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Packaging Materials for Cured Meat Products: a Sustainability Challenge

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Summary

Conventional packaging for cured meat products relies on fossil-based, multi-material packaging systems due to their excellent functional properties. However, these materials pose sustainability challenges, because of their origin from non-renewable sources and their non-recyclability on a large scale, contributing to massive plastic waste generation. This Ph.D. project focuses on investigating industrial-level packaging solutions for cured meat products with improved circularity and sustainability and on developing a holistic approach to evaluating the sustainability of food packaging solutions.

The study is based on an in-depth analysis of current packaging trends in the market and highlights innovative solutions for cured meat packaging. Based on the information gained after a literature research, conventional and alternative packaging solutions for cured meat products were selected. In this context, nine packaging materials, including tray and lid films, for chilled-MAP products with a potential improvement in sustainability were investigated. In particular, the materials selected were conventional plastic multi-materials, conventional plastic multi-material packaging with a weight plastic reduction, potential recyclable mono-material solutions, i.e., mono-PET and paper-based systems (coupled with a PE-EVOH-PE barrier layer), and bio-based polymers. Overall, the two mono-materials demonstrated the best compromise between the potential sustainability based on the literature and European environmental policies and their functional properties performances (i.e., acceptable mechanical strength and excellent oxygen and carbon dioxide properties). Based on these results, two life cycle assessment (LCA) studies were carried out to investigate the environmental profiles of conventional multi-material and potential recyclable mono-material packaging designed for packaged sliced cooked ham (mono-PET and paper, respectively). Results showed that mono-materials have higher environmental impacts due to the shorter shelf-life compared to the conventional solution, which leads to a greater amount of potential food waste generation. To date, conventional multi-material packaging, despite being a not recyclable complex system, offers the best efficiency in terms of barrier properties and thus adequate shelf-life and reduced food waste.

This Ph.D. project highlighted the relevance of adopting a packaging eco-design approach that should involve collaboration between stakeholders, to create packaging that balances functional efficiency, reduced waste, and minimal environmental impact.

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General introduction and research objectives

1. General introduction

Over the past decades, the global demand for packaged food has surged due to changing lifestyles, urbanization, and the growing need for ready-to-eat or easy-to-prepare meals (Aday & Yener, 2014). The global packaged food market is expected to grow from its 2023 valuation of USD 4,079,495 million to an estimated USD 6,211,619 million by 2033 (FMI, 2023). Food packaging is widely acknowledged for providing numerous benefits throughout the food supply chain to stakeholders for a wide range of foodstuffs categories, including fresh and chill food, ready-to-eat, dairy, and confectionery products (Trubetskaya et al., 2022). These advantages include extended shelf-life and reduction of food waste, ease of use and portioning, labeling and traceability, logistics and transport, and marketing and communication (Ahmed et al., 2005). However, the rapid expansion of this market has also raised concerns about its sustainability. In particular, packaging environmental implications are mainly associated with its manufacturing which causes raw materials depletion and emissions (Arfelli et al., 2024). The current applied linear production model, composed of four macro areas, i.e. take-make-use-dispose which leads to a great waste pollution (Marino & Pariso, 2016), prompting the industry to seek more sustainable solutions (Pauer et al., 2020). Therefore, it is essential to redesign food packaging in a more environmentally responsible manner according to the principles of the circular economy (Oloyede et al., 2021; Herrmann et al., 2022; European Commission, 2020). In order to minimize packaging's environmental impact throughout the entire life cycle, emphasizing less use of raw materials and waste reduction with reusable, recyclable, recycled packaging solutions are the main targets for the European environmental policies (European Commission, 2020). Among packaged foodstuffs, cured meats are increasingly consumed as packaged food combined with a modified atmosphere. In this context and thanks to the collaboration with an international meat company, "Parmacotto", this products category has been selected. Most of the cured meats are ready-to-eat products, and as example, cooked ham, sausages, bacon, and bologna fall in this category (Guerrero-Legarreta et al., 2014). Several processes, such as curing, heat treatment, smoking, salting, seasoning, drying, pickling, extraction, extrusion, or a combination of these processes are used during the production of cured meat. In particular, cured meats are characterized by the application of a curing mixture, containing sodium and/or potassium salts of nitrates and nitrites in the ingredients list, which is capable of inhibiting the growth of bacteria (Guerrero-Legarreta et al., 2014). Cured meats are O_2-sensitive food, where oxygen in the packaging headspace is the key factor of cured meat deterioration, resulting in either the oxidation of its components and/or spoilage by aerobic microorganisms (Smiddy et al., 2002). Overall, these products are very perishable food and sensitive to deterioration phenomena due to the presence of moisture, fat, and protein, which mainly lead to microbial spoilage, fat oxidation, and color changes (Figure 1) (Toldrà, 2008). Therefore, packaging plays a crucial role, especially acting as an effective oxygen barrier, in maintaining the quality, flavor, and freshness of cured meat products, thus reducing quality depletion, and ensuring the longest possible shelf-life of these products.

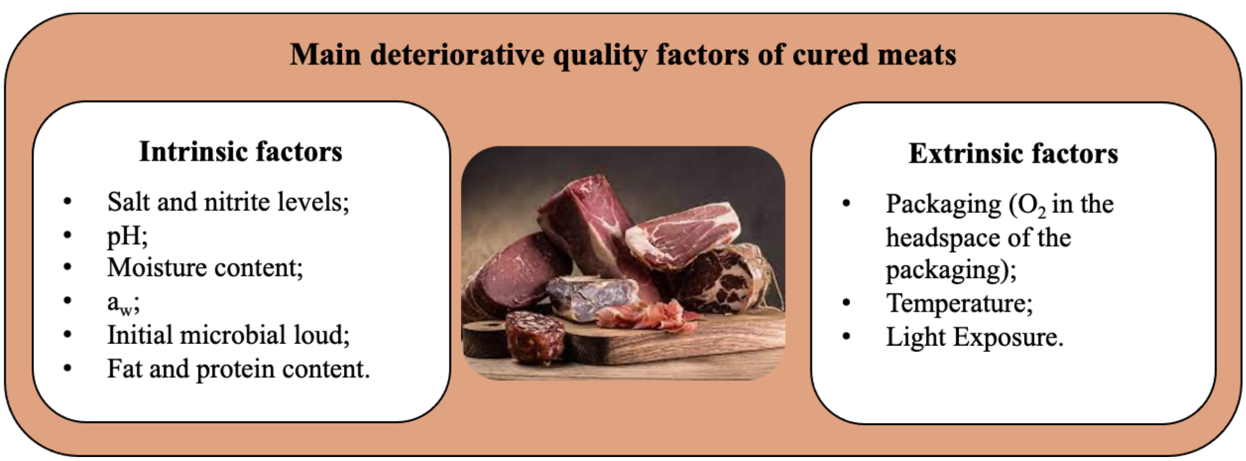

Figure 1. Main intrinsic and extrinsic factors affecting the quality of cured meats (Toldrà 2008; Dominguez et al., 2019).

Packaging materials for cured meat products must provide the required gas and water vapor barrier characteristics together with good sealing properties to maintain the vacuum or the modified atmosphere inside the package.

Conventional packaging for cured meat products typically involves a combination of modified atmosphere packaging (MAP) and a sealed two-component lid/tray system. This system usually comprises multiple joined plastic material layers, such as low-density polyethylene (LDPE), polyamide (PA), polypropylene (PP), polyethylene terephthalate (PET), and ethylene-vinyl-alcohol (EVOH) (Seier et al., 2022; McMillin, 2017). Plastic polymers possess all the techno-functional properties required for such perishable products as cured meats, including optical, sealing, mechanical and barrier properties (Bauer et al., 2021). However, all these individual layers involved in multi-material packaging cannot be mechanically and/or chemically recycled in an economically viable manner using current industrial sorting techniques (CEFLEX, 2020). This non-recyclability, which leads to an inevitable pollution generation, together with the plastic polymers manufactured from fossil fuels, pose sustainability concerns regarding the overall environmental impact of multi-material plastic packaging (Seier et al., 2022; Walker et al., 2020). Ideally, sustainable packaging is designed to be safe for both the environment and human health, aiming for a circular production model (Nguyen et al., 2020; Dorney et al., 2023). In Europe, the European Strategy for Plastics, the Circular Economy Action Plan, and recent updates on Packaging and Packaging Waste Regulation highlight the application of more sustainable solutions (European Commission, 2018; European Commission, 2020; European Union, 2024). In particular, the environmental challenges placed by food packaging must be addressed by introducing alternative solutions that include reducing overpackaging and the complexity of packaging (e.g., reducing layers in multi-material solutions), use of recycled and recyclable materials, and bio-based materials with compostable/biodegradable end-of-life (European Union, 2024; European Commission, 2018; European Commission, 2020). However, especially for meat sector and perishable products in general, food quality and safety should be the primary aspect for sustainable packaging to consider, as the environmental impact of the food waste is significantly higher than that of the packaging (Arfelli et al.,2024; Casson et al., 2022; Matar et al., 2021). Therefore, following an eco-design approach that aims to apply sustainable packaging solutions to minimize its environmental impact throughout the entire life cycle, all the aspects of food packaging must be considered to provide a full picture of its sustainability (Molina-Besch et al., 2019; Pauer et al., 2019). The most used tool to measure the sustainability of a system and/or a process is the Life Cycle Assessment (LCA), which is a method for assessing the whole packaging sustainability. LCA is a tool for evaluating emissions and resource use across a product's entire life cycle (i.e., raw material extraction, production, retail/distribution, household, and end-of-life), by linking these emissions and resource flows to potential environmental impacts (ISO 2006a, b). All these phases are called the direct effects of packaging's environmental impact. Moreover, LCA allows the inclusion of indirect effects of packaging, relating the shelf-life with the probability of potential food waste (PFW) (Gutierrez et al., 2017). Shelf-life inclusion permits the evaluation of the protection capacity of food packaging, which can reduce or not reduce food waste generation during retail/distribution and household stages (Gutierrez et al., 2017). Only recently LCA studies included the indirect effect of food packaging to assess the whole sustainability of fresh meat, cheese, and confectionary food products (Dilkes-Hoffman et al., 2018; Casson et al., 2022; Gutierrez et al., 2017). All studies highlighted food waste as a critical issue, emphasizing that reducing it is a key design consideration. Consequently, the indirect impact of food waste is becoming increasingly important in fully assessing the sustainability of food-packaging unit systems.

However, to the authors' knowledge, no studies have been conducted on packaging designed for cured meat products packaged in MAP. For these reasons, the investigation of more sustainable solutions for packaging specifically for cured meats must consider multiple aspects, from functionality to effective sustainability, considering both direct and indirect effects.

2. Research objectives

This Ph.D. project addresses the critical need for sustainable packaging solutions in the cured meat industry. The overall objective of this thesis was to explore and investigate industrial-level packaging solutions that enhance circularity and environmental performance without compromising the functional integrity required to preserve product quality. Moreover, a holistic packaging eco-design approach to support and guide the application of more sustainable packaging solutions has been developed.

The specific objectives of the research project conducted in the thesis are (figure 2):

- To offer a comprehensive overview of current market trends in packaging and innovative solutions for cured meat, with an in-depth analysis of the current state of cured meat packaging that can guide the industry and other key stakeholders towards reduced resource use and waste.

- To investigate the most important functional properties of conventional multilayer, multi-material and alternative packaging with improved sustainability specifically used for modified atmosphere (MAP) and chilled food products.

- To assess the environmental impact, using Life Cycle Assessment (LCA), of two packaging solutions for sliced cooked ham: a conventional multi-material structure and an alternative mono-material option, both incorporating a modified atmosphere. Alongside the direct environmental impact of the packaging systems, the potential food waste (indirect effects) was also analyzed. Furthermore, a sensitivity analysis was conducted to examine the impact of recycling the packaging compared to conventional end-of-life (EoL) treatments such as landfill, incineration, and open burning.

- To investigate and assess the environmental impact, through LCA, of a multi-material system and two different types of paper-based packaging (direct environmental impact), for sliced cooked ham, also considering the environmental impact of potential food waste related to the different shelf-lives (indirect effects).

A schematic representation of the chapters within this thesis and their interlinkages is presented Figure 2.

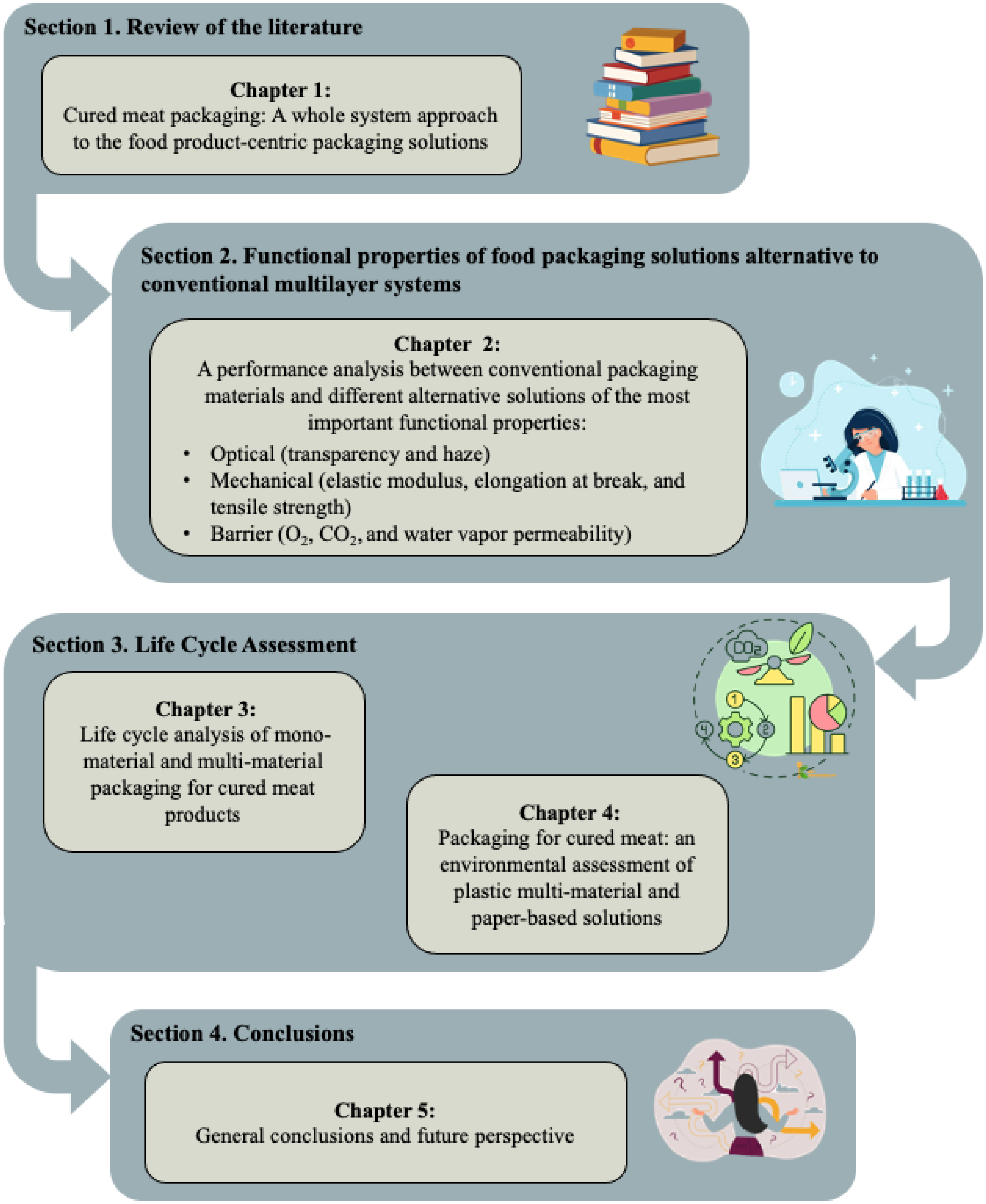

Figure 2. A graphic representation of the sections and chapters within the Ph.D. thesis.

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Chapter 1

Cured meat packaging: A whole system approach to the food product-centric packaging solutions

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1. Introduction

The global packaged food market, valued at $ 1.9 trillion in 2020 and projected to reach $ 3.4 trillion by 2030 (Kan et al., 2022), has raised environmental and health concerns over the past decades due to the constantly increasing of single-use plastic waste, mostly made from fossil-based polymers, despite the measurements and efforts made at global and EU level toward recycling more and landfilling less (European Parliament, 2023; World Economic Forum, 2021; European Commission, 2020). One of the products largely consumed as packaged food is processed meat, which possesses worldwide a large market, and is estimated to increase from 523 US $ billion to 737 US $ billion between 2020 – 2026 (Godfray et al., 2018). This expansion is also supported by the steady increase in the amount of meat produced in Europe, the USA, Asia, and China, which has reached about 65, 48, 152, and 92 million tons of production in 2021, respectively (FAOSTAT, 2023). In particular, in the USA, processed meat products represent 22% of meat intake, while in Europe, available data has noted the consumption over the recommended guidelines for adults (i.e., no more than 500 g of red and processed meat per week) (Hong et al., 2023; European Commission, 2021). Another example is Italy, where packaged cured meat products have undergone rapid sales with an increase of cured meat products sold (cooked hams, dry hams, salami, etc.) from 1093 tons to 1169 million tons (+ 7.0%) in 2021 (ASSICA, 2022).

The packaging materials commonly used for meat products are traditional petroleum-based plastics, including polyethylene terephthalate (PET), polyethylene (PE), polypropylene (PP), polyamide (PA), ethylene-vinyl-alcohol (EVOH), polyvinylchloride (PVC) or polyvinylidene chloride (PVDC) (McMillin, 2017). These plastic materials are low cost, lightweight, long-term durable, and meet the needs for the preservation of a broad range of food products from high gas and water vapor barriers to good mechanical strength and thermal stability. Further, they are easy-to-process materials and can readily be converted into targeted shapes such as pouches, films, and trays (Gil & Rudy, 2023). However, these structures are not appealing from the circular perspective of post-consumer packaging waste as they are assembled from non-renewable sources, such as fossil fuels and natural gas, and the recycling process is still an open issue due to challenges with layers separation (Horodytska et al., 2018). Today's early-stage emerging technologies for recycling post-consumer multilayer, multi-material plastic packaging waste may become part of the solution, however further research is needed to validate them (Tito et al., 2023; Laredo et al., 2023).

The European Union (EU) Packaging and Packaging Waster Regulation (PPWR) adopted in April 2024 (European Union, 2024) has placed a set of key emphases on safer and more sustainable packaging systems, by requiring all packaging to be recyclable, minimizing the presence of harmful substances, avoiding unnecessary packaging, boosting the uptake of recycled content, and setting up reuse, return and refill systems. Similar regulations have been implemented in UK, South Korea and Australia but to a varying extent, while USA has not banned the single-use plastics nationwide, but several states have implemented regulations (Thapliyal et al., 2024). With these ambitious goals, a substantial transition must take place towards zero waste principles that require a detailed design of the packaging to ensure a balance between packaging performance, food quality and safety, and circularity or sustainability. Although plastic packaging waste is a contributor to the carbon footprint, food waste indeed contributes more than plastics and the impact of food and packaging needs to be assessed together throughout the entire supply chain from the sources up to disposal and the end-of-life cycle. The focus should be to prevent waste from being created in the first place, maintain the product in use as long as it is compliant with the requirements of food contact, dispose of it when it can no longer be used, and manage the waste efficiently and safely (Dörnyei et al., 2023). This approach can only resolve waste bottlenecks by establishing truly sustainable and circular strategies.

Over the last few years, consumers' awareness and understanding of sustainability challenges have significantly increased, and consumers are continuously expecting products and their related packaging with low environmental impact and high sustainability features, including recyclability, reusability, and compostability at the end-of-life together with the incorporation of recycled materials in the packaging and elimination of over-packaging (Tachie et al., 2023; Otto et al., 2021). In particular, over-packaging has led to consumer dissatisfaction within the sustainability context and become a global issue for German, Danish, Slovakian, and Spanish consumers (Toràn-Pereg et al., 2023; Hermann et al., 2022).

This review provides a comprehensive overview of the currently used conventional packaging and recently adopted, or in-progress sustainable packaging alternatives specifically designed for cured meat products. The main classes of cured meat products available on the market (dry- and wet-cured products), including the processing technologies and the variables responsible for their quality decay are discussed and a detailed elaboration about the status quo in processed meat packaging to improve sustainability in the sector has been provided.

