfolk, K., 2014. Thermal and mechanical durability of starch-based dual polymer coatings in the press forming of paperboard. Packaging Technology and Science, 27(5), Pp. 353-363.

Theller, H.W., 1989. Heatsealability of flexible web materials in hot-bar sealing applications. Journal of Plastic Film & Sheeting, 5(1), Pp. 66-93.

Thorat Sachin, NA. Vacuum Thermoforming For Plastic Sheets | Advantages and Disadvantages [Online]. Available at: < https://learnmech.com/vacuum-thermoforming-advantages-and/ > [Accessed 18 March 2023].

Throne, J., 2011. Thermoforming. In Applied plastics engineering handbook (Pp. 333-358). William Andrew Publishing.

Toldra, F. (2017) Lawrie's Meat Science (8th Edition). 8th edition. Cambridge: Elsevier, Pp. 1- 730.

Troughton, M. J. (2008) Handbook of plastics joining a practical guide. 2nd ed. Norwich, NY: William Andrew, Pp. 1-600.

Vähä-Nissi, M, Rintanen, J & Savolainen, A 1999, Tailoring Barrier Dispersion Coatings. in Pita Coating Conference, Coating for Performance in Print and Packaging, Conference Proceedings, EICC Edinburgh, 3rd & 4th MARCH 1999. Pp. 63-72.

Vishtal, A. and Retulainen, E., 2012. Deep drawing of paper and paperboard: The role of material properties. BioResources, 7(3), Pp. 4424-4450.

Vishtal, A., Hauptmann, M., Zelm, R., Majschak, J.P. and Retulainen, E., 2014. 3D forming of paperboard: The influence of paperboard properties on formability. Packaging technology and science, 27(9), Pp. 677-691.

Vishtal, A., Retulainen, E., Khakalo, A. and Rojas, O. (2015) Improving the extensibility of paper: Sequential spray addition of gelatine and agar. Nordic Pulp & Paper Research Journal, Vol. 30 (Issue 3), Pp. 452-460. https://doi.org/10.3183/npprj-2015-30-03-p452-460

Yamaguchi, N., 1990. Vacuum packaging. In Food Packaging (Pp. 279-292). Academic Press.

Yuan, C.S. and Hassan, A., 2007. Effect of bar sealing parameters on OPP/MCPP heat seal strength. Express Polym Lett, 1(11), Pp. 773-779.

Zhang, Z., Britt, I.J. and Tung, M.A., 2001. Permeation of oxygen and water vapor through EVOH films as influenced by relative humidity. Journal of Applied Polymer Science, 82(8), Pp. 1866-1872.

ZY Automation, NA. Thermoforming Machines [Online]. Available at: <https://www.zyautomation.com/products/Thermoforming-machines.html > [Accessed 18 March 2023].