2. Cured meat products

2.1. Category definition

The most comprehensive meat definition and differentiation are given in EU Regulation 853/2004, which is divided into classes: i) fresh meat, ii) meat preparation, and iii) meat product. Fresh meat is defined as meat that has not undergone any preserving process other than chilling, freezing, or quick-freezing, including meat which is vacuum-wrapped or wrapped in a controlled atmosphere. Meat preparation indicates fresh meat, including the one reduced to fragments, with the addition of foodstuffs, seasonings, or additives, or meat undergone processes insufficient to modify the internal muscle fiber structure and thus eliminate the characteristics of fresh meat.

Finally, meat products include products resulting from meat processing, including heat treatment, smoking, salting, seasoning, drying, pickling, extraction, extrusion, or a combination of such processes typical in processed meat products (European Commission, 2004b; European Commission, 2004c).

Within the meat product category, cured meat covers a wide number of meat products, highly influenced by the country of origin and representing a large part of the meat products on the European market, especially in the Mediterranean countries (Flores & Toldrá, 1993). Cured meat products can be categorized into two groups: dry and wet-curing (Toldrà, 2008) (Figure 1). The main technological process to produce these products is the use of a curing mixture, composed of bacteriostatic compounds, such as sodium chloride and sodium nitrite but also spices such as onion, garlic, and pepper, to improve quality, ensure safety, and extend the shelf-life (Guerrero & Chabela, 1999).

The dry-curing process involves i) the addition of salt and/or nitrite/nitrate on the surface of an entire piece, ii) the direct mixing of the aforementioned ingredients with the mince, or iii) the soaking step with a brine mix. All these products, which do not undergo thermal treatment, can be smoked and aged for different periods (up to years) (Moschopoulou et al., 2019). Some examples of this category are dry-cured ham, dry-fermented sausages (salami), and bacon (Italian speck). The wet-curing process consists of i) injecting fresh meat with a curing solution, ii) soaking the entire piece of meat into the curing brine, or iii) mincing with the brine to form a batter. After the curing process, meat products undergo heat treatment, and eventually smoking steps (Munekata et al., 2022; Moschopoulou et al., 2019). Cooked ham, "Frankfurts", and "Bologna" (Italian Mortadella) represent the main products in this food category (Toldrá, 2008).

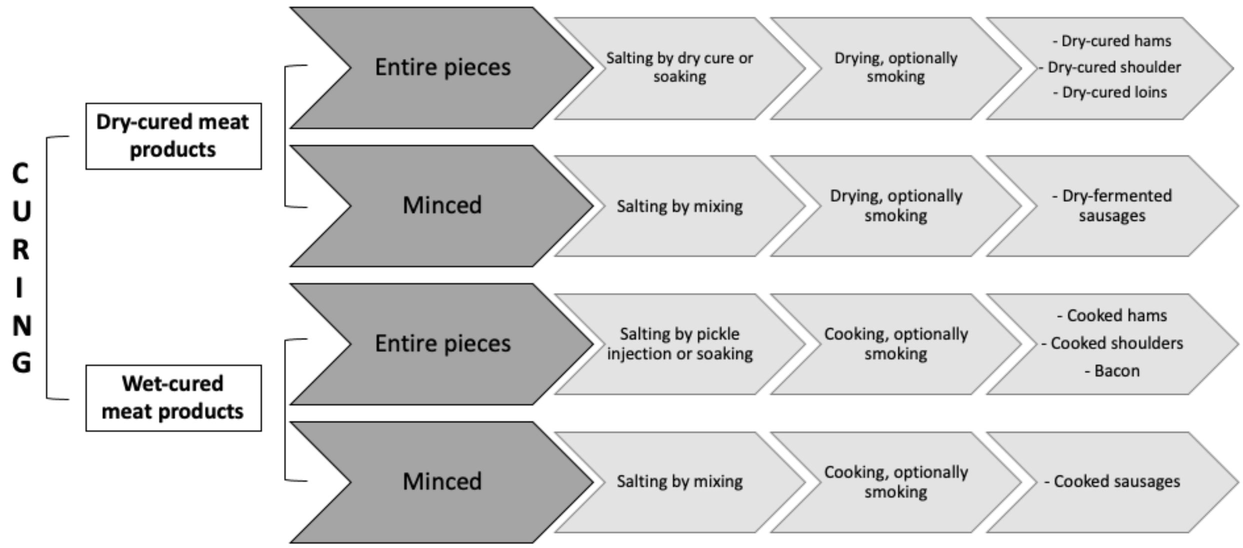

Figure 1. Classification of the most important cured meat products and the main differences between dry- and wet- curing (adapted from Toldrá, 2008).

2.2. Main factors affecting cured meat products during storage

Intrinsic as well as extrinsic variables influence the quality of food and thus its shelf-life. Intrinsic factors include, amongst others, pH, water activity (a_w), initial microbial flora, and nutrient content, while extrinsic factors are related to the packaging system and surrounding environment. Generally, the deterioration of meat products is caused by three main factors: microbial spoilage, oxygen, and light exposure (Sørheim et al., 2017).

Microbial spoilage: Cured meat products are very sensitive to microbial spoilage, being an excellent growth substrate for a variety of microbiome (bacteria, yeast, and molds), including also pathogens (Dave & Ghaly, 2011). The microbiology stability of cured meat products is intrinsic and extrinsic factor-dependent, therefore associated with the product's composition, storage conditions (temperature and light exposure), and packaging system, i.e. modified atmosphere packaging (MAP), or vacuum packaging (VP) (Raimondi et al., 2019; Vasilopoulos et al., 2008).

The dominant microbiome of cured meat products in a modified atmosphere stored at refrigerated temperature is constituted by lactic acid bacteria (LAB) since they are not affected by nitrite addition (Samelis et al., 2000; Audenaer et al., 2010) or microaerophilic conditions thus becoming the main responsible for microbial spoilage and causing a decrease in pH, gases and slime production, and off-flavors formation (Borch et al., 1996; Guerrero & Chabela, 1999). In cured and cooked meat products under MAP conditions, the lactic flora is mainly represented by Lactobacillus spp. (i.e., *L. sake* and *L. curvatus*) (Dykes & Von Holy, 1994; García-Esteban et al., 2004). In detail, several studies referred to a preferable presence of psychrotrophic lactic acid bacteria, such as *Leuconostoc carnosum*, *Leuconostoc gelidum*, *Lactobacillus sakei*, *Lactobacillus curvatus*, *Carnobacterium divergens*, *Carnobacterium maltaromaticum*, which represent predominantly found microorganisms at the end of the shelf-life in cooked ham (Raimondi et al., 2019). On the other hand, in dry-cured products, *Brochothrix thermosphacta*, *Moraxella spp*., *Psychrobacter spp*., and *Pseudomonas spp*., as well as yeasts, are found (Dowdell & Board, 1968; Borch et al., 1996). It is well known that the combinational impact of MAP and cold storage can help in maintaining microbial safety, as well as improve the quality, and thus increase shelf-life. For example, a modified atmosphere with high concentrations of CO_2 in cured meat products block the growth of pathogenic bacteria such as *Staphylococcus aureus*, *Salmonella spp*., *Escherichia coli*, *Yersinia enterocolitica* and *Listeria monocytogenes* (Parry, 2012).

Lipid oxidation: Lipids are responsible for many desirable characteristics of cured meat products since they influence the flavors and contribute to improving the textural attributes. However, lipid oxidation, which covers enzymatic lipid oxidation (i.e., lipoxygenase), photo-oxidation (Domínguez et al., 2019) and iron catalyzed oxidation, is, after microbial growth, the main cause of quality deterioration in meat products (Baele et al., 2020). Despite the presence of nitrites capable of ensuring antioxidant protection, cured meat products are also characterized by processes that can promote oxidation, i.e. aging, comminuting, slicing, cooking, and fat addition (Goethals et al., 2020). Lipid oxidation is a very complex phenomenon that includes a multitude of reactions where one is concatenated with the other and oxygen acts as the initial trigger factor in a triplet electronic state. Primary lipid oxidation products are generally hydroperoxides which are odorless and tasteless. However, the secondary oxidation products generated from hydroperoxides negatively influence all the aroma perception, resulting in undesirable sensorial attributes, such as rancid odors and off-flavors, texture, and color changes. It is important to note that lipid oxidation causes a reduction in the nutritional value of meats, due to the loss of essential fatty acids and vitamins and the production of multiple toxic compounds (Domínguez et al., 2019; Purrinos et al., 2011; Lonergan et al., 2019).

Oxidation can also occur through an enzyme-mediated mechanism. This phenomenon is caused mainly by lipoxygenase thanks to an active site capable of bonding and reacting with oxygen, creating hydroperoxides too (Domínguez et al., 2019). Iron acts as a catalyst for lipid oxidation by participating in redox reactions that generate reactive oxygen species and which in turn trigger the peroxidation of polyunsaturated fatty acids (Minotti & Aust, 1987; Flores, 2018). In addition, light can also be a triggering factor causing lipid oxidation in meat products and this will be further explored in the following paragraph (Böhner et al., 2014; Baele et al., 2020).

Changes in color: Color is the most important parameter from a consumer acceptability viewpoint and is considered a quality indicator that influences purchase in the retail environment (Pateiro et al., 2019). Color stability of cured meat packaged under modified atmosphere conditions is influenced by a complex combination of the residual O_2 in the headspace of the package, product to headspace volume ratio and light exposure in ultraviolet and visible spectra at the display (Møller et al., 2003; Bohner et al., 2014). Nitrosylmyoglobin, (MbFe(II)NO) and nitrosohemochrome pigments that are responsible for the color of uncooked dry-cured and cooked wet-cured meat products, respectively, are both photo- and oxygen- sensitive (Parra et al., 2012). This oxidative process can be initiated by light, particularly at 420, 545, and 575 nm across the excitation of singlet sensitizer as myoglobin or hemoglobin by absorbing light energy (Møller et al., 2003; Domínguez et al., 2019). Photo-oxidation of nitrosyl myoglobin or nitrosohemochrome leads to the generation of denatured metmyoglobin, which has a pro-oxidative ability and creates a brown-grey color to the product (Baele et al., 2021). Photo-oxidation is a faster reaction, even more than auto-oxidation and in fact, discoloration of illuminated cured meat products can take place during the first 6 – 24 hours of illumination (Pateiro et al., 2019; Bohner et al., 2014). For this reason, packaging capable of absorbing UV-light could help to protect these products against quality decay (Pateiro et al., 2019; Bohner et al., 2014). In particular, Baele et al. (2021) reported that 0.15% of oxygen was the highest acceptable amount of O_2 at the time of illumination to prevent discoloration of packaged cured cooked ham (Baele et al., 2021). In fact, in cured cooked meat products when exposed to typical refrigeration light, even small amounts of oxygen (0.1 – 0.5%) in the headspace of the package cause a color change from fresh pink to grey within 6 to 8 hours (Møller et al., 2000; Larsen et al., 2006). Hence, the amount of oxygen available in the package for pigment oxidation is crucial to the color stability of cooked meats. In addition, Møller et al. (2003) reported that the headspace volume ratio plays a significant role in color stability since the higher the volume ratio, the higher the amount of oxygen available for oxidation processes in the packages. For these reasons, oxygen is generally not included in the gas mixture of cured meat products and its removal can help to maintain the cured color longer, preventing browning, greying, and fading (Parry, 2012).

3. Cured meat specific packaging systems

3.1 Packaging materials and technologies

The selection of cured meat packaging materials is crucial to reduce quality depletion and ensure the longest possible shelf-life of the products. Packaging materials must provide a required gas and water vapor barrier together with good-sealing properties to maintain the modified or desired atmosphere inside the package, and need to be mechanically robust, tough and ductile, and optically desirable (depending on the product, transparency for high product visibility or UV- or light barrier at specific wavelengths) (Taherimehr et al., 2021; Kim et al., 2014; Bauer et al., 2021). Packaging must be designed to ensure a desired shelf-life maintaining high-quality characteristics of the product as well as for easy opening and high product visibility (Parry, 2012). Above and beyond all other considerations, given that new sustainable materials and approaches are recently centralized in the packaging ecosystem, a critical facet of this priority lies in the safety of the food product during the given shelf-life (Dörnyei et al., 2023), avoiding the migration of intentionally and non-intentionally added substances from packaging (i.e., bisphenol A, phthalates) into food and must comply with a range of regulations (European Commission, 2004a; European Commission, 2006). In this section of the review, the role of packaging technologies (e.g., MAP, VP) and materials specifically used for cured meat products are discussed in detail.

Over the last decades, the food industry has developed several packaging technologies to extend the shelf-life of perishable food such as cured meat products and cheese. These technologies include vacuum, which evacuates air from within a package to prevent contamination and evaporative losses, and MAP, which modifies the package environment during storage with specific gases (García-Esteban et al., 2004; Kandeepan & Tahseen, 2022). More specifically, in vacuum technology, high gas and water vapor barrier film is preferred and generally adheres closely to the product (Santos et al., 2005).

Modified atmosphere packaging is based on the use of a specific gas mixture (CO_2, N_2) in the headspace of packaging, and is recognized as a well-established and consumer-approved solution for the shelf-life extension of cured meat products (Parry, 2012; Bauer et al., 2021). The main technical role of MAP during shelf-life is its impact on water vapor, gas composition, and partial pressure in the headspace of packaged food (Kerry, 2012), which can be regulated by the right choice of packaging material to maintain the atmosphere within packaging at the desired level. Depending on the chosen MAP gas composition, shelf-life can be extended even by 50 – 400%, resulting in less food waste with efficient product logistics (McMillin, 2017). Optimization and maintenance of gas mixture in cured meat products is even more critical compared to fresh meat products as they require a lower presence of oxygen in the MAP during the shelf-life period (McMillin, 2008; Nethra, et al., 2023). In particular, as highlighted in Table 1, the two main gases present in cured meat products packaged under MAP atmosphere are CO_2, which has bacteriostatic properties, and N_2 which is inert and is used as a filler, capable of preventing pack collapse (García-Esteban et al., 2004). Unlike gas mixture in MAP of fresh meat (e.g. 80% O_2: 20% CO_2), oxygen, instead, is not present in the mixture, thus ensuring an anoxic environment and limiting microbial growth, lipid oxidation, and discoloration of the typical pink/reddish cured color (McMillin, 2017).

Table 1. Gas compositions of the main cured meat products in a modified atmosphere for O_2, CO_2 and N_2 (adapted from Parry, 2012).

Product Type	**Gas (%)**		
	O_2	**CO_2**	**N_2**
Bacon, sliced	-	20 – 35	65 – 80
Cooked meat	-	20 – 40	60 – 80
Cooked meat, sliced	-	80	20
Cured meat	-	20 – 50	50 – 80
Ham	-	20 – 35	65 – 80
Ham, Italian, sliced	-	20	80
Ham, sliced	< 0.3*	60	40
Salami	-	20 – 35	65 – 80
Sausage, sliced	-	20 – 30	70 – 80
Sausage, smoked	-	30	70
Turkey, cooked	< 0.2*	30	70

*Residual oxygen

The typical MAP tray and lidding film solutions involve polymeric flexible packages but also rigid or semi-rigid structures, such as thermoformed base trays made from PVC/PE, PET/PE, polystyrene/EVOH/PE (PS/EVOH/PE), or PE/EVOH/PE while preformed base trays are often made from PET, polypropylene (PP), or PVC/PE. Lidding films are mainly composed of PVC-coated PP/PE (PVDC-PP/PE), PVDC-coated PET/PE, or PA/PE) (Parry, 2012; McMillin, 2008). More recent approaches include active packaging where antioxidant and/or antimicrobial compounds are incorporated into the package, and intelligent packaging, where the condition of packaged food and/or the package environment are monitored by sensors or indicators (McMillin, 2017; Katekhong et al., 2022). Active and intelligent packaging are promising solutions and evolving in response to sustainable needs for extending product shelf-life and communicating product freshness with consumers or other stakeholders in the food supply chain; however, their application at the industrial level is relatively small due to the higher cost, safety and legislation concerns. Such types of packaging are not scoped in this review paper; however, detailed information on active and intelligent packaging for meat products can be found in the recent review papers (Uysal-Unalan et al., 2024; Jacinto-Valderrama et al., 2023; Nunes et al., 2023).

In plastic thermoformed semi-rigid trays consisting of a barrier bottom paired with a clear and barrier top lidding film, the multilayer, multi-material structure is broadly implemented to response to different needs of the product such as excellent mechanical strength and required barrier performance e.g. moisture or oxygen barriers (Maga et al., 2019; Bauer et al., 2021). In a typical complex multilayer, multi-materials tray structure (Figure 2), each layer serves certain purposes: EVOH, AlOx, or SiOx layers are used as gas barrier; PET or PA provides thermal resistance during sealing (Bauer et al., 2021); LLDPE or VLDPE (very linear low-density polyethylene) provides mechanical resistance to the material and EVA, LLDPE, PE act as a sealant layer (Morris, 2017; Barlow & Morgan, 2013; Bauer et al., 2021). The lidding film is made of a barrier layer (on the outside) and a non-barrier layer to seal the tray (Belcher, 2006), and the required optical properties (gloss, high clarity, and low haze) are usually achieved using PET, EVA, EVOH, and SiOx (Coles, 2003; Morris, 2017).

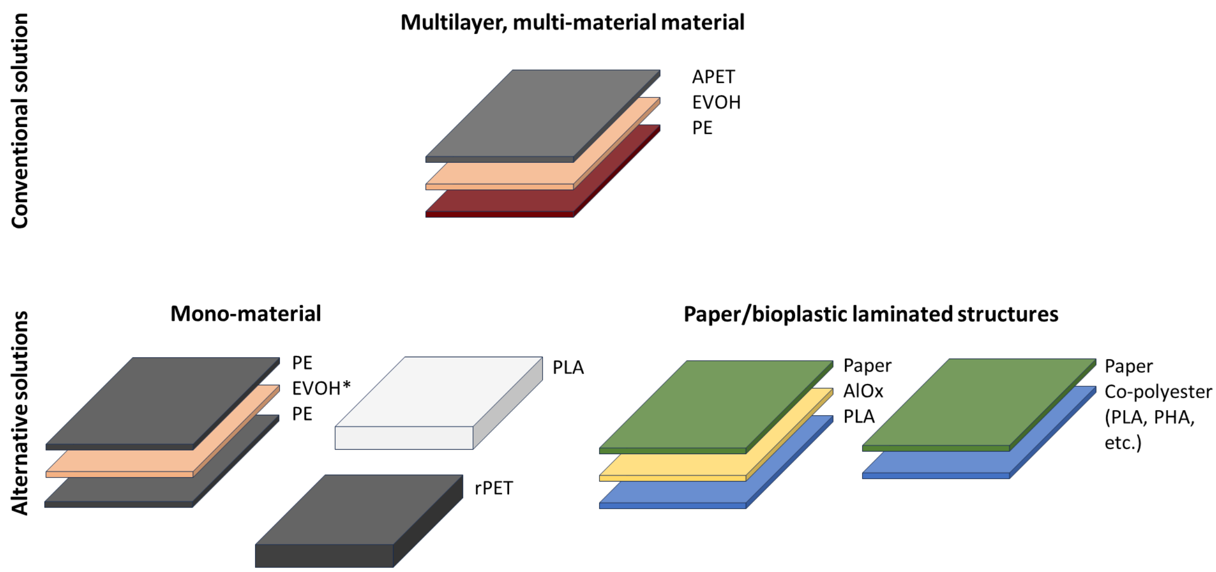

Figure 2. Examples of conventional and alternative packaging solutions for cured meat products (EVOH*- if EVOH is less than 5% of the total packaging weight, the packaging structure can be considered as mono-material) (Adapted from Morris, 2017, Bauer et al., 2021; Peelman et al., 2014).

The thermoformable tray can be also based on paper that has been specifically developed for refrigerated sliced meat and meat products. However, the paper itself would not be enough to guarantee the required barrier need, therefore it must be laminated with PE and other barrier layers mentioned before, to make it heat sealable and improve gas and moisture barrier properties (Raheem et al., 2013).

As previously highlighted, barrier layer functions of packaging are extra crucial for cured meat products to preserve their quality (Barlow & Morgan, 2013). In this regard, PE is used for its moisture barrier, as well as aluminum oxide and silicon oxide, while EVOH is the most used material which ensures an excellent oxygen barrier (Bauer et al., 2021).

Since oxygen concentration needs to be minimized in the headspace of the package during the storage period, it is important to measure its transmission through the film. This measurement, named oxygen transmission rate (OTR), is normally performed at standard conditions, relative humidity of 50% and 23°C (America Society for Testing and Materials, ASTM). OTR is affected by the material's thickness, humidity, and storage temperature, and approximatively, is halved when the temperature is reduced by 8 – 10 °C (Parry, 2012; Zabihzadeh Khajavi et al., 2020). In cured meats, OTR must be generally lower than 100 cm^3 m^{-2} day^{-1} atm^{-1} (at 23°C), and if the cured meat products are more O_2-sensitive the OTR value needs to be lower than 1 cm^3 m^{-2} day^{-1} atm^{-1} (at 23°C) (Parry, 2012). The water vapor transmission rate (WVTR), another important attribute in the film's choice for cured meat products, governs the mass transfer of moisture, thus causing dehydration and moisture absorption of the products which result in deteriorative reactions. In particular, if the product absorbs water, microbial growth, and texture deterioration takes place. On the other side, in food with higher water activity such as cooked ham, mortadella, and frankfurters, product dehydration can also occur (Salmieri et al., 2014). WVTR is the standard indicator of how easily moisture can permeate through the packaging film and its most common units of measurement are g m^{-2} day^{-1}. It is usually measured both at ASTM standard conditions of 38°C with a relative humidity of 90%, (i.e., tropical conditions) and 23°C with a relative humidity of 60% (i.e., temperate conditions). The driving force of the diffusion, in this case, corresponds to the difference in vapor pressure between the two sides of the material and it is influenced by moisture difference and temperature. WVTR for cured meat products should be in the range of 3 – 8 g m^{-2} day^{-1} to retain water vapor inside the package, avoiding water loss from the product (Morris, 2017).

Looking at more industrial applications, the main packaging used for cured meat products packaged in MAP conditions is multilayer, multi-material packaging where PE or PET are laminated with very thing barrier coating such as EVOH, AlOx, and SiOx for additional barrier (e.g., APET-PE/EVOH/PE; PET/PE-EVOH-PE; PET/PE-AlOx) or solutions where paper is laminated with plastic materials (i.e., paper/PE-EVOH-PE). In addition, these barrier layers can also be applied to mono-materials as, for example, the cases with PE or PET (e.g. PE-EVOH-PE) up to 5% of the weight of the total packaging structure which can only have a minor impact on the quality of the recyclate (CEFLEX, 2023). This approach is considered more sustainable with less environmental impact, and indeed in such context it allowed an effective extension of the shelf-life of perishable MAP products, including cured meats. More recent work has been conducted to measure OTR and WVTR of packaging materials designed for MAP meat products including multilayer, multi-material (APET-PE/EVOH/PE; PET/PE-EVOH-PE; PET/PE-AlOx), SiOx laminated PET (PET/SiOx/PET) and paper laminated with plastic packaging. OTR and WVTR, key properties in ensuring adequate food preservation, have been reported to be between 0.01 and 3.18 $cm^3\ m^{-2}\ day^{-1}$, and between 1.51 and 25.80 $g\ m^{-2}\ day^{-1}$, respectively (Mengozzi et al., 2024).

Currently, bioplastic is becoming available for packaging cured meat in the form of trays and lids. However, it is important to highlight that the term bioplastic is poorly defined and creates not only confusion among the stakeholders but also greenwashing (Uysal-Unalan et al., 2024). According to the European Bioplastics Organization, the three main bioplastic categories based on the raw materials' origin and its biodegradability are: (1) non-biodegradable, but bio-based or partially bio-based (bio-PE; bio-PET; bio-PP; bio-PA; etc); (2) biodegradable and bio-based (thermoplastic starch TPS; polylactic acid, PLA; polyhydroxyalkanoate, PHA; polybutylene succinate, PBS; Polypropylene succinate, PPS) (3) biodegradable but fossil-based (polybutylene adipate-co-terephthalate, PBAT; polycaprolactone, PCL; polyvinyl alcohol, PVOH; polyglycolic acid, PGA) (European Bioplastics, 2023; Costa et al., 2023). Among these categories, PLA is the most widely studied bioplastic for cured meat packaging due to its relatively better physical properties such as moderate gas and water vapor barrier, processability, commercial availability and cost efficiency. When replacing conventional fossil-based plastic with bioplastic, trade-offs should be considered from different sustainability dimensions e.g. technical, economic, environmental and social (Gerassimidou et al., 2021; Uysal-Unalan et al., 2024). Bio-based and biodegradable/compostable plastics have less durability and moderate barrier function compared to most conventional plastic which can be well suited for short shelf-life cured meat. At the end, compostable packaging can be treated as organic waste, on the cases where mechanical recycling is not possible due to the food contamination or lack of recycling infrastructure. More investigation is required to clarify the impact of bioplastics including well-established PLA and other emerging polymers e.g. PHA on the quality and shelf-life of cured meat products and waste management.

3.2. Impact of packaging technologies on cured meat product quality

Cured meat products' quality during storage is affected by several factors such as intrinsic and extrinsic parameters as discussed in Section 2. Most sliced ready-to-eat cured meat products last for 2 – 3 weeks at the refrigerator and for 3 – 5 days at ambient temperature (Moschopoulou et al., 2019; Parry, 2012; Prabhakar 2014). However, their shelf-life can be extended by implementing the air-drying process and/or choosing the right packaging materials and technology e.g. vacuum packaging which is specific to chosen cured meat product and its storage conditions.

In this study, a systematic literature review analysis was performed using a research engine (Scopus) to find all studies associated with the packaging technologies (materials and atmospheric conditions) with the safety and quality attributes of cured meat products during storage. The search was conducted in January 2024 for articles published since 1993. A combination of relevant keywords including "pack*", "cur*", and "meat" was used. Boolean operator "AND" was used to combine the three defined research keywords. Articles were sorted by relevance with 'cured meat products packaging type, sustainable packaging, VP and MAP, storage, and shelf-life studies' found anywhere in the title and text of the articles. A total of 398 articles were initially identified and after removing duplicates and the articles not belonging to food-related journals or written in non-English, 64 articles remain. The relevant abstracts underwent further review to identify the aim and to review the overall work. Some articles were excluded after the final review process because their primary focus was intelligent and active packaging, which is mostly in the research phase and is not yet ready to be commercialized and therefore considered out of scope of this work. A total of 18 papers published in the last 20 years were deemed and considered for this review paper.

Table 2 summarizes the details of the identified most relevant studies demonstrating the packaging structure and technology used, targeted cured meat products, and key findings of each case on product quality and shelf-life. The products were packaged under vacuum or modified atmosphere conditions, with several different gas percentages (N_2, CO_2, Ar): N_2 and CO_2 with values ranging between 20 – 80 % and argon with value of 70%. All the two packaging solutions, as reported in, were plastic multilayer, multi-material packaging, with the main materials represented by PET, PE, PA and EVOH. Microbiological analysis, pH, water activity, lipid oxidation, color, and sensorial analysis were the main tests carried out on these meat products during storage. All the studies evidenced that both MAP and VP demonstrated high eligibility in ensuring safety, acceptability, and long-term storage. In particular, for dry-cured products, the shelf-life ranged from 2 months to 6 months, while for wet-cured products, the longest shelf-life was found to be 1 month. However, when comparing MAP and VP technologies in cured meat products, it can be highlighted that during storage both VP and MAP allowed the retention of high-quality parameters such as color, product appearance, and only slight differences can be observed between these two packaging technologies. In particular, in dry cured products (i.e., Serrano ham slices), MAP technology (20% CO_2 and 80% N_2) was able to extend the lightness of the products over 8 weeks at 4°C, and no significant color differences were found in vacuum products (Bosse et al., 2018; Garcia-Esteban et al., 2004). In addition, neither MAP nor vacuum affected the sensorial properties and led to obtaining safe products (Garcia-Esteban et al., 2004; Parra et al., 2010). The studies provided an overview of the barrier properties of packaging generally used in cured meat products and their link with the quality during storage. The packaging material's OTR (measured on flat film) ranged between 5 and 40 $cm^3\ m^{-2}\ day^{-1}\ atm^{-1}$ and most of the results did not observe significant differences in quality between the products packaged in vacuum or modify atmosphere. However, at low OTR (0.5 $cm^3\ m^{-2}\ day^{-1}\ atm^{-1}$), only Kim et al. (2014) observed that MAP product had a lower microbial count than VP product in PE plastic bag. WVTR of packaging for cured meat products ranged between 3 and 8 $g\ m^{-2}\ day^{-1}$ to retain water vapor inside the package, avoiding water loss from the product (Morris, 2017).

On the other hand, only a few studies have focused on the quality attributes of cured meat products packaged with more sustainable solutions, including multilayer, multi-material packaging with less material weight, mono-material packaging, and bioplastic packaging (Figure 2). In particular, Kurek et al. (2021) investigated the quality parameters during the storage of Dalmatian dry-cured ham in MAP-polylactic acid (PLA) packaging and in commercial bilayer plastic packaging (PA/PE). The results showed that dry ham packaged in MAP-PLA underwent a higher increase in pH, oxidation, and drying during 6 months of storage than the products packaged in the multilayer, multi-materials packaging due to the high-water vapor permeability of bioplastics. It was also found that the oxidation of proteins and fats changed the most after 1 month in the MAP-PLA packaging, mainly due to the high oxygen content in the package. In addition, the sensory evaluation confirmed that MAP-PLA packaging could be used for short-term storage and similar quality attributes similar to those in conventional PA/PE packaging. In another study, the quality attributes of ham sausage packed on a PLA tray with a PLA top film or an APET/LDPE tray sealed with a PET/EVOH/PE top film were investigated over 28 days of storage (Peelman et al., 2014). Ham packaged in PLA had higher discoloration than multilayer, multi-materials packaging, while no significant differences in microbial spoilage, pH, aw, peroxide values and malondialdehyde content were observed during the storage period between the two packaging materials. Overall, these studies showed that in cured meat products bioplastics (i.e., PLA) materials have similar performances to conventional multilayer, multi-material plastic packaging at short and medium storage, but it is important to highlight that studies for cured bioplastic packaging are very limited and resulting conclusions are contradictory. On the other hand, for long storage, there are still some limitations and challenges in the use of PLA and sustainable packaging due to their suboptimal gas, water, and UV-VIS barrier properties, which are of great importance for MAP products. These challenges, therefore, offer a great opportunity to all the scientists and companies working in the material science area.

It is worth highlighting that these articles exploit only the use of bio-based plastics as alternative sustainable materials, but the other strategies including light-weighting, reusing, and recycling are also being investigated and promoted (European Union, 2018; European Commission, 2018; European Commission, 2020; Soro et al., 2021). For instance, Korte et al. (2023) recently studied the quality of cured meat products (Mortadella, ham sausage, and mushroom sausage) packaged in conventional multilayer plastic solution, including a multi-material packaging with thickness reduction, and two mono-material packaging i.e. mono-PET and paper film. The authors showed that the conventional multilayer, multi-material solution was the most effective compared to alternative packaging in preserving the quality of the cured ham sausages. In general, alternative materials caused an increase in O_2 concentration leading to an overall decrease in the quality acceptability of ham sausages compared to the conventional packaging. Similarly, other researchers have shown that during storage in plastic weight reduction, mono and bio-based materials the quality parameters (color, microbial count, pH) did not significantly change during storage (up to 70 days) (Nobile et al., 2024).

In response to the increasing growth in food and packaging waste generation, more work is needed to investigate and identify the specific technical characteristics of sustainable packaging material alternatives and required packaging technologies for cured meat products stored at certain storage conditions.

Table 2. Most relevant studies regarding the packaging structure and technology designed for cured meat products.

Packaging (material and thickness)	Packaging barrier properties	Packaging technology	Product	Monitored parameters	Storage conditions	Key findings	References
				Dry-Cured Meat Products			
Multilayer, multi-material plastic bag: PE/MDPE/PA - EVOH - PA/LDPE/EVA (140 mm)	**OTR**: 8.3 $cm^3 m^{-2} day^{-1}$ (23 °C, 0% RH, 1 atm)	- VP - MAP 100% N_2 - MAP 80% N_2 20% CO_2	**Serrano raw hams**	• Microbial count • Color • Texture • Moisture • Oxygen in the headspace	4 °C 8 weeks	No significant differences among the three packaging systems for color, texture and microbial quality were found.	*Garcìa-Esteban et al., 2004*
Plastic bag: Cryovac®	**OTR:** 5 $cm^3 m^{-2} day^{-1}$ (22°C, 65% RH)	- VP - MAP 0% CO_2+20% N_2	**Sliced cooked cured pork shoulder**	• Microbial count • pH • a_w • Acetate content	4 °C 28 days	Similar inhibitory capacity of bacteriocins from different microorganism were reported in both VP and MAP products.	*Mataragas & Drosinos, 2003*
Multilayer, multi-material plastic bag: OPA/EVOH/PE	**OTR**: 5 $cm^3 m^{-2} day^{-1}$ (23 °C, 50% RH, 1 atm) **WVTR**: 15 g $m^{-2} day^{-1}$ (38 °C, 90% RH, 1 atm)	- MAP 50% N_2 50% CO_2	**Turkish Pastirma (made from frozen/thawed or fresh meat)**	• Residual nitrate	4 and 10 °C 150 days	Residual nitrite in samples made with frozen/thawed meat was higher than that made from fresh meat during storage. High product quality was reported at both 4 and 10 °C for 150 days.	*Aksu et al., 2005*

Multilayer, multi-material plastic bag: PA/PE Plastic packaging: PS tray	**OTR**: 30 - 40 $cm^3m^{-2}day^{-1}$ (23 °C, 50% RH, 1 atm) **WVTR**: 2.5 g $m^{-2}day^{-1}$ (23 °C, 50% RH) **OTR**: 1.8 $cm^3m^{-2}day^{-1}$ (20 °C, 65% RH, 1 atm)	- VP - MAP 20% N_2 80% CO_2 - MAP 80% N_2 20% CO_2	**Dry cured beef: Cecina de Leòn**	• Microbial count • Gas composition • pH • a_w • Color • Sensory evaluation	6 °C 210 days	At 60 days of storage MAP was better than VP from a microbiological point of view. No differences in color data between VP and MAP, however VP scored better than MAP when the color was assessed by the sensory panel.	*Rubio et al., 2006*
Multilayer, multi-material plastic bag: PA/PE Plastic packaging: PS tray + high barrier lid film	**OTR**: 30 - 40 $cm^3m^{-2}day^{-1}$ (23 °C, 50% RH, 1 atm) **WVTR**: 2.5 g $m^{-2}day^{-1}$ (23 °C, 50% RH) **OTR**: 1.8 $cm^3m^{-2}day^{-1}$ (20°C, 65% RH, 1 atm)	- VP - MAP 20% N_2 80% CO_2 - MAP 80% N_2 20% CO_2	**Dry cured beef (Cecina de Leòn)**	• Microbial count • Gas composition • pH • a_w • Color • Texture • Sensory evaluation	6 °C 210 days	No significant differences between VP and MAP from a microbial and physicochemical stability point of view. VP and MAP 80/20% CO_2/N_2 packaging preserved the rest of sensory properties studied efficiently, while long-term packaging in 20/80% CO_2/N_2 caused a decrease in the sensory quality.	*Rubio et al., 2007*

Multilayer, multi-material plastic packaging: PA/PE	**OTR**: 30 - 40 $cm^3m^{-2}day^{-1}$ (23 °C, 50% RH, 1 atm) **WVTR**: 2.5 g $m^{-2}day^{-1}$ (23 °C, 50% RH)	-	VP	**Dry fermented sausage (Salchichón)**	• Chemical composition • pH • a_w • Color • Fatty acids content • Lipid oxidation	6 °C 210 days	No significant differences in color and lipid oxidation stability were reported between VP and MAP.	*Rubio et al., 2008*
Multilayer, multi-material plastic packaging: high barrier film	**OTR**: 5 $cm^3m^{-2}day^{-1}$ (23 °C, 50% RH, 1 atm) **WVTR**: 19 g $m^{-2}day^{-1}$ (23 °C, 90% RH)	-	MAP 80% N_2 20% CO_2					
Multilayer, multi-material plastic bag: PE/PA	**OTR**: 40 - 50 $cm^3m^{-2}day^{-1}$ (23 °C) **WVTR**: 100 g $m^{-2}day^{-1}$ (23 °C)	-	Air	**Turkish Pastirma**	• pH • Color • Lipid oxidation • Microbial count • Hexanal content • Sensory analysis	4 °C 120 days	MAP preserved the chemical, microbiological and sensory properties of Turkish. MAP resulted in better overall quality compared to AP or VP.	*Gök et al., 2008*
Plastic bag: Cryovac®	**OTR**: 30 $cm^3m^{-2}day^{-1}$ (23 °C, 70% RH) **WVTR**: 20 g $m^{-2}day^{-1}$ (38 °C)	-	VP					
Plastic packaging: tray + lid film	**Tray film** **OTR**: 5 $cm^3m^{-2}day^{-1}$ (23 °C, 50% RH, 1 atm) **WVTR**: 15 g $m^{-2}day^{-1}$ (38 °C, 90% RH) **Lid film** **OTR**: 5 $cm^3m^{-2}day^{-1}$ (23 °C, 50% RH, 1 atm) **WVTR**: 19 g $m^{-2}day^{-1}$ (38 °C, 90% RH)	-	MAP 65% N_2 35% CO_2					

Multilayer, multi-material plastic packaging: tray PA/PE	**OTR**: 38 $cm^3m^{-2}day^{-1}$ (1 atm)	- VP - MAP 60% N_2 40% CO_2 - MAP 70% N_2 30% CO_2 - MAP 70% Ar 30% CO_2 - MAP 80% N_2 20% CO_2	**Iberian raw ham**	• Microbial count • Gas headspace composition • Moisture content • pH • Color • Nitrosyl myoglobin content • Lipid oxidation	4 °C 120 days	No differences in microbiological parameters were reported. High lipid oxidative stability in VP was observed.	*Parra et al., 2010*
Multilayer, multi-material plastic packaging: PA/PE	**OTR**: 38 $cm^3m^{-2}day^{-1}$ (38 °C, 90% RH, 1 atm) **WVTR**: 10 g $m^{-2}day^{-1}$ (38 °C, 90% RH)	- VP - MAP 70% N_2 30% CO_2 - MAP 70% Ar 30% CO_2	**Iberian dry-cured ham**	• Microbial count • Gas headspace composition • Moisture content • pH • Color • Nitrosyl myoglobin content • Lipid oxidation • Sensory analysis	4 °C 60 days	After 30 and 60 days, VP samples showed the highest a* values compared to N_2 and Ar MAP. VP samples showed lower TBARS values than N_2 and Ar MAP. Higher microbial count in VP was reported compared to MAP. Hygiene quality was maintained at all the conditions for 60 days.	*Parra et al., 2012*

Plastic bag: PE	**OTR**: 0.5 $cm^3m^{-2}day^{-1}$ (90% RH, 1 atm)	- VP - MAP 75% N_2 25% CO_2	**Dry-cured pork neck**	• Microbial count • pH • Moisture, a_w • Color • Lipid oxidation • Sensory analysis	10 °C 90 days	VP preserved the quality (color, lipid oxidation, pH and tenderness) of dry-cured pork neck products better than the MAP. MAP had lower microbial count than VP.	*Kim et al., 2014*
Multilayer, multi-material plastic bag: PA/PE (70 mm)	**OTR**: 38 $cm^3m^{-2}day^{-1}$ (1 atm)	- VP	**Dry-cured ham**	• Microbial count • Color • pH • a_w	2 and 7 °C 63 days	Acceptable quality parameters for 42 days were observed.	*Piras et al., 2016*
Plastic bag Plastic packaging: PS tray (150 mm) + PE lid film (70 mm)	**O_2 Permeability:** 9.3 $mLO_2m^{-2}day^{-1}$ (0 °C) **<u>Tray film</u>** **OTR**: 3.2 $cm^3m^{-2}day^{-1}$ (23 °C, 1 atm) **<u>Lid film</u>** **OTR**: 1 $cm^3m^{-2}day^{-1}$ (23 °C; 50% RH, 1 atm) **WVTR**: 2.2 g $m^{-2}day^{-1}$ (23 °C; 50% RH)	- VP - MAP 70% N_2 30% CO_2	**Iberian raw ham**	• Sensory analysis • Consumer preference	4 °C 90 days (75 days in darkness and 15 days under 600 lux)	High acceptability in MAP compared to VP products was observed.	*Ortiz et al., 2020*

			Wet Cured Meat Products				
Multilayer, multi-material bag: Cryiovac™ + impermeable aluminum foil laminate	**O_2 Permeability:** 30 - 40ml $m^{-2}day^{-1}atm^{-1}$ (25 °C, 75% RH)	- VP packaging - VP with 500 mL CO_2	**Cooked ham**	• Microbial count • Sensory analysis	3 °C 4 weeks	The addition of CO_2 did not improve the quality.	*Boerema et al., 1993*
Plastic bag	/	- MAP 70% N_2 30% CO_2 (a MAP flushed with a dose of 50% gas mixture of 70% N_2 and 30% CO_2 after 80% vacuuming) - MAP 70% N_2 30% CO_2 (a MAP flushed with a dose of 50% gas mixture after 98% vacuuming)	**Cooked ham**	• Color • Lipid oxidation	4 °C 35 days	Better color stability in MAP with less residual oxygen was reported.	*Haile et al., 2013*

ALTERNATIVE PACKAGING MATERIALS							
Multilayer, multi-material plastic packaging: APET/LDPE tray (200 mm) + PET/EVOH/PE lid film (12 mm)	**<u>Tray film</u>** **OTR**: 20.6 $cm^3m^{-2}day^{-1}$ **WVTR**: 4 g $m^{-2}day^{-1}$ **<u>Lid film</u>** **OTR**: < 8 $cm^3m^{-2}day^{-1}$ **WVTR**: 3.5 g $m^{-2}day^{-1}$	- MAP 40% N_2 20% CO_2	**Ham sausage**	• Packaging light transparency • Gas composition • Microbial count • pH • a_w • Lipid oxidation • Color • Sensory evaluation	4 °C 29 days	Higher discoloration in PLA was observed compared to multilayer packaging. No differences in microbial spoilage, pH, a_w and oxidation were reported.	*Peelman et al., 2014*
PLA/cellulose packaging: Ingeo2002D tray (200-300 mm) + Natureflex™N913/ PLA lid film (60 mm)	**<u>Tray film</u>** **OTR**: 46.8 $cm^3m^{-2}day^{-1}$ **WVTR**: 3.8 g $m^{-2}day^{-1}$ **<u>Lid film</u>** **OTR**: 11 $cm^3m^{-2}day^{-1}$ **WVTR**: 11.3 g $m^{-2}day^{-1}$						

Multilayer, multi-material plastic bag: PA/PE smooth side (89 mm) + PA/PE ribbed side (88.7 mm)	**PA/PE smooth side** **O_2 Permeability:** 6.18×10^{-4} $cm^3 m^{-1} s^{-1} Pa^{-1}$ **Water Vapor Permeability:** 0.70×10^{-12} $g\ m^{-1} s^{-1} Pa^{-1}$ **PA/PE ribbed side** **O_2 Permeability:** 28.02×10^{-4} $cm^3 m^{-1} s^{-1} Pa^{-1}$ **Water Vapor Permeability:** 9.75×10^{-12} $g\ m^{-1} s^{-1} Pa^{-1}$	- Air - VP - MAP 70% N_2 30% CO_2	**Dalmatian dry-cured ham**	• Packaging thickness and permeability • Gas composition • Sensory evaluation • Moisture content • pH • Lipid oxidation	4 °C 180 days	Similar changes in the above parameters were also observed in the control sample (packed in air-PA/PE) while vacuum-PA/PE and MAP-PA/PE showed significantly better results. VP PA/PE and MAP-PA/PE samples had better quality than air PA/PE MAP-PA/PE and VP-PA/PE samples had similar shelf-life (5 months).	*Kurek et al., 2021*
PLA bag: NATIVIA® (36.6 mm)	**O_2 Permeability:** 557.60×10^{-4} $cm^3 m^{-1} s^{-1} Pa^{-1}$ **Water Vapor Permeability:** 29.56×10^{-12} $g\ m^{-1} s^{-1} Pa^{-1}$	- Air - VP - MAP 70% N_2 30% CO_2				MAP-PA/PE and VP-PA/PE samples had similar shelf-life (5 months).	

Multilayer, multi-material plastic packaging: PET-based tray + APET/EVOH/PE lid film PLA trays (500 µm) + PLA lid (55 µm)	**OTR**: 4.07 $cm^3\ m^2 \cdot d \cdot bar$ **OTR:** < 5 $cm^3 m^{-2} day^{-1}$ **WTR:** < 20 g $m^{-2}\ day^{-1}$	-	MAP 70% N_2 30% CO_2	**Italian salami**	• Microbial count • pH • Color • Volatile compound • Sensory analysis	4 and 8 °C 70 days	PLA maintained the red color throughout the entire shelf life. pH was constant during storage.	*Nobile et al., 2024*
Multilayer, multi-material tray and lid film: tray APET/PE-EVOH-PE (300 mm) + PET/PE-PA-EVOH-PA-PE lid film (62 mm) Multilayer, multi-material tray and lid film: tray APET/PE-EVOH-PE (250 µm) + PET/PE-PA-EVOH-PA-PE lid film (47 µm) Multilayer, multi-material tray and lid film: tray APET/PE-EVOH-PE (230 µm) + PET/PE-PA-EVOH-PA-PE lid film (62 µm)	**Tray film** **OTR**: < 3 $cm^3 m^{-2} day^{-1}$ **WVTR**: < 9 g $m^{-2} day^{-1}$ **Lid film** **OTR**: 2.5 $cm^3 m^{-2} day^{-1}$ **WVTR**: 1.2 g $m^{-2} day^{-1}$ **Tray film** **OTR**: < 3 $cm^3 m^{-2} day^{-1}$ **WVTR**:< 9.5 g $m^{-2} day^{-1}$ **Lid film** **OTR**: 2.5 $cm^3 m^{-2} day^{-1}$ **WVTR**: 1.2 g $m^{-2} day^{-1}$ **Tray film** **OTR**: < 3 $cm^3 m^{-2} day^{-1}$ **WVTR**: < 9.5 g $m^{-2} day^{-1}$ **Lid film** **OTR**: 2.5 $cm^3 m^{-2} day^{-1}$ **WVTR**: 1.2 g $m^{-2} day^{-1}$	-	MAP 70% N_2 30% CO_2	**- Pure emulsion-type sausage (Mortadella)** **- Ham sausage (Bierschinken)** **- Mushroom ham sausage (Champignon-Schinkenwurs)**	• Gas barrier properties • Microbial count • Color	7 °C 28 days	Control multi-layer tray (300 µm)/lid film (62 µm) was the most effective in keeping the quality of the emulsion-type sausages and preserving an acceptable product quality during its shelf-life.	*Korte et al., 2023*

Mono-material tray and multilayer, multi-material lid film: APET-barrier-APET tray (200 µm) + OPET-PE-EVOH/PET lid film (52 µm)	**<u>Tray film</u>** **OTR**: < 1 $cm^3 m^{-2} day^{-1}$ **WVTR**: < 9.5 g $m^{-2} day^{-1}$ **<u>Lid film</u>** **OTR**: < 3 $cm^3 m^{-2} day^{-1}$ **WVTR**: < 9.4 g $m^{-2} day^{-1}$
Multilayer, multi-material tray and lid film: paper-PE-EVOH tray (400 µm) + PET/PE-PA-EVOH-PA-PE lid film (62 µm)	**<u>Tray film</u>** **OTR: <** 3 $cm^3 m^{-2} day^{-1}$ **WVTR**: < 8 g $m^{-2} day^{-1}$ **<u>Lid film</u>** **OTR**: 2.5 $cm^3 m^{-2} day^{-1}$ **WVTR**: 1.2 g $m^{-2} day^{-1}$

4. Sustainability aspects of cured meat packaging a focus on recycling technologies

4.1 Recycling technologies for plastic materials

Multilayer, multi-material structure systems, which are generally constituted of plastic polymer, paper, and organic and inorganic coatings (i.e., PE, EVOH, aluminum), account for 26% of the weight of flexible packaging in food products (Bauer et al., 2021; Schmidt et al., 2022). The presence of different materials negatively impacts recyclability since the recycling industry is not currently able to identify, collect, and separate the different layers (Horodytska et al., 2018). Nowadays the most widely employed recycling process for post-consumer plastic waste is mechanical recycling, which is based on the first sorting, shredding, washing, the second sorting, and re-granulation. During the last step, the different melting points cause immiscibility among the plastic materials (Garcia & Robertson, 2017). Compatibilizers could solve the problem, but this procedure is currently limited to specific applications not related to food and is characterized by high costs (Geueke et al., 2018). In this regard, the European Union within the "European Strategy for Plastics in a Circular Economy" aims to improve the separation and collection of plastic waste, to increase and modernize the EU's sorting and recycling capacity, and last to create viable markets for recycled and renewable plastics. The improvement of recycling infrastructure and technology is crucial to reach by 2030, and all packaging on the EU market must be reusable or recyclable in an economically viable way (European Commission, 2020). Similar actions have been also considered and implemented in other countries including the USA (EPA, 2024), India (Central Pollution Control Board, 2021) and Australia (Australian Government, 2022). Whilst recycling is viewed as a viable approach to reducing the environmental and waste management issues connected to the use of plastics, 30% of plastic packaging materials may never be suitable for recycling without a substantial change in the redesign of the materials used (Ellen MacArthur Foundation, 2017).

Figure 3 provides an overview of the technological recycling pathways for mono- and multi-material plastic packaging, including organic recycling.

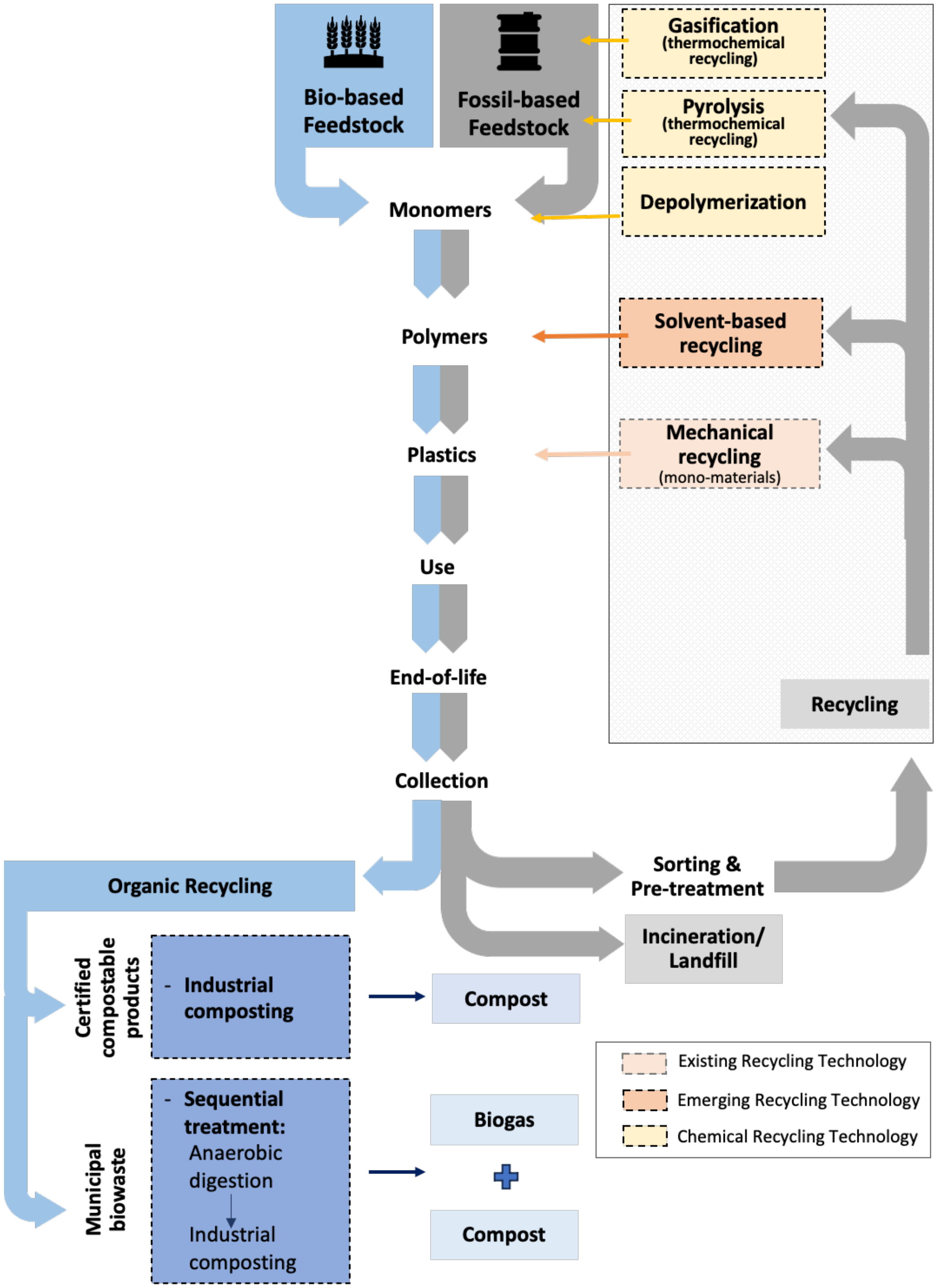

Figure 3. Plastic packaging value chain and its recycling routes, including existing and emerging, and chemical recycling technologies (adapted from De Mello Soares et al., 2022; Ragaert et al 2023; Paul-Pont et al., 2023; Cucina, 2023; European Bioplastics, 2024).

At the current state of waste management infrastructures, these multilayer, multi-material packaging solutions cannot be recycled into high-value products on a large scale (Ragaert et al., 2017). A potential approach for recycling multilayer, multi-material packaging includes chemical recycling, which traditionally is not environmentally and economically sustainable (Ragaert et al., 2017; Thuy et al., 2020). Chemical recycling is an umbrella term describing a range of different technologies including depolymerization (so-called monomer or oligomer recycling), and pyrolysis and gasification (so-called thermochemical recycling) (Ragaert et al., 2023). However, as new technologies are coming out, their classification into the main recycling categories is becoming more challenging and creating even more confusion. Very recent work has assessed recycling technologies according to their working principles and outcomes and has cleared up the misleading terminology in plastic recycling in the light of the European policy terminology (Ragaert et al., 2023). Current European standardization is based on changes in the chemical structure of the material as a consequence of the recycling process (Laredo et al., 2023). According to this distinction, chemical recycling refers to technologies that intentionally lead to major changes in the chemical structure of plastics to produce basic chemicals or other feedstocks e.g. monomers, while mechanical recycling, also referred to as physical recycling, involves the processing of plastic materials without intentionally altering their chemical structure (Ragaert et al., 2017). As a new subset of chemical recycling, hydrothermal liquefaction is accepted as an emerging technology that can sit between pyrolysis and gasification (Ragaert et al., 2023). It is in its early stage but recent studies on recycling multilayer, multi-material plastic waste have so far demonstrated its promising potential at more energy-efficient and safer levels, compared to pyrolysis (Tito et al., 2023; Rahman et al., 2023; Laredo et al., 2023). Another recycling technology for multilayer, multi-material packaging is solvent-based recycling. In solvent-based (dissolution) processes, targeted polymer from mixed plastic wastes can be dissolved in a polymer-specific solvent while, unlike chemical recycling, the chemical structure of the polymer remains intact. Other plastic components (e.g. additives, fillers, non-targeted polymers) remain undissolved and can be cleaned from the dissolved target polymer (Ragaert et al., 2023). However, currently, due to the complex material composition of multilayer, multi-material packaging and lack of efficient and scale-up process for such packaging, they are generally collected as mixed plastic waste in post-consumer streams and are mostly incinerated for energy recovery purposes. In the worst cases, this plastic waste ends up in landfills or is dispersed into the environment, causing pollution on a large scale (De Mello Soares et al., 2022). These technologies can be an answer for recycling multi-material packaging; however they are relatively new, and more research is needed to optimize them and overcome the challenges associated with their widespread such as designing reactors that achieve a specific target product composition and uncertainty of their environmental impact on a large scale.

In this complex scenario, where reducing, reusing and recycling are the key elements to minimizing packaging waste, European environmental policies are oriented toward the reduction of unnecessary generation of plastic waste, including waste from single-use items and over-packaging, as well as the designing for reuse and recyclable packaging, and the reduction of the complexity of packaging materials (European Commission, 2020). On April 24, 2024, the European Parliament adopted the PPWR (European Union, 2024) for safer and more sustainable packaging, which aims to tackle constantly growing waste, harmonize internal market rules and boost the circular economy and it sets the following packaging reduction targets: 5% by 2030, 10% by 2035 and 15% by 2040. Aside from fostering reduction, all packaging must be recyclable by 2030. However, this is not an easy task. Hence, Europe is pushing towards packaging design following current and upcoming legislation to switch from non-recyclable flexible multilayer, multi-materials to separately collectible and recyclable, predominantly mono-material packaging solutions for better collection and higher recycling rates. Possible mono-material solutions include polyolefins since these polymers are compatible with other types of polyolefins and PET (De Mello Soares et al., 2022). However, the improvement in recyclability is directly proportional to the reduction in packaging efficiency. For this reason, materials could include barrier layers (EVOH, SiOx, AlOx) unless these secondary materials do not surpass critical levels (currently, the limit is set at 5% of the total packaging weight) (CEFLEX, 2023; Horodytska et al., 2018). Moreover, reducing the complexity of packaging often goes hand in hand with heavier and thicker structures, which increases the environmental impact of the packaging (Bauer et al., 2021). Therefore, the implementation of the redesign-focused strategy on recyclability needs the collaboration of all the packaging stakeholders, starting from the scientific community to government and political institutions (Nguyen et al., 2020).

4.2 Recycling technologies for bioplastic materials

An additional sustainable solution supported by European environmental policies includes the adoption of bioplastic packaging that can be either bio-based or biodegradable or both. Within this material, three different categories can be identified: i) bio-based or partly bio-based non-biodegradable plastics (e.g. bio-PE, bio-PP, or bio-PET), ii) plastics that are both bio-based and biodegradable plastics (e.g. PLA, PHA or PBS), and iii) biodegradable fossil-based plastics (e.g. PBAT) (European Bioplastics, 2023). In the last decade, the use of bio-based packaging as an alternative to conventional multilayer, multi-material plastic packaging has received great interest in the food packaging industry (Cruz et al., 2022; Ghasemlou et al., 2024), however, their application in cured meat products is still limited (Kurek et al., 2021; Peelman et al., 2014). On the other hand, if the packaging is compostable, diverting post-consumer packaging waste to composting can be a viable waste management strategy, reducing a large amount of waste derived from conventional waste streams, i.e. landfills and incinerators, and increasing organic waste collected, converting it into good quality biogas, bioproducts or compost to be used in local gardens, parks, and agricultural (Paul-Pont et al., 2023; Rajesh Banu & Godvin Sharmila, 2023). When compostable bioplastics are heavily contaminated with food, economic and technological concerns together with limitations to get rid of the food scraps from packaging as a part of the mechanical recycling process are obvious. However, in certified compostable bioplastic packaging, food scrap contamination may not represent an issue, being direct to composting, and alternatively the sequential anaerobic digestion and composting, can boost the composting process (European Bioplastics, 2024; Gadaleta et al., 2022; Battista et al., 2020). Anaerobic digestion is a biological process that turns organic matter into biogas (e.g. mixture of CO_2, CH_4, and other gases) and digestate. Subsequently, because of the low degradation rate that occurs in anaerobic digestion, the obtained organic waste is aerobically decomposed (composting) producing heat, humidity, CO_2, and nutrient-rich soil (compost) that can be used as nutrients (Gadaleta et al., 2021; Su et al., 2024). However, full degradation of biodegradable bioplastics packaging is not always ensured at the end of the process (Sikorska et al., 2021) and future studies should focus on the reduction of high bioplastic content of the final compost and digestate, which limits their use in the agricultural sector (Gadaleta et al., 2021). It is worth addressing that the assessment of bioplastic's biodegradability is extremely related to the conditions of the standard evaluation experiments, which often do not reflect the reality due to the different conditions present in the waste treatment plants (such as temperature, mixing, and test duration). To fill this research gap, research studies should mainly focus on the investigation of bioplastics' degradation in different non-standardized environments to estimate the bioplastic fragmentation and biodegradation in conditions close to the one applied at an industrial level as possible to reality (Folino et al., 2023). A recent review outlined the current knowledge of integrated anaerobic digestion and composting systems to treat organic waste together with biodegradable bioplastic waste (Cucina, 2023). The so far reported results indicated some benefits of such systems yet are very limited to conclude it effectiveness for circularity in waste management systems. Increasing the fraction of bioplastics in municipal organic waste streams requires the current way of managing organic waste updated, therefore, further research is needed to exploit its technological, safety, and economical outcomes to leverage its competitive advantage.

In connection with their biodegradability merits, biodegradable polymers that are certified for their compostability, do not convert into permanent secondary microplastics upon degradation, because microorganisms in compost media are able to metabolize them. Even biodegradable polymers that have no compostable certification have less residence time compared to conventional plastic materials. This is another clear benefit of biodegradable polymers in reducing environmental and health effects (European Bioplastics, 2021).

4.3 Life cycle assessment of packaging materials

The environmental impact of food packaging needs to be quantified by employing an inclusive life cycle assessment (LCA) to manage all aspects of the life cycle of packaging and food, including production, use, and end-of-life (Molina-Besch et al, 2019; Dörnyei et al., 2023; Boz et al., 2020; Desole et al., 2021). This whole system approach-based LCA can identify the stages of the entire chain of food-packaging unit whose impact and benefits come from resources consumed and food and packaging waste generated that promotes truly sustainable practices in the era of food packaging. However, to the best of the authors' knowledge, no studies have been found on packaging specifically used for cured meat products, while most of the LCA studies focus on fresh meat (Wikström et al., 2016; Maga et al., 2019; Dilkes-Hoffman et al., 2018; Ingrao et al., 2015). Among them, only a few LCA studies have particularly focused on packaging materials including conventional plastics and bio-based plastics, in the form of films or tray structures for fresh meat i.e., PET (Wikström et al., 2016), PLA (Maga et al., 2019), PP (Dilkes-Hoffman et al., 2018), and PS (Ingrao et al., 2015). All these studies considered packaging suitable for fresh meat based on mono-material solutions, highlighting the importance of considering as many aspects as possible in the environmental impact assessment, including food waste, user behavior, and the end-of-life scenario. Instead, the study of Hutchings et al. (2021) compared, through an LCA method, a biodegradable multilayer lidding film, polyhydroxyalkanoate/butanediol vinyl alcohol (PHA/BVA) with a conventional multilayer lidding film made of LDPE/EVOH/LDPE. The results showed that by incorporating specific waste management for biodegradable films and better farming practices for the feedstock production of PHA, the global warming potential of biodegradable film could be up to 92% lower than that of conventional film. Likewise, another study investigated the environmental impact of different types of trays made from mono-material and multilayer multi-material structures, including but not limited to PET, PET/PE, PS, PP and PLA (Maga et al., 2019). The LCA findings showed that the production phase of the trays has a major overall impact on the entire packaging life cycle, while the end-of-life stage has crucial effects on the environmental performances of the several trays, with the multilayer materials having a higher environmental impact than mono-material solutions. Another highlight from the study reported that the resulting benefits due to the less plastic usage for meat tray production outweigh possible benefits from their recycling. Various materials (for example, bio-based, compostable, recycled/recyclable plastics, reusable plastics) are becoming available as packaging materials, however, the requirements for packaging can be different even for the same product in different supply chains depending on several factors, including the packaging technology (e.g. MAP or VP), duration of transportation, and temperature range needed (e.g. ambient, cold, or frozen storage). Thus, to have a realistic and holistic understanding of the sustainability aspects of packaging in the meat sector, future LCA research should grow on the focus on the different environmental impacts of each sustainable packaging solution designed for cured meat products considering the entire supply chain and subsequent consequences due to the high production of packaged meats and the consequent massive generation of non-recyclable plastic waste. Only, the combination of these findings with the current status quo could lead to proper design for such meat products soon.

5. Conclusion

Cured meat products are very sensitive to deterioration phenomena and are traditionally packaged in modified atmosphere, or vacuum conditions, combined with multilayer plastic packaging. Given that some contradictory findings are available and the data for more sustainable packaging alternatives for cured meat are scarce, the current state of the knowledge for dry and wet cured packaging is not sufficient to reach a concrete conclusion. However, storage studies have so far demonstrated that cured meat products packed in MAP conditions have a better or similar microbial quality to those packed in vacuum conditions yet less sensorial acceptance (e.g. not appealing color). Multilayer, multi-material packaging is generally made of PET and PA to provide a printing surface and thermal resistance, PE to confer mechanical properties, and EVOH, AlOx, or SiOx as gas barrier polymers. Despite their good functional properties, these structures negatively impact mechanical recyclability, since the recycling industry is not currently able to identify, collect, and separate the different layers. Recently proposed emerging recycling technologies supporting or complementing the mechanical recycling of multilayer, multi-material packaging are still in their early stages. The EU has adopted new binding measures on sustainable and safe packaging to overcome ever-growing mountains of waste being produced across the EU. Therefore, research should focus on transforming packaging from waste to a resource and minimizing food waste with less overall carbon footprint at product-centric systems. This requires a fundamental understanding of the interactions between selected food (e.g. low-high pH, low-high fat, dry-humid) and packaging (e.g. material properties (OTR, WTR) and implemented packaging technology (VP and MAP)) under the given storage conditions through the supply chain including food and packaging waste generated along the chain and eventually how these wastes are managed. However, only a few studies have focused on the quality attributes of cured meat products packaged in sustainable solutions, thus limiting their application. While moving to more circular solutions and economy (e.g. reduction of packaging weight/size, less complex structures, renewable bio-based resources, reusable systems), pollution of society with chemicals and microplastics leading to human, animal, and environmental health concerns should be prevented. At the forefront of innovative and sustainable solutions, this literature review examines and synthesizes advances and potential practices in the direction of a circular approach to food and packaging waste, focusing on both bio-based and fossil-based packaging of cured meat applications. The challenge is not just about waste, it is vital managing and using resources responsibly to create a sustainable future. Food waste still remains a key challenge throughout the supply chain and is not solely a loss of the actual food, but the loss of all the resources put in its production, processing, packaging, transportation, distribution and storage at the retail store and household. Therefore, when designing packaging, a whole system approach where preserving food quality and safety is given as a highest priority and plastic material is given a circular life can be targeted at the first place, among the other sustainable alternatives, to reduce resources across industries. This holistic yet food-specific approach implemented in this review will guide several key actors in the food and packaging ecosystem in designing packaging with circularity targets.

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Chapter 2

Functional properties of food packaging solutions alternative to conventional multilayer systems

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1. Introduction

Fostered by convenience, functionality, and excellent quality and safety, the consumption of packaged foods has increased significantly over the last decades (Kan et al., 2022; Asgher et al., 2020). The global packaged food market accounted for $ 1.9 trillion in 2020 and is bound to reach a value of $ 3.4 trillion by 2030 (Kan et al., 2022). Hence, packaging plays a crucial role in the food industry, providing quality preservation and safety maintenance of food products (McMillin, 2017). The main goal of packaging is to protect food from deterioration due to biological (e.g., microbial spoilage, and enzymatic reactions) and physicochemical factors (e.g., gas transfer, moisture loss/uptake, and mechanical stresses), while facilitating all the logistic phases from the company to the consumer's home (Asgher et al., 2020). However, nowadays food packaging waste represents an important issue that must be addressed to possibly tackle the environmental challenges caused by improper waste management (Kan et al., 2022). In Europe, petroleum-based plastics are mostly used to produce food packaging in both rigid and flexible configurations (Kan et al., 2022). Plastic polymers are usually combined to create multilayer packaging systems endowed with excellent functional features, such as mechanical strength, barrier properties, and heat sealability, but also low cost (Bauer et al., 2021). Nevertheless, heterogeneous multilayer plastics are not environmentally sustainable: their short service life and their non-renewable origin, together with the high volume of waste generated, pose serious risks to the environment (Asgher et al., 2020). In addition, the combination of materials with different chemical compositions, such as polyethylene terephthalate (PET) and polyolefins like polyethylene (PE) or polypropylene (PP), is one of the main causes complicating their mechanical recycling, together with the difficult identification, collection, and separation of the different plastic layers within current recycling plants (Kaiser et al., 2018).

Therefore, considering the increasing demand for packaged food products worldwide, there is an urgent need to switch to alternative packaging materials able to ensure food quality and safety similar to conventional multilayer packaging, but with a reduced environmental impact (Kan et al., 2022). In this scenario, the outlined strategies of the European Commission aiming for a green transition in packaging development encompass i) the reduction of over-packaging by decreasing the overall thickness and unnecessary packaging, ii) the reduction of packaging complexity by using easily recyclable materials (e.g., mono-materials or recycled materials), and finally iii) the use of bio-based and/or biodegradable/compostable materials (European Union, 2018; European Commission, 2018). Hence, replacing heterogeneous multilayer plastic packaging with materials and configurations that allow for over-packaging reduction, increase the recycling rate, and reduce the upstream amount of plastics of fossil origin can represent a viable strategy to fulfill a circular economy approach in the food packaging sector (Bauer et al., 2021; Kaiser et al., 2018).

Several packaged foods rely on modified atmosphere packaging (MAP) to maintain safety and extended shelf-life (McMillin, 2017). MAP techniques have been used on a wide range of fresh or chilled foods, including raw and cooked/processed meat, fish and poultry, fresh pasta, fresh and cut fruits and vegetables, as well as coffee, tea, and confectionary products (Goswami, & Mangaraj, 2011). Moreover, foods stored under MAP require highly efficient packaging materials in terms of barrier properties since the gas/vapor permeability of the package may alter the internal atmosphere (Langhe & Ponting, 2016).

The packaging solutions employed for the storage of chilled food products under MAP involve a two-component lid/tray sealed system generally made of different plastic layers, such as PET, PE, linear low-density polyethylene (LLDPE), and polyamide (PA). The latters are often coated with barrier coatings, e.g., ethylene vinyl alcohol (EVOH), aluminum oxide (AlOx), and silicone oxide (SiOx), to maximize the barrier performance, thus limiting any gas exchange across the packaging material and preserving the modified atmosphere over storage (Galikhanov et al., 2015; McMillin, 2017; Schneider et al., 2009; Korte et al., 2023). In particular, for foods sensitive to oxygen-dependent decay mechanisms (microbiological spoilage, lipid oxidation, and discoloration), MAP must provide and maintain an anoxic environment either by using passive systems (e.g., high oxygen barrier materials) or active devices (e.g., oxygen scavengers) (Langhe & Ponting, 2016). Nowadays, there are only a few alternative packaging solutions for chilled food under MAP aimed at improving sustainability at the same level of protection granted by multilayer configurations (Korte et al., 2023). One example is given by paper-based trays or pouches, intended for refrigerated sliced meat and cheese products or fresh vegetables, which can be sorted in the paper stream collection in Europe (McMillin, 2017).

Based on the above considerations, in this work, a comparative performance analysis between conventional packaging materials (both tray and lid films) and different alternative solutions reliant on plastic weight reduction, use of potentially recyclable packaging such as mono materials (i.e., mono-PET and paper), and bio-based materials was executed. To this end, optical (transparency, and haze), mechanical (elastic modulus, elongation at break, and tensile strength), and barrier (carbon dioxide, oxygen, and water vapor transmission rates) properties of tested materials were assessed. The outcomes of this work will help in supporting further innovations in the development of MAP systems for chilled foods, also considering the increasing requirements for high sustainability, food safety, and quality imposed by European legislation.

2. Materials and methods

2.1. Packaging materials and thickness measurement

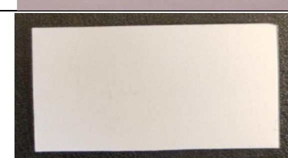
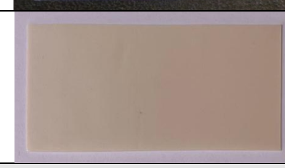
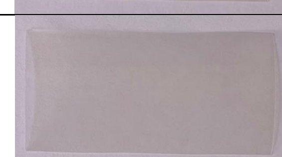
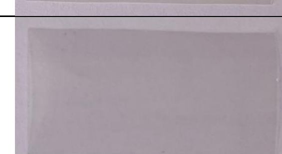
The different commercial configurations of both trays and lids (Table 1) were gently provided by different packaging companies based in EU and were selected for this study due to their specific application in chilled food products stored under MAP (e.g., cured ham, cheese).

The conventional solution for the tray, coded as T-STD$_{250}$, consisted of a coextruded amorphous polyethylene terephthalate (APET) film of 200 µm thickness with an oxygen/water vapor barrier PE/EVOH/PE structure. Four alternative configurations were also investigated, namely i) the same coextruded material as that previously described, but with a 15% thickness reduction on the APET layer (T-STD$_{220}$); ii) a coextruded three-layer mono-material, coded as T-PET, based on both virgin and recycled PET (r-PET), iii) a laminated multilayer material (T-P) made of a 360 µm thick paper sheet with a PE-EVOH-PE system, and iv) a coextruded bio-based mono-material (T-Bio) made by a specific type of polyester obtained upon polycondensations of diacids and diol (confidential info).

In the case of the lids, coextruded standard configurations (i.e., L-EVOH and L-AlOx) involved a layer of either EVOH or AlOx onto a 12 µm-thick PET film, with the latter being further combined with a 60 µm-thick PE film. Once again, two alternative solutions were scouted, such as a coextruded SiOx-treated PET (L-PET$_{SiOx}$), and a laminated bio-polymeric material (L-Bio) coupling cellulose and polylactic acid (PLA).

The thickness (δ, in µm) of tray and lid films was measured employing a digital micrometer (Dialmatic DDI030M, Bowers Metrology, Bradford, UK) with an accuracy of 1 µm at 15 different random locations. Finally, the averaged thickness was considered for all executed measurements (Farris et al., 2009).

Table 1. Composition and overall thickness of tray and lid samples tested in this work.

Sample	Coded name	Composition (from internal to external side)	δ (μm)	Images
Tray (T)				
Standard 250	T-STD_{250}	PE/EVOH/PE (50 μm) – APET (200 μm)	249.8 ± 1.3	
Standard 220	T-STD_{220}	PE/EVOH/PE (50 μm) – APET (170 μm)	213.2 ± 2.9	
MonoPET	T-PET	PET/r-PET/PET	272.0 ± 2.8	
Paper	T-P	PE/EVOH/PE (30 μm) – Paper (360 μm)	406.0 ± 8.0	
Biopolymer	T-Bio	Biopolymers from biomass	408.8 ± 10.9	
Lid (L)				
Standard-EVOH	L-EVOH	PE (60 μm) – EVOH – PET (12 μm)	76.8 ± 3.9	
Standard-AlOx	L-AlOx	PE (60 μm) – PET/AlO_x (12 μm)	72.6 ± 1.8	
MonoPET-SiOx	L-PET_{SiOx}	PET/SiO_x/PET	39.0 ± 1.9	
Biopolymer	L-Bio	Cellulose-based/PLA	82.8 ± 2.9	

When available, the thickness of each layer forming tested materials was retrieved from suppliers' technical sheets.
Legend: APET = amorphous polyethylene terephthalate, PE = polyethylene, EVOH = ethylene vinyl-alcohol, PET =

polyethylene terephthalate, r-PET = recycled polyethylene terephthalate, AlOx = aluminium oxide, SiOx = silicon oxide, PLA = poly-lactic acid.

2.2. Analytical determinations

2.2.1. Optical properties

Transparency (T550, in %) and haze (H, in %) of all the investigated packaging materials were evaluated through a high-performance UV-Vis spectrophotometer (Lambda 650, PerkinElmer, Waltham, MA, USA), capable of scanning within a broad wavelength range of 190 – 900 nm. Specifically, T550 was measured following the ASTM D1746 in terms of specular transmittance, obtained when the transmitted radiant flux includes only the light transmitted in the same direction as that of the incident flux at 550 nm. Such wavelength is usually chosen to compare the transparency of samples at conditions to which human eyes are highly sensitive (Farris et al., 2010).

On the other hand, the haze was determined according to the ASTM D1003 standard within the wavelength range of 380 – 780 nm, using a 150 mm integrating sphere that allowed to trap also the diffused transmitted light. Haze is defined as the scattering of light by a specimen responsible for the reduction in contrast of objects viewed through it and indicates the percentage of incident light that deviates by more than 2.5° through the specimen from the original direction of the incident light. Low haze values are associated with high clarity of the materials (Farris et al., 2009). For both transparency and haze, the final data are collected by averaging among a triplicate of analyses.

To investigate the UV-Vis transmission properties of tested samples, transmittance spectra were also captured in the wavelength region of 200 – 800 nm.

2.2.2. Mechanical properties

The elastic modulus (E, in MPa), elongation at break (EAB, in %), and tensile strength (TS, in MPa) of the different materials were obtained by tensile tests using a Z005 dynamometer (Zwick Roell, Ulm, Germany), coupled to the software TestXpert V10.11 for data elaboration. Following the ASTM D882 standard method, film strips of 15 cm in length and 2.5 cm in width were mounted between two clamps 10 cm apart and tested using a 5 kN load cell and a crosshead speed varying between 50 and 500 mm/min depending on the elongation of the specimens. Each average value has been calculated from at least 5 replicates.

2.2.3. Gas and water vapor barrier properties

Measurements of carbon dioxide, oxygen, and water vapor barrier properties of tested materials were executed on a 50 cm^2 surface via a TotalPerm permeability analyzer (ExtrasolutionSrl, Capannori, Italy) equipped with an electrochemical sensor for oxygen detection and an infrared sensor for carbon dioxide and water vapor detection, respectively. The XS-Pro software (Extrasolution Srl, Capannori, Italy) was used for data acquisition and analysis.

The carbon dioxide transmission rate (CO_2TR, in cm^3 m^{-2} day^{-1}) and oxygen transmission rate (O_2TR, in cm^3 m^{-2} day^{-1}) were determined at 23°C and 50% relative humidity (RH) according to the ASTM F2476 and ASTM F2622, respectively. According to the isostatic method, a constant partial pressure difference between the two semi-chambers of the permeation cell of 1 atm was kept throughout the analysis, with a nitrogen carrier flow of 10 mL min^{-1}. The water vapor transmission rate (WVTR, in g m^{-2} day^{-1}) was determined using the standard method ASTM F1249, again with a nitrogen flow of 10 mL min^{-1}, at 38°C and 90% RH (tropical conditions). All the experiments were performed by placing the external side of each sample towards the upper semi-chamber, where the humid test gas (i.e., oxygen, and carbon dioxide) was flushed. Only for the cellulose/PLA sample, specimens were masked using an aluminum-tape mask at the edges to avoid lateral permeation through the fibrous network (Rovera et al., 2020). Each CO_2TR, O_2TR, and WVTR value is derived from at least three analyses (Carullo et al., 2023).

2.3. Statistical analysis

The statistical significance of differences in the properties and behavior of packaging films was determined by one-way analysis of variance (ANOVA) using the SPSS 27 software (SAS, Cary, NC). When significant differences were found, Tukey's post-hoc test was used to detect significant differences at $p < 0.05$ in case of equal variances. Dunnett's T3 test was used when the variances were not equal.

3. Results and discussion

3.1. Optical properties of packaging materials

The optical properties of food packaging are of utmost importance as they allow one to see through the wrapping, thus showing the appearance of the food. This indicator is known to drive consumers' purchasing choices (Farris et al., 2009). In the specific case of chilled food products, packaging materials must be highly transparent, whilst sheltering from specific light wavelengths that may trigger oxidation and discoloration phenomena (Baele et al., 2021; Domínguez et al., 2019).

Figure 1 shows the UV-Vis transmission spectra (200 – 800 nm) for both tray and lid films. All the tested packaging materials were endowed with a UV-shielding behavior as they displayed a drop in light transmission below 400 nm. Similar UV-light spectra were retrieved by Jakobsen et al. (2005) who dealt with the characterization of APET-PE films destined for cured meat. In our case, a sharp decrease in the material transmittance at around 400 nm until reaching a value close to zero in the UV-C region (100 – 280 nm) was observed. This behavior is attributed to the aromatic ring and the carbonyl group of PET, which blocks the penetration of wavelengths below 315 nm (Curtzwiler et al., 2017). Such a trend was more pronounced for those materials containing a PET layer, including T-STD_{250}, T-STD_{220}, T-PET, L-EVOH, L-AlOx, and L-PET_{SiOx} (Figure 1).

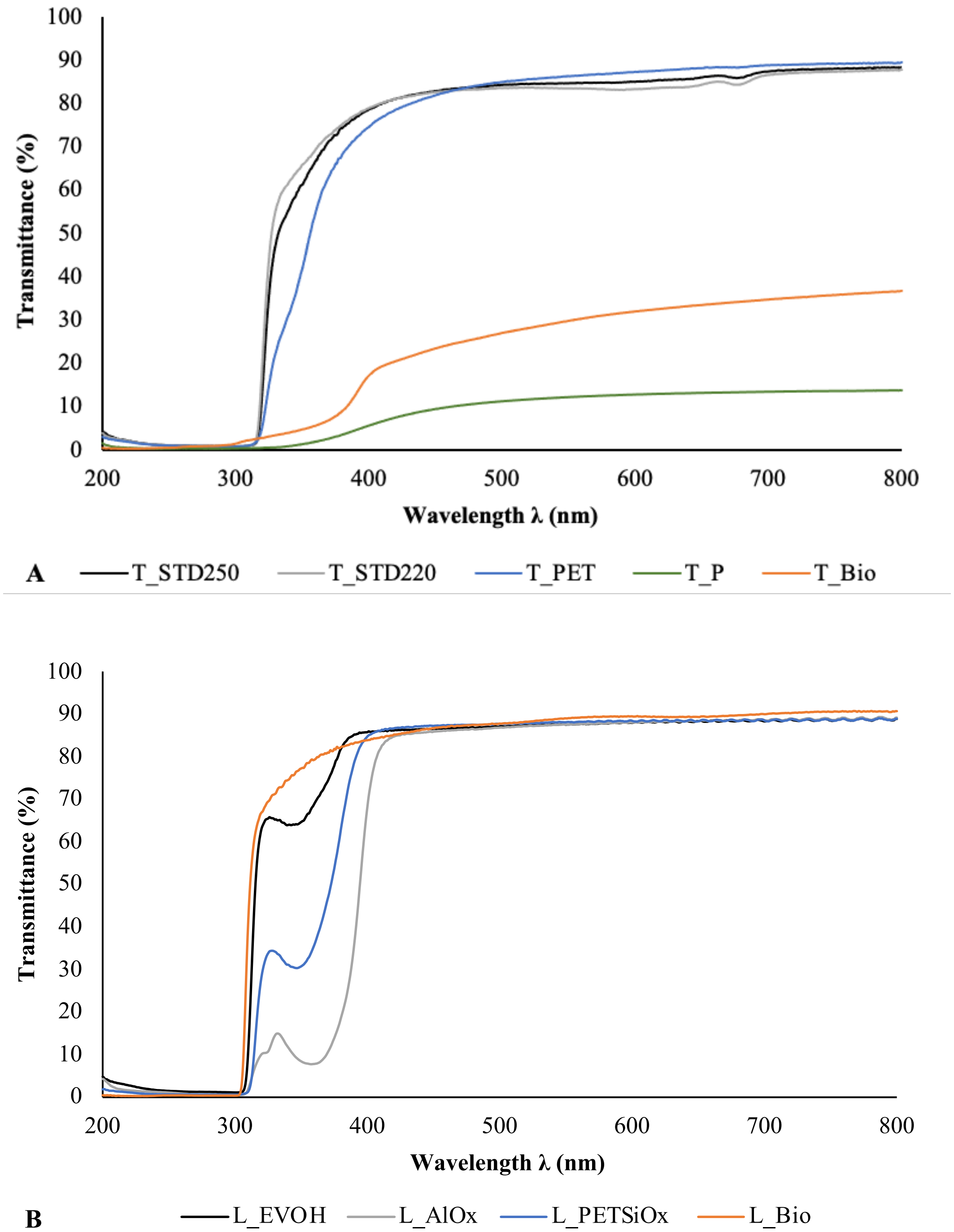


Figure 1. UV-Vis transmission spectra of the trays (A) and lids (B) packaging materials tested in this work.

Concerning the transparency analysis (Table 2), T-STD_{250}, T-STD_{220}, and the T-PET tray films exhibited the highest transmittance values within the visible region (84% < T550 < 86%), thus indicating a moderate degree of transparency. These results are mainly ascribable to the high clarity of amorphous PET, being the main component of the abovementioned plastic tray films (Nisticò, 2020). In agreement with our results, Lim et al. (2020) found the transparency of trays mainly composed of PET to be approximately 86%. On the other hand, the paper and biopolymer-based tray films are characterized by very low transmittance values at 550 nm (12% and 29%, respectively), owing to the intrinsic opacity of the films. These poor optical properties are also confirmed by the high haze values (92.11% and 97.70% for T-P and T-Bio, respectively), which exceeded the 30% threshold value for light diffusion (Chatterjee et al., 2014). However, the lid films behaved decidedly better, with transparency values between 87% and 89%. This has great practical importance since the top view of a package is, in most cases, the dominant one at the retailers. Noteworthy, all the films, except for the tray biopolymer, include a barrier layer, i.e. EVOH, AlOx, and SiOx, which does not affect the transparency as already observed by Bauer et al. (2021).

Table 2. Values of the transparency (T_{550}) and haze (H) for the packaging materials tested in this work.

Material	T_{550} (%)	H (%)
Tray		
T-STD_{250}	84.7 ± 0.1[b]	13.4 ± 0.7[b]
T-STD_{220}	83.4 ± 0.3[b]	14.0 ± 0.8[b]
T-PET	86.2 ± 0.1[a]	4.7 ± 0.2[c]
T-P	12.1 ± 0.4[d]	92.1 ± 7.0[a]
T-Bio	29.8 ± 1.1[c]	97.7 ± 1.6[a]
Lid		
L-EVOH	87.5 ± 0.2[b]	9.9 ± 0.6[b]
L-AlOx	87.6 ± 0.1[b]	14.1 ± 1.0[a]
L-PET_{SiOx}	88.0 ± 0.1[b]	9.2 ± 0.3[b]
L-Bio	88.9 ± 0.3[a]	6.6 ± 0.3[c]

[a, b, c, d] For each parameter and packaging type (tray or lid), different letters within the same column denote significant differences ($p < 0.05$) among samples.

3.2. Tensile properties of packaging materials

Resistance to tearing, vibration, shocks, compression/crushing, and good machine handling features play a vital role in keeping package integrity throughout the food supply chain. In particular, stiffness, flexibility, and toughness are strictly sought after in semi-rigid thermoformed tray solutions for food applications (Buntinx et al., 2014).

The results of tensile tests carried out on selected packaging materials both in machine and in transverse directions (MD, and TD, respectively) are reported in Table 3. The plastic multilayer films exhibited on average an elastic modulus of 1900 MPa in both machine and transverse directions. Nevertheless, the T-PET film showed a significantly ($p < 0.05$) higher elastic modulus (2289 and 2250 MPa for transverse and machine direction, respectively) as compared to the other multilayer films, owing to the absence of weak PE layers and, hence, displaying good toughness.

Good mechanical properties were recorded for the paper-based film due to the coupling with a PE-EVOH-PE layer (Shorey et al., 2022). However, statistical differences ($p < 0.05$) within the paper-based film were highlighted in terms of elongation at break and tensile strength between the tested directions (39.7% and 49.4 MPa in TD vs. 13.7% and 33.3 MPa in MD, respectively). As expected, the bio-based polymer tray was characterized by the greatest elastic modulus, as well as by the lowest elongation at break (Table 3), due to its high rigidity, brittleness, and reduced degree of plasticity pertaining to biobased polyesters (De Beukelaer et al., 2022). These characteristics may potentially lead to the formation of discontinuities, cracks, or even large breakages upon mechanical stresses (e.g., shocks, vibration, and compression/crushing) likely occurring during the processing and transportation phases (Pietrosanto et al., 2020).

As far as the lid films are concerned, L-EVOH and L-AlOx multilayer systems showed comparable ($p > 0.05$) mechanical properties, with a percentage of elongation at break ranging between 39% and 47%. Interestingly, similar values of E, EAB, and TS were disclosed by Carullo et al. (2023) when characterizing three multi-layer systems currently commercialized for food packaging purposes. This pinpoints that L-EVOH and L-AlOx structures have “acceptable” mechanical properties, that is, they are suitable to undergo industrial applications. The L-PET_{SiOx} film showed the highest value of E, together with extensibility ranging between 29% and 39% in TD and MD, respectively. The high strength of the above sample is surely imparted by the rigidity of the silicon oxide layer ($E_{metal} \approx 80$ GPa) that, in turn, curbs flexibility (Howells et al., 2008; Galotto et al., 2008). Such toughness can be also observed in the high tensile strength values (133.8 MPa and 135.3 MPa in TD and MD, respectively) in conventional lids ($p < 0.05$). Alike tray films, the biopolymer lid had a higher E and significantly lower elongation at break in MD (7%) as compared to the conventional materials ($p < 0.05$), likely due to the PLA layer which provides brittleness and rigidity to the material (Pietrosanto et al., 2020).

Table 3. Values of elastic modulus (E), elongation at break (EAB), and tensile strength (TS) in both transverse (MD) and machine direction (TD) for the packaging materials tested in this work.

Material	E (MPa)	EAB (%)	TS (MPa)
Tray – TD			
T-STD$_{250}$	1982 ± 58^{c}	$^{*}5.0 \pm 2.7^{b}$	50.2 ± 1.4^{a}
T-STD$_{220}$	1828 ± 28^{b}	3.8 ± 0.2^{ab}	49.6 ± 1.4^{a}
T-PET	2289 ± 43^{d}	15.0 ± 2.0^{c}	58.3 ± 2.7^{b}
T-P	1604 ± 62^{a}	$^{*}39.7 \pm 1.7^{d}$	$^{*}49.4 \pm 6.9^{a}$
T-Bio	4544 ± 226^{e}	2.5 ± 0.1^{a}	45.2 ± 2.8^{a}
Tray – MD			
T-STD$_{250}$	1900 ± 76^{A}	$^{*}10.5 \pm 1.2^{B}$	51.5 ± 3.1^{C}
T-STD$_{220}$	1851 ± 18^{A}	3.8 ± 0.2^{A}	49.6 ± 1.4^{C}
T-PET	2250 ± 26^{B}	16.0 ± 3.9^{B}	59.9 ± 1.8^{D}
T-P	1745 ± 105^{A}	$^{*}13.7 \pm 3.3^{B}$	$^{*}33.3 \pm 1.0^{A}$
T-Bio	4082 ± 130^{C}	2.2 ± 0.2^{A}	40.9 ± 1.3^{B}
Lid – TD			
L-EVOH	1343 ± 152^{a}	39.9 ± 7.0^{bc}	37.8 ± 2.0^{a}
L-AlO$_{x}$	1166 ± 39^{a}	45.4 ± 4.1^{c}	39.2 ± 1.7^{a}
L-PET$_{SiOx}$	4575 ± 488^{c}	29.5 ± 7.6^{a}	133.8 ± 17.9^{c}
L-Bio	2817 ± 347^{b}	$^{*}33.6 \pm 5.6^{ab}$	63.8 ± 2.3^{b}
Lid – MD			
L-EVOH	1356 ± 43^{A}	47.5 ± 7.2^{BC}	37.8 ± 1.1^{A}
L-AlO$_{x}$	1090 ± 62^{A}	53.2 ± 9.1^{C}	39.4 ± 2.0^{A}
L-PET$_{SiOx}$	4698 ± 144^{C}	40.0 ± 7.1^{B}	135.3 ± 8.8^{C}
L-Bio	2998 ± 337^{B}	$^{*}7.2 \pm 3.9^{A}$	65.5 ± 2.6^{B}

[a, b, c, d] For each parameter and packaging type (tray or lid), different lowercase and uppercase letters within the same column denote significant differences ($p < 0.05$) among samples when analyzed in TD and MD, respectively. When reported, the symbol * denotes a significant difference ($p < 0.05$) between MD and TD within a same material.

3.3. Barrier properties of packaging materials

The barrier properties of packaging materials to gases and moisture are known to affect the quality of food items throughout storage (Bauer et al., 2021). Most of the products with MAP require an atmosphere devoid of oxygen to prevent lipid oxidation, color/flavor instability, and microbial spoilage (Langhe & Ponting, 2016). Therefore, the associated packaging material must display adequate barrier properties that reduce/minimize gas exchange. Table 4 shows the CO_2TR, O_2TR, and WVTR of the investigated samples. Regarding the CO_2 barrier properties, T-Bio showed the lowest value as compared to the standard multilayer film, which suggests the presence of a barrier layer within the biopolymer tray film structure. Significantly ($p < 0.05$) different O_2TR values were instead detected when dealing with the two multilayer conventional plastic films. The excellent oxygen barrier properties (< 1 cm^3 m^{-2} day^{-1}) belonging to these samples are imparted by the EVOH layer sandwiched between the two PE layers, being the most commercially employed material when high oxygen sheltering effects are required (Bauer et al., 2021; Farris et al., 2009). This agrees with the performances already reported in the literature for multilayer plastic films mainly made of APET and PE (Buntinx et al., 2014). Finally, it is interesting to note that T-STD_{220}, T-PET, and T-Bio exhibited similar WVTR values ($p > 0.05$). However, the paper tray film (T-P) showed a significantly ($p < 0.05$) higher value (25.80 g m^{-2} day^{-1}) in comparison to all the other materials. This can be attributed to the porosity of the paper-based layer which favors the diffusion of vapor, even though the presence of hydrophobic polyolefins (e.g., double PE layer) already guarantees good moisture barrier properties (Carullo et al., 2023).

L-EVOH and L-PET_{SiOx} showed comparable CO_2TR and O_2TR values ($p > 0.05$), thus clearly indicating that both barrier layers (i.e., EVOH and SiOx) impaired the transport of carbon dioxide and oxygen across the lidding films (Korte et al., 2023). Together with EVOH, silicon oxide (SiOx) coatings can successfully boost the gas barrier properties of bare plastic packaging, owing to a 100-fold reduction in the permeation of gases through polymer film (Howells et al., 2008). L-AlOx and L-Bio lid films have similar CO_2TR values, despite being both significantly higher ($p < 0.05$) as compared to L-EVOH and L-PET_{SiOx}. L-AlOx showed a good performance in terms of oxygen and moisture barrier properties, confirming the barrier capacity of the AlOx layer (Galikhanov et al., 2014; Butler & Morris, 2016). The comparison among samples concerning the WVTR revealed that all lid materials performed well with very similar values, except for the L-EVOH film lid, which was characterized by a significantly ($p < 0.05$) higher value (4.97 g m^{-2} day^{-1}). Overall, the best performance in terms of gas/water vapor transmission rates was shown by the L-PET_{SiOx} sample, which had the lowest CO_2TR, O_2TR, and WVTR (Table 4).

Table 4. Values of carbon dioxide transmission rate (CO_2TR), oxygen transmission rate (O_2TR), and water vapor transmission rate (WVTR) for the packaging materials tested in this work.

Material	CO_2TR (cm^3 m^{-2} day^{-1})	O_2TR (cm^3 m^{-2} day^{-1})	WVTR (g m^{-2} day^{-1})
Tray			
T-STD_{250}	1.53 ± 0.17^b	$^*0.33 \pm 0.06$	< LDL
T-STD_{220}	4.67 ± 0.52^c	$^*0.78 \pm 0.09$	3.97 ± 0.33^a
T-PET	< LDL	< LDL	3.96 ± 0.27^a
T-P	< LDL	< LDL	25.80 ± 1.92^b
T-Bio	0.53 ± 0.10^a	< LDL	2.85 ± 0.27^a
Lid			
L-EVOH	4.32 ± 0.32^a	0.11 ± 0.02^a	4.97 ± 0.58^b
L-AlO_x	18.19 ± 1.17^b	3.18 ± 0.36^b	1.51 ± 0.20^a
L-PET_{SiOx}	3.20 ± 0.38^a	0.49 ± 0.07^a	0.86 ± 0.11^a
L-Bio	19.74 ± 1.42^b	< LDL	2.18 ± 0.21^a

[a, b, c, d] For each parameter and packaging type (tray or lid), different letters within the same column denote significant differences ($p < 0.05$) among samples. When reported, the symbol * denotes a significant difference ($p < 0.05$) with a Student's t-test when comparing only two samples.

Legend: LDL = lower detection limit (0.25 cm^3 m^{-2} day^{-1} for CO_2TR, 0.01 cm^3 m^{-2} day^{-1} for O_2TR, and 0.0022 g m^{-2} day^{-1} for WVTR).

4. Conclusions

This study highlighted the great potential of alternative packaging solutions to replace conventional multilayer configurations for MAP chilled food products as far as their functional properties are concerned, thus aligning with the rising demand for greater sustainability and encompassing factors like reduced weight, enhanced recyclability, and utilization of bio-based materials.

All the alternative packaging configurations tested in this work showed good transparency and UV-shielding behavior, as well as comparable or superior mechanical/gas-vapor barrier properties to those on conventional solutions. Future studies will focus on the effectiveness of the tested alternative packaging systems to guarantee the required shelf-life of MAP chilled food products as compared to conventional solutions and will provide a quantitative assessment of their environmental sustainability through a life cycle assessment (LCA) analysis.

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Chapter 3

Life Cycle Assessment of Mono-material and Multi-material Packaging for Cured Meat Products

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Declaration: This chapter was written by Anna Mengozzi and reviewed by all co-authors.

1. Introduction

In the last decades, the consumption of cured meat products, including cooked ham, cured raw ham, and salami has steadily risen worldwide (FAOSTAT, 2022). In particular, in Italy, packaged cured meat products have always been highly appreciated by consumers with substantial economic relevance for the meat market. Recently, these products have experienced notable growth, with a 6.7% increase in sales from 2022 to 2023 (ISIT, 2024).

Cured meat products are characterized by high perishability and susceptibility to physicochemical degradation and microbial spoilage, which strongly limit their shelf-life. Therefore, adequate packaging design represents an important element in extending as much as possible the safety and quality during their life cycle (Sørheim et al., 2017; Korte et al., 2023). Common packaging for cured meat products relies on multi-material films that allow the maintenance of a modified atmosphere packaging (MAP) (composed of a different percentage of carbon dioxide (CO_2), oxygen (O_2), and nitrogen (N_2)) within a tray/lid film sealed system (Onyeaka, & Nwabor, 2022). According to Schmidt et al. (2022) and Seier et al. (2023), multi-material packaging constitutes between 17% to 30% of all plastic packaging. This packaging is largely applied in the food sector because of its excellent sensorial barrier properties and efficiency in quality and safety preservation. The combination with a modified atmosphere hinders the proliferation of microorganisms and delays deterioration phenomena (e.g., lipid oxidation and discoloration), allowing the shelf-life extension between 35 and 45 days of sensitive and perishable food like cured meat products (McMillin, 2017; Korte et al., 2023; Parry, 2012). The tray and lid films are composed of a combination of several polymers, including polyolefins, polyamide (PA), and polyethylene terephthalate (PET), together with different types of barrier layers, like ethylene vinyl alcohol (EVOH), or inorganic coatings such as aluminum oxide (AlOx), and silicone oxide (SiOx) (McMillin, 2017; Galikhanov et al., 2015; De Mello Soares et al., 2022).

Multi-material food packaging at its end-of-life (EoL) poses significant challenges for mechanical recycling because the combination of different polymers complicates the recycling process since separating these components is often inefficient and costly. As a result, multi-material packaging ends up in landfills or incineration facilities, contributing to environmental pollution due to its inability to be efficiently recycled (Kaiser et al., 2018; Bauer et al., 2020; Schmidt et al., 2022). To overcome this constraint and to comply with the European Union (EU) Packaging and Packaging Waste Regulation (PPWR) (European Union, 2024), which emphasizes the use of materials with recyclability characteristics, innovative recycling technology solutions are being explored, including the use of compatibilizers, depolymerization, pyrolysis, and gasification. However, these technologies have yet to be effectively implemented on a large scale (Ragaert et al., 2023; Thuy et al., 2020; Matthews et al., 2021). A promising solution to recycling is mono-material packaging solutions, which are more likely to be managed with the current existing mechanical recycling infrastructure than multi-material packaging (Bauer et al., 2021; De Mello Soares et al., 2022).

In particular, mono-PET tray/lid film sealed systems could be suitable for MAP, but no valid applications for cured meats are present in the supermarket. Packaging companies are working on two strategies to optimize mono-PET packaging systems: increasing the thickness of both the tray and lid films and including a barrier layer with a weight lower than 5% of the total packaging weight (CEFLEX, 2020; Bauer et al., 2021). Recently, Korte al. (2023) have shown that a mono-PET packaging solution with EVOH as a barrier layer allows the preservation of several types of cured meat products (i.e., pure emulsion-type sausage, ham sausage, and mushroom ham sausage) for up to 26 days. However, even though the use of mono-PET seems promising for both potential applications with MAP and recycling possibilities, only a little information is available on the applicability and sustainability of this material at the industrial level (Packaging Europe, 2022; CEFLEX, 2020).

Therefore, an environmental assessment is crucial to determine the sustainability of this type of packaging for cured meats and to evaluate if a shorter or longer shelf-life influences the overall environmental impact. This evaluation can be conducted using the Life Cycle Assessment (LCA) methodology, which consists of the compilation and evaluation of the inputs, outputs, and corresponding environmental impacts of a product throughout its life cycle (ISO, 2006 a, b). When considering food packaging, it is important to consider direct environmental impacts, such as those associated with packaging production and EoL processes, and indirect impacts, including the influence of the package on the potential food waste (PFW) throughout the food system life cycle, i.e. retail/distribution and households and its relation to shelf-life (Molina-Besch et al., 2019; Tetteh et al., 2024). LCA has been applied to assess the environmental impacts of packaging and many authors have evaluated the environmental performances (only direct effects) of several types of trays packaging for fresh meat (i.e., polystyrene, polystyrene containing EVOH, recycled PET, recycled PET with PE layer, amorphous PET, polypropylene and polylactic acid) (Maga et al., 2019; Ingrao et al., 2015). The results underlined that the most relevant environmental impact came from polymer extraction and film production. However, these studies did not include the packaging protection performances, i.e. shelf-life variations, that could significantly influence the outcomes. In recent years, LCA studies of food packaging, i.e., plastic multi-material and bio-based packaging for fresh meat (Casson et al., 2022), cheese (Dilkes-Hoffman et al., 2018) and cheesecake (Gutierrez et al., 2017) have analyzed food packaging systems, considering both packaging and packed food, and including direct packaging environmental impacts and indirect food waste generation environmental impact, linked to the effective shelf-life of the packaging. These studies identified food waste as a hotspot, underlining the need to reduce food waste as a key design consideration in packaging selection. Therefore, addressing the indirect impact associated with food waste is crucial for a comprehensive evaluation of the overall sustainability of food systems.

The purposes of this study are two: 1) to compare the environmental impacts of mono- and multi-material MAP packaging for sliced cooked ham from a cradle-to-grave approach, and 2) to assess the influence of the PFW throughout the system life cycle, which derives from the shelf-life of the two different packaging system. In addition, a sensitivity analysis was carried out to assess the influence of including recycling packaging on the environmental impacts rather than their conventional EoL (landfill, incineration, and open burn).

2. Material and methods

This environmental assessment applies the principles, framework, and guidelines from the ISO 14040 and 14044 standards (ISO 2006a, b).

2.1. Systems analyzed, functional unit, and system boundaries

The two packaging encompass a tray and lid film with different polymeric structures and the same gas mixture ratio, dimensions, and volume, as presented in Table 1. Therefore, two packaging were studied as follows:

(1) mono-material, comprising a PET and EVOH for the tray, and APET and aluminum oxide (AlOx) for the lid film (Table 1);

(2) multi-material, comprising three multi-material tray and lid films made of APET or PET, PE and EVOH for both tray and lid films (Table 1).

The expected shelf-life of cooked ham was 21 and 35 days for the mono-material and the multi-material packaging, respectively. During the shelf-life test, microbiological and quality parameters of the two packaging systems were monitored during storage at 4°C (replicating the same illumination conditions as a supermarket shelf). The test highlighted that in the mono-material packaging the limiting factor affecting the shelf-life was a decay on the quality of the ham, which was dehydrated and showed a released of an exudate after 21 days. On the other hand, the ham in the multi-material packaging preserved its quality attributes for 35 days (data not shown).

Table 1. Packaging layers composition, gas mixture, dimensions, weight, volume, and effective shelf-life of packaging systems under study.

	Unit	**Mono-material**	**Multi-material**
Tray film[a]	-	PET-EVOH-PET	APET-PE-EVOH-PE
Lid film[a]	-	APET-AlOx-APET	PET-EVOH-PE
Gas mixture	%	45:55 (CO_2: N_2) (residual $O_2 < 0.1$)	45:55 (CO_2: N_2) (residual $O_2 < 0.1$)
Dimensions (L x W x H)	cm	23.5 x 20 x 1.2	23.5 x 20 x 1.2
Total weight	g	17.6	16.4
Tray weight	g	15	12.8
Lid weight	g	2.6	3.6
External volume	cm^3	464	464
Effective shelf-life	day	21	35

[a]acronymous: APET- amorphous polyethylene terephthalate; PET- polyethylene terephthalate: PE-polyethylene; EVOH- ethylene vinyl alcohol; AlOx- aluminum oxide.

The functional unit (FU) is one packaging unit that contains 100 g of sliced cooked ham, considering the specific effective shelf-life for each cooked ham-MAP packaging system as stated in Table 1, and the losses and potential waste of cooked ham and packaging generated over the supply chain. The shelf-life values are referred to 4ºC of storage (Section 2.2.2.).

The system boundaries include seven stages as follows: (1) flexible film production; (2) sliced cooked ham production and cooked ham EoL (3) – considering both losses and PFW of cooked ham generated throughout the supply chain; (4) sliced cooked ham packing; (5) retail/distribution; (6) household, and (7) packaging EoL (empty package) (Figure 1).

Flexible film production includes all operations from raw materials extraction and polymer processing to mono-material and multi-material packaging production by coextrusion and lamination, respectively. The sliced cooked ham production consists of the operations regarding pork meat production (farming, slaughtering), refrigerated transport, and all cooked ham processing, i.e, brining, molding, cooking (65°C – 75°C for 15 – 18 hours), cooling and storage. Then, the entire cooked ham piece is transported (refrigerated) to the cooked ham company packing and logistic site.

At the sliced cooked ham packing stage, all operations – cooked ham slicing, thermoforming of the tray film, MAP mixture injunction, and sealing with the lid film – occur under refrigerated conditions (temperature 4°C). The solid waste generated during this stage – cooked ham losses, film losses, and packaged cooked ham waste – is subjected to incineration treatment (Figure 1).

The retail/distribution stage considers the refrigerated distribution of packaged cooked ham to the large-scale retail trade all over the Italian territory (islands excluded) and the final product at the retail, i.e. sale points, and the treatment of the related potential cooked ham and packaging waste.

The household stage considers refrigerated storage (4ºC) and the waste treatment of the related potential cooked ham waste and potential packaging waste produced during this stage.

The packaging EoL stage encompasses the treatment of the empty package (Figure 1).

The consumption of cooked ham was excluded from the system boundaries because of its significant dependence on consumer behaviors (i.e., habits, cooking/heating processes, and geography), which can result in variations in food waste at this stage (Casson et al., 2022). The transport of workers and machinery was excluded, as was the production of capital goods (buildings, machinery, and equipment). It is important to note that the excluded processes are likely to have a minimal contribution to the overall environmental impacts.

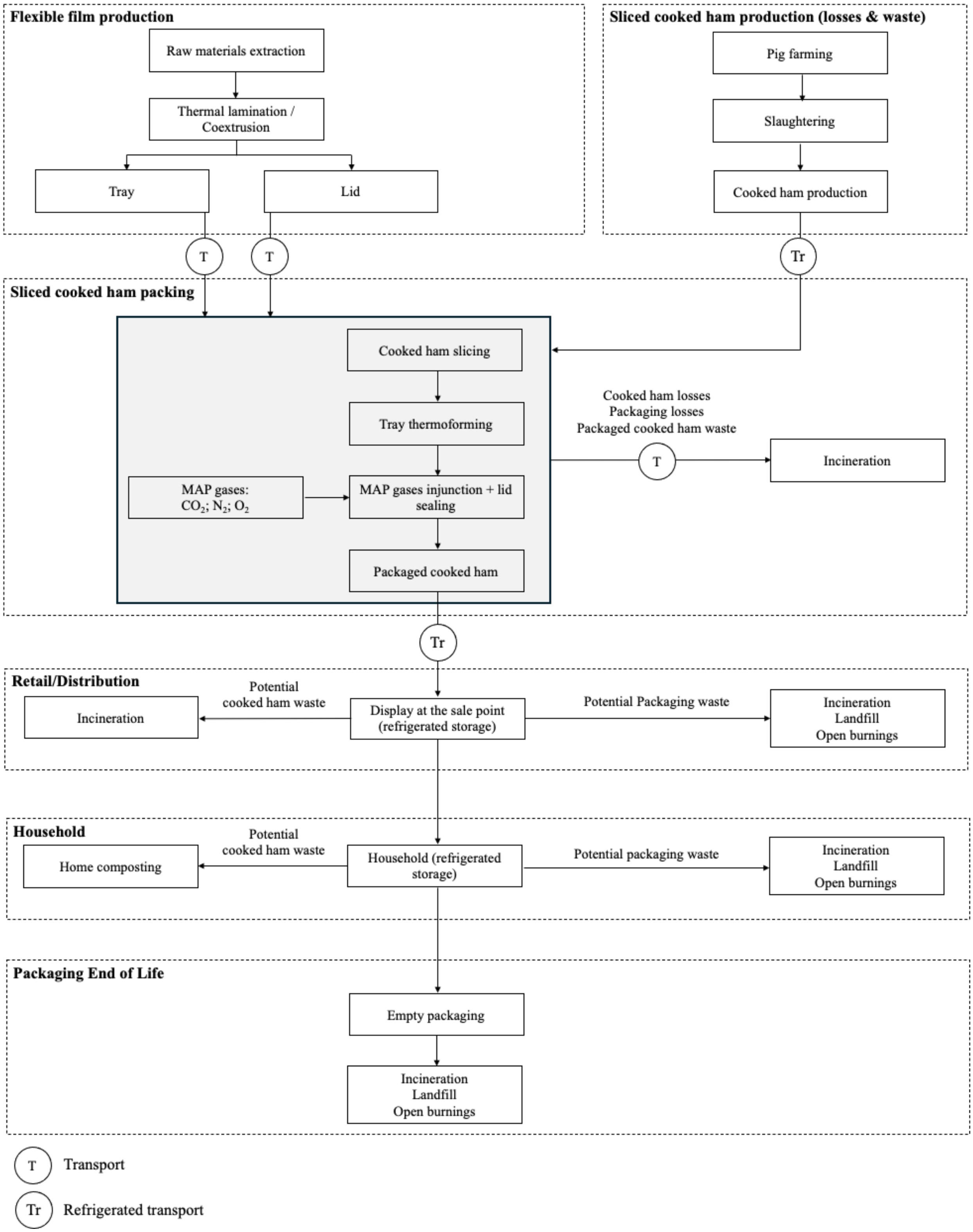

Figure 1. System boundaries.

2.2. Inventory analysis

2.2.1. Packaging systems

The inventory data to produce the cooked ham have been sourced from the World Food LCA database (WFLDB) v3.5 (Nemecek et al., 2019) available in SimaPro software (Pré Consultants, 2021), complemented with primary data provided by a facility in the North of Italy to the cooked ham production. Table 2 presents the inventory data for the packaging systems under study.

Regarding flexible film and packaging production, the quantity of input polymers, gas mixture, electricity consumption and cooked ham and packaging waste, were collected from a representative Italian company for the year 2022. This survey was complemented with information from the Ecoinvent v3.9.1 database (Wernet et al., 2016), concerning the co-extrusion of mono-material tray and lid films. Moreover, for multi-material tray and lid films, data on electricity consumption for tray thermal lamination and lid solventless lamination were sourced from He et al. (2021).

Average distances of 1) 2080 km and 1673 km by truck (Euro 5) from the mono-material tray and lid film producers, respectively, and 2) 357 km and 203 km by truck (Euro 5) from the multi-material tray and lid film producers, respectively, to the cooked ham company (production site), were considered. Moreover, an average distance of 24.2 km from the production site to the packing and logistic site of the cooked ham company, were considered.

Concerning the cooked ham packing, for both packaging systems, it was considered: 1) an unpackaged cooked ham loss of 7%, 2) a packaged cooked ham waste of 1%), and 3) a package loss of 22.9% (including empty packages generated before the modified atmosphere adjustment and all the cuttings from the coil). Therefore, cooked ham losses are equal for both packaging solutions. According to the producer, this packaging losses are submitted to incineration. Also, the unpackaged cooked ham and the packaged cooked ham were directed to incineration with energy recovery. A distance of 14.9 km from the cooked ham company (production site) to the waste management operator was considered.

Regarding the retail/distribution stage, an average distance of 373 km by refrigerated truck from the cooked ham company (packing and logistic site) to the logistics warehouses/supermarkets was considered. This distance was estimated based on a weighted average distance from the company to every region's capital (islands excluded) and the inhabitants' numbers per region (EUROSTAT, 2022). Data on electricity consumption for the refrigerated storage of packaging systems at warehouses/supermarkets were estimated based on the average electricity consumption of a retail refrigerator of 4.8E-6 kWh/cm^3/day (Fricke & Becker, 2010), the average volume occupied by a packaged cooked ham in the refrigerator (464 cm^3), and the fact that, on average, a meat product spends 20% of its shelf-life at retail (Roccato et al., 2017).

Regarding the household stage, data on electricity consumption for the refrigerated storage of packaging systems were estimated based on the average volume of a consumer refrigerator (300 kWh/year), the total capacity of 250 L (International EPD® System, 2021), and the average time that the packaging spends a household, i.e., 80% of the total shelf-life (Roccato et al., 2017).

The electricity generation was adapted to the Italy electricity mix that consider the electricity consumed in Italy and related data was retrieved from the Ecoinvent database.

At the retail/distribution, households and EoL (empty package) stages, the packaging treatment was considered the specific share of plastic waste management operations in Italy, comprising incineration (44%), landfill (55%), and open burning (1%) (Wernet et al., 2016), for both packaging systems.

2.2.2. Effective shelf-life and cooked ham potential waste

The potential cooked ham waste generated during retail/distribution and household stages, along with the effective shelf-life of each packaging system under study (Table 1) was estimated using the approach developed by Casson et al. (2022). A shelf-life ratio (SLR) for the cooked ham-MAP packaging systems, the weight of cooked ham (100 g), and the food waste percentage probability (FWPP) generated during retail/distribution and household stages were considered. The shelf-life ratio was defined by the worst-case scenario and the effective shelf-life of each packaging system (Table 1). The worst-case scenario refers to the effective shelf-life of 21 days for mono-material packaging (the shorter the shelf-life is linked to the higher the probability of the food not being consumed and thus becoming waste). The SLRs were calculated as 1 and 0.6 for the mono-material and the multi-material respectively. According to Caldeira et al., (2019), a food waste probability of 2.8 and 11.8% were considered for both cooked ham-MAP packaging systems, respectively, at the retail/distribution and household stages. Applying the SLR, the FWPP and the cooked weight of the FU, the potential food waste for every single packaging solution has been quantified as following:

$$PFW = \text{Cooked ham} \times SLR \times FWPP$$

The potential packaging waste during the retail/distribution and household stages was calculated using a similar approach, which considers a proportional relationship between the PFW and the corresponding packaging waste.

The end-of-life of potential cooked ham waste generated at retail/distribution, for both cooked ham-MAP packaging systems under study, was retrieved from the Ecoinvent database, considering 100% of incineration. On the other side, the end-of-life of the potential cooked ham waste generated during households was assumed to be a biowaste treatment (home composting), retrieved from Econinvent.

Table 2. Inventory data per FU for the two cooked ham-MAP packaging systems under study.

Stages		Unit	Mono-material	Multi-material
Flexible film production	**Inputs**			
	Tray:			
	APET	g	-	4.53
	r-APET	g	-	10.57
	PET	g	23.01	-
	PE	g	-	2.98
	EVOH	g	0.71	0.33
	Lid:			
	APET	g	3.95	
	PET	g	-	1.80
	PE	g	-	3.06
	EVOH	g	-	0.32
	AlOx	g	0.16	-
	Electricity	kWh	0.0196	0.0022
	Outputs			
	Tray film	g	22.99	18.41
	Lid film	g	3.98	5.18
Cooked ham production	**Inputs**			
	Meat pork	g	22.59	16.75
	Electricity	kWh	0.026	0.035
	Outputs			
	Cooked ham	g	22.59	16.75
Cooked ham packing	**Inputs**			
	Tray film + lid film	g	26.97	23.59
	Cooked ham	g	22.59	16.75
	Gases MAP:	g	0.45	0.45
	CO_2	g	0.27	0.27
	N_2	g	0.14	0.14
	O_2	g	0.04	0.04
	Electricity	kWh	0.07	0.07
	Outputs			

	Packaged cooked ham	g	35.56	27.15
	Cooked ham + tray and lid losses	g	14.45	13.64
Retail/distribution	**Inputs**			
	Packaged cooked ham	g	35.56	27.15
	Electricity	kWh	0.011	0.019
	Outputs			
	Packaged cooked ham	g	32.23	25.2
	Potential cooked ham	g	2.76	1.65
	Potential packaging waste		0.57	0.30
Household	**Inputs**			
	Packaged cooked ham	g	32.23	25.2
	Electricity	kWh	0.031	0.052
	Outputs			
	Packaged cooked ham	g	18.04	16.85
	Potential cooked ham waste	g	11.83	7.10
	Potential packaging waste	g	2.36	1.25
Packaging EoL	Atmospheric emissions:			
	CO_2	g	0.27	0.27
	N_2	g	0.14	0.14
	O_2	g	0.04	0.04
	Empty packaging waste	g	17.6	16.4

2.3. Impact assessment

The environmental impacts were assessed for seven impact categories – global warming (GW), ozone formation (terrestrial ecosystems) (OF-TE), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), mineral resource scarcity (MRS), and fossil resource scarcity (FRS), by applying the characterization factors from the ReCiPe 2016 midpoint v.1.01 method (Huijbregts et al., 2016). GW was selected for its significance in evaluating the effects of global climate change. The other impact categories were chosen to ensure a comprehensive and consistent environmental assessment of packaging systems, with particular attention to FRS, considering that the polymers' origins are derived from fossil fuels.

3. Results and discussion

3.1. General environmental assessment

Table 3 presents the total environmental impacts obtained per FU of the two cooked ham-MAP packaging systems under study. Figure 2 shows the relative contribution of each stage within the system boundaries to the total impact obtained per FU for the two cooked ham-MAP packaging systems.

Table 3. Impact assessment results per functional unit for the two cooked ham-MAP packaging systems under study.

Impact categories	Unit	Mono-material	Multi-material
GW	kg CO_2 eq	3.38E-01	2.49E-01
OF-TE	kg NO_x eq	9.17E-04	6.47E-04
TA	kg SO_2 eq	1.27E-03	9.08E-04
FE	kg P eq	6.91E-05	5.94E-05
ME	kg N eq	2.13E-04	1.61E-04
MRS	kg Cu eq	5.82E-04	3.94E-04
FRS	kg oil eq	7.50E-02	4.95E-02

GW: global warming; OF-TE: ozone formation (terrestrial ecosystem); TA: terrestrial acidification; FE: freshwater eutrophication; ME: marine eutrophication; MRS: mineral resource scarcity; FRS: fossil resource scarcity.

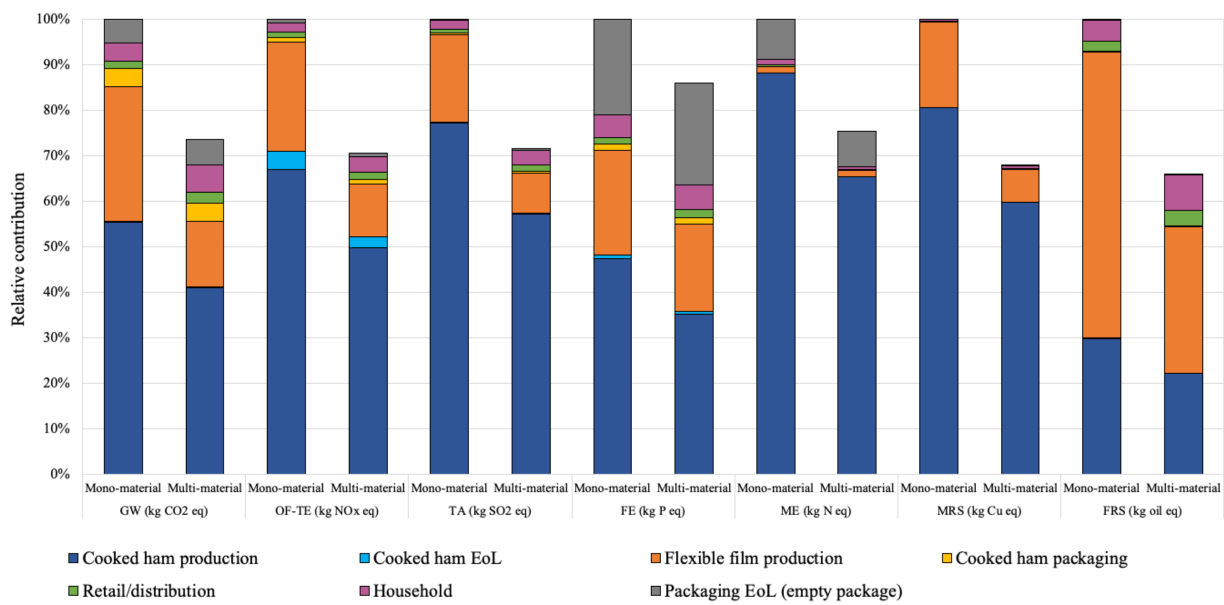

Figure 2. Comparison of the environmental impact of mono-material and multi-material cooked ham-MAP packaging systems.

Overall, the mono-material presented the highest environmental impact across all the impact categories, demonstrating a greater impact than the multi-material, with differences ranging from 15% (for FE) to 35% (for FRS). This remarkable impact difference between the two cooked ham-MAP packaging systems was mostly related to the cooked ham production stage in almost all of the impact categories (6 out of 7), except for the FRS. The shorter mono-material shelf-life of 21 days compared to the multi-material one of 35 days leads to a higher generation of PFW and therefore, higher production of cooked ham is required (Table 1). The shorter shelf-life of the mono-material can be attributed to the low water vapor barrier properties of the tray film (3.96 g m^{-2} day^{-1}), which allows the migration of water vapor through the packaging, leading to a dehydration of the cooked ham and compromising the final quality of the cooked ham. For FRS, the difference is related to the flexible film production stage, as the mono-material requires a higher quantity of raw materials to produce PET, in both tray and lid film (Table 1).

Figure 2 shows the relevance of flexible film production for the total impacts, presenting a contribution from 57% (FRS) to 1% (ME) for mono-material and from 47% (FRS) to 1% (ME) for multi-material. The high contribution of flexible film production in mono-material is due to the higher quantity of polymer to produce the packaging (Table 1), and to the fact that film is produced from 100% virgin PET, unlike multi-material tray, which consists of 80% recycled PET and only 20% virgin PET.

Moreover, in the discussion surrounding mono-material versus multi-material cooked ham-MAP packaging systems, recyclability remains a key focus. The mono-PET packaging under study is a non-complex system composed only of one layer, that could become recyclable shortly, supported by advancements in plastic sorting and recycling technologies within European infrastructures (COREPLA, 2022). However, the use of a single polymer (i.e., PET), along with the requirement that the barrier layer must constitute less than 5% of the total packaging weight to be considered as mono-material, compromises the barrier properties of the packaging and may lead to a reduction in the shelf-life of highly perishable food. Manufacturers often mitigate this limitation by increasing packaging thickness, resulting in negative environmental impacts due to the increased weight of raw materials. While multi-material packaging is inherently a more complex system and is currently non-recyclable, combining various polymers enhances the shelf-life performance resulting in greater efficiency and a reduction in plastic polymers' overall weight (Bauer et al., 2021).

For FE and ME, the packaging EoL assumes a contribution from 20% (FE) to 8% (ME) for mono-material and from 22% (FE) to 7% (ME) for multi-material. This impact is mainly attributed to the fraction of packaging waste (55%) that is disposed into landfills, which in FE and ME leads to the leaching of COD (chemical oxygen demand) and BOD5 (biological oxygen demand over

5 days), and nitrogen emissions, respectively, that potentially contaminates the groundwater (Nagarajan et al., 2012).

3.2. Environmental impact comparison considering only the packaging life cycle

The contribution of each packing life cycle to the different impact categories is shown in Figure 3, considering only the packaging analyzed.

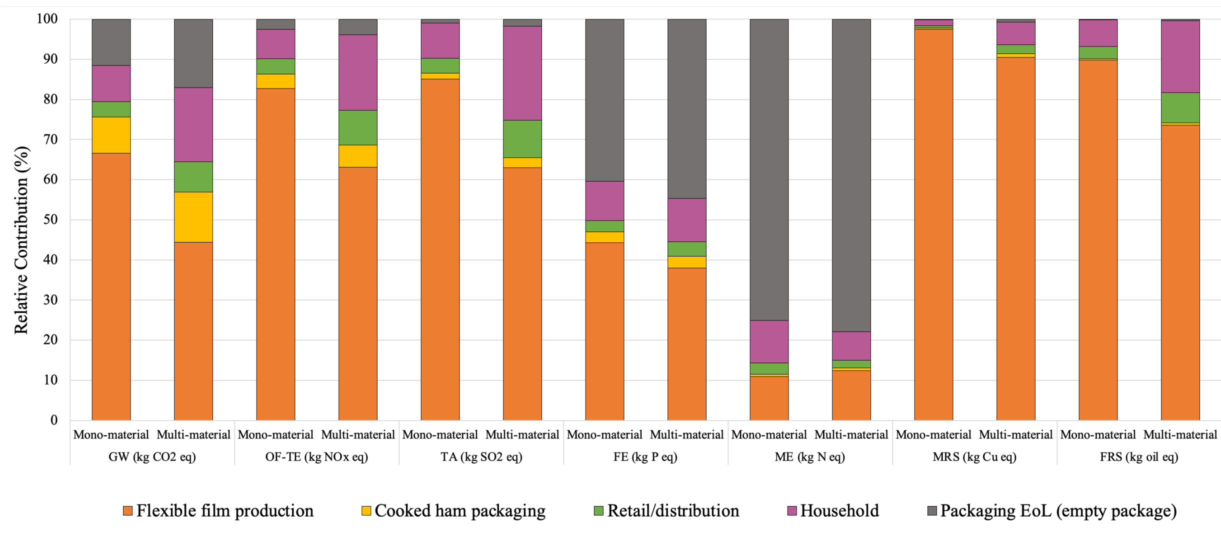

Figure 3. Comparison of the only packaging environmental impact for mono-material and multi-material packaging.

Focus only on the packaging, the flexible film production, particularly tray and lid films, was particularly relevant for all impact categories, with contributions that range from 97% (MRS) to 10% (ME) for mono-material packaging and from 90% (MRS) to 12% (ME) for multi-material packaging. The impacts result mainly from the production of PET polymer resin, as mentioned in section 3.1.

The main contributors to GW, OF-TE, and TA were the direct emissions of non-methane volatile compounds and nitrogen oxides associated with producing purified terephthalic acid during PET manufacturing (Akanuma et al., 2014). For MRS and FRS, the impacts are due to the extraction of cobalt and crude oil polymers, respectively. In FE, flexible film production and packaging EoL have similar impact contributions for both packaging solutions. In mono-material, flexible film production and packaging EoL are responsible for 44% (main hotspot) and 40%, respectively. In multi-material, flexible film production and packaging EoL are responsible for 38% and 44% (main hotspot), respectively. Regarding ME, packaging EoL is responsible for 75% (mono-material) and for 77% (multi-material). These impacts are mainly due to the packaging disposal at the landfill, as explained in section 3.1. Furthermore, the packaging EoL is the second hotspot from GW in both packaging solutions, with a contribution of 11 and 17 % for mono-material and multi-material packaging, respectively. This impact is related to the direct carbon emissions to the air deriving from the incineration treatment. This contribution is close to the contribution of cooked ham packaging (9% and 12%, for mono-material and multi-material, respectively), mainly due to electricity consumption.

Within flexible film production, the tray was the hotspot for all the impact categories in both packaging systems, ranging from 70% (MRS) to 9% (ME) for mono-material and from 76% (MRS) to 9% (ME) for multi-material, to the total impacts of flexible film production. Regarding, the lid, for mono-material packaging, the lid impact ranges from 14% (MRS) to 1% (ME), while for multi-material packaging, the lid's contribution ranges from 19% for MRS to 2% for ME to the total impacts of flexible lid production. The higher environmental impact of the multi-material lid is attributed to its greater weight compared to that of the mono-material lid.

The household stage was raised as the second hotspot for GW, OF-TE, TA, MRS and FRS, mainly due to electricity consumption, which in Italy, selected country for this study, predominantly comes from fossil fuels (European Commission, 2024), with contributions ranging from 10% (ME) to 1% (MRS) for mono-material and from 23% (TA) to 5% (MRS) for multi-material packaging. The higher impacts of multi-material packaging are mainly due to higher electricity consumption, which in turn is due to the longer effective shelf-life, resulting in extended refrigeration time.

Even though other studies have compared the environmental impacts of packaging (it is important to note that a comparison between the results of this earlier study with those of the present study should be considered with caution because a different impact assessment method and methodological aspects were used. For instance, Maga et al. (2019) have compared the environmental impacts of tray solutions for meat packaging from a "cradle-to-gate with the EoL", and defined the FU as a tray with a volume of about 1 L for preserving 500 g of fresh meat. Among several types of trays analyzed in the article, only a recycled mono-PET tray (18.43 g) and a multi-material tray composed of recycled PET and PE (17.65 g) were considered for the comparison. The recycled mono-PET tray (18.43 g) and a multi-material tray (PET-PE) (17.65 g) presented GW values of 0.103 kg CO_2 eq/tray and 0.067 kg CO_2 eq/tray, respectively. These values are 36 and 46 % lower than those obtained for mono-material and multi-material packaging in this study (0.150 kg CO_2 eq/FU and 0.11 kg CO_2 eq/FU for mono-material and multi-material, respectively). Although Maga et al. (2019) considered packaging with a higher weight, i.e., 18.43 g for the recycled mono-PET tray and 17.65 g for the multi-material tray composed of recycled PET and PE, than the packaging systems under study (Table 1), they used recycled PET, resulting in a low total environmental impact.

3.3. Environmental impact comparison considering only the food waste life cycle

Figure 4 shows the relative percentage of environmental impact responsibilities of packaging (direct environmental impacts of packaging) and cooked ham (indirect environmental impacts of packaging) life cycle.

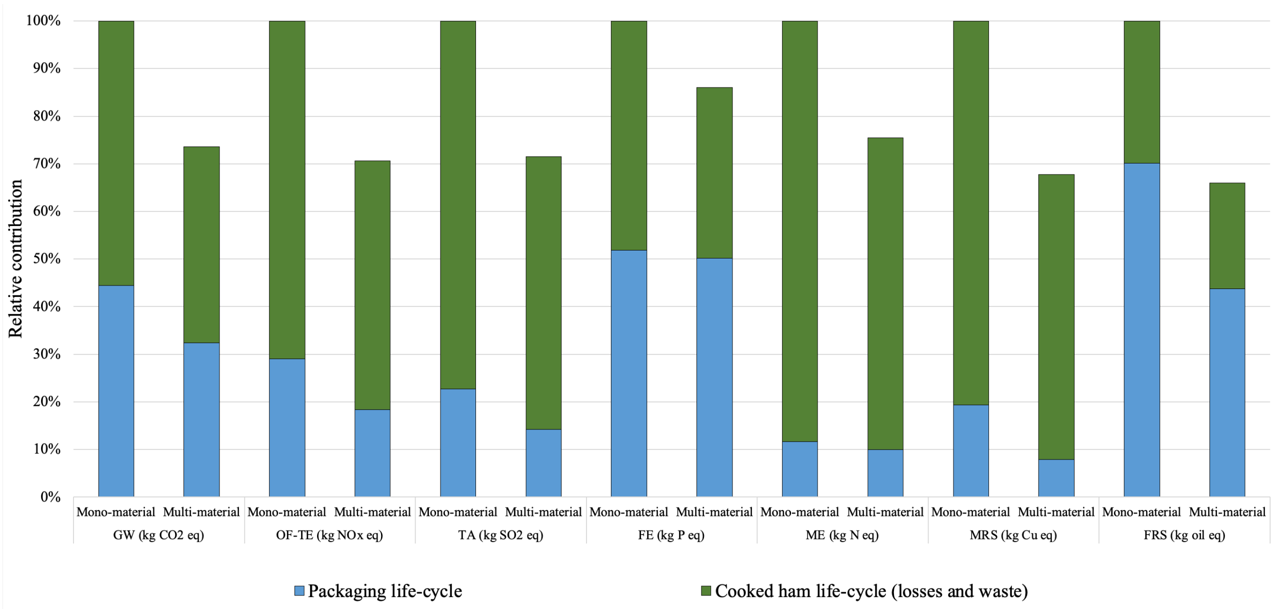

Figure 4. Environmental impact hotspot considering both packaging and cooked ham life cycle for both cooked ham-MAP packaging systems.

By considering the cooked ham losses and waste over the system life cycle, the mono-material system generates the greatest environmental impact in all the impact categories, generating an average percentage of 30% higher than the multi-material.

Cooked ham losses and waste arise as the main contributors to the total impacts, ranging from 29% (MRS) to 88%% (ME) for mono-material and from 22% (MRS) to 65% (FE) for multi-material, mainly due to cooked ham waste produced during the retail/distribution and household stages. This high impact derived cooked ham production, in particular from pig farming (cultivation of feedstock for feeding). The exception is the FE and FRS, for which the packaging life cycle is the hotspot, with contributions of more than 50% for FE and more than 65% for FRS for both packaging systems.

The higher environmental impact associated with cooked ham waste from the mono-material cooked ham-MAP packaging systems, compared to the multi-material one, was directly linked to its lower protection performance, resulting in a shorter effective shelf-life of 21 days and, consequently, higher levels of food waste. Therefore, the environmental performance of the two systems studied is influenced by the indirect environmental impacts of packaging, specifically the food waste generated due to effective shelf-life limitations. This emphasizes the critical relationship between the protective function of packaging and its environmental impact. These findings highlight the importance of selecting packaging systems based on their protective performance to effectively prevent food waste and mitigate associated environmental impacts.

3.4. Sensitive analysis

Currently, multi-material tray packaging cannot be mechanically recycled (Maga et al., 2019) because of the presence of different polymers, such as PET, PE, and EVOH, which create immiscibility and incompatibility issues (Bauer et al., 2021; Maga et al., 2019). These challenges are significant because Europe continues to rely on conventional mechanical recycling methods, including regranulation processes. The thermal incompatibility of the combined materials presents a major barrier to effective recycling (Bauer et al., 2021; Garcia & Robertson, 2017). Moreover, while the mono-PET tray/lid system is considered a mono-material (given that the secondary barrier layer material constitutes less than 5% of the total packaging weight), as mentioned in section 1 and this is theoretically recyclable, practical impossibilities remain. By 2030, the European Commission has established an ambitious goal to enhance plastic recycling rates, targeting a mass-based recycling of 55% while restricting landfill disposal to 10%. Consequently, the remaining 35% of plastic waste would be managed through incineration. To assess the impact of alternative EoL treatment options aligned with these future European targets, particularly focusing on increased recycling, on the overall environmental performance of packaging systems under analysis, the following EoL treatment options have been considered: 55% recycling, 35%

incineration, and 10% landfill, according to the European Commission's strategy for plastics within a circular economy by 2030 as outlined in Directive (EU) 2018 (European Union, 2018). Regarding recycling waste management, and following a cut-off approach, recycling activities were not assigned to packaging that reaches the EoL at the entrance of the recycling facility.

Figure 5 shows the sensitivity analysis results for the packaging under analysis, considering the plastic EoL treatment mix in Directive (EU) 2018 (European Union, 2018). FE and ME showed reductions of approximately 37% and 67% for mono-material and multi-material packaging, respectively, compared to the reference scenario (Figure 5). These reductions are attributed to decreased plastic disposal in landfills, which in turn reduce the emissions of nitrogen-based emissions, ammonium, and nitrates to water during landfilling. GW presented reductions of around 9 to 12% for mono- and multi-material packaging systems, respectively (Figure 5), mainly related to the lower amount of packaging waste in incineration (35%) compared to the reference scenario (55%). For the remaining impact categories, slight reductions around 0.1 and 2% were obtained compared to the reference scenario.

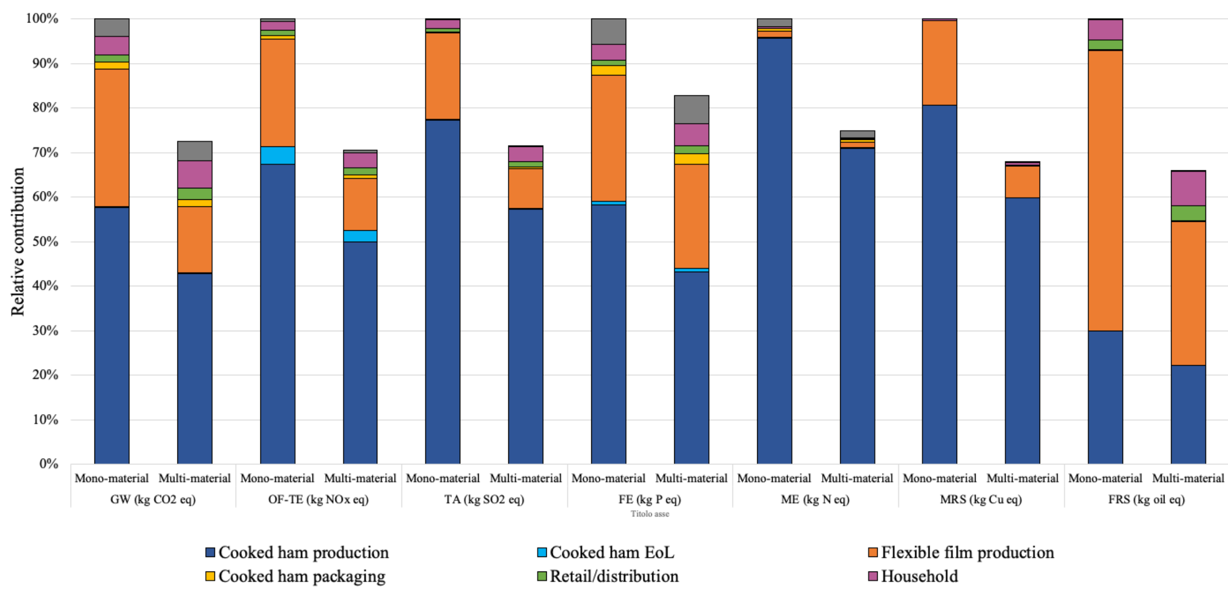

Figure 5. Comparison of the environmental impact of mono-material and multi-material packaging systems considering the EoL-sensitive scenario.

4. Conclusions

This study compared the environmental performance of mono-material and multi-material cooked ham-MAP packaging systems. Overall, mono-material presented the worst environmental performance for all impact categories. This can be attributed to the impacts related to cooked ham production and flexible film production, with the farmer linked to the amount of PFW generation due to the shelf-life of the packaging system and the latter being influenced by the higher quantity of polymer needed to produce films.

Packaging plays a crucial role in maintaining the safety and quality of food throughout its shelf-life and extending a product's shelf-life can substantially reduce the amount of food waste generated across the retail/distribution and household stages of the supply chain. Therefore, to minimize the overall environmental impact of a packaging system, it is essential to relate packaging type, shelf-life, and PFW. In this context, packaging with a long shelf-life, i.e. multi-material, results in less food waste and thus, a lower environmental impact.

The study also highlights that while mono-material packaging (mono-PET) is potentially recyclable in the future, its current inability to be mechanically recycled and its higher weight, resulting from thicker barrier layers, contribute to a higher environmental impact. Conversely, multi-material packaging, despite its complexity, offers better barrier properties and greater shelf-life efficiency, resulting in lower environmental impact.

The EoL stage of packaging also significantly affects the overall environmental impact, with recycling shown to mitigate some of the impacts of plastic waste disposal in landfills. In particular, in the sensitivity analysis, an alternative EoL scenario for 2030 was investigated following the targets listed in the European strategy for plastics in a circular economy. The results obtained showed that environmental reductions of approximately 37% and 67% for mono-material and multi-material packaging systems, respectively, can be achieved for the FE and ME impact categories.

Overall, the findings suggest that while mono-material systems may appear more sustainable due to their recyclability, their shorter shelf-life and greater material consumption make multi-material packaging a more environmentally favorable option in the context of this study. Future LCA studies should focus on alternative materials and their ability to extend shelf-life, as this directly influences food waste and overall environmental impact. These results offer valuable insights for the meat industry in designing packaging solutions that prioritize both sustainability and food preservation.

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Chapter 4

Packaging for cured meat: an environmental assessment of plastic multi-material and paper-based solutions

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Declaration: This chapter was written by author Anna Mengozzi and reviewed by all co-authors.

1. Introduction

The sustainability of food packaging has become increasingly important with the growth of the global packaged food products market (FMI, 2023). Virgin plastic and paper remain the most used primary materials for food packaging, accounting for approximately 40% and 60% of the market, respectively (Plastic Europe, 2023; CEPI, 2022). Moreover, both paper and cardboard, and plastic represent 40 % and 19%, respectively, of the waste material in the EU municipal waste (EUROSTAT, 2022). The Packaging Waste Regulation (PPWR) intends to reduce the amount of packaging waste generated in the EU. This regulation introduces stricter limits on allowable packaging materials and provides detailed guidelines to encourage the adoption of recyclable and reusable packaging solutions (European Union, 2024). The PPWR established an increase in recycling targets for packaging by 2030, raising the rate from 25% to 50% for plastic and from 50% to 75% for paper (European Union, 2024).

Packaged cured meats have grown significantly in popularity due to their convenience, functionality, and long shelf-life. Traditional packaging for cured meat products, particularly those requiring modified atmosphere conditions, typically relies on multi-material plastic systems, composed of multilayers, each serving a specific function (McMillin, 2017). These packaging systems offer several advantages that make them ideal for food applications, including chemical inertness in contact with food, lightweight design, mechanical resistance, transparency, and optimum barrier properties (Bauer et al., 2021).

However, multi-material packaging raises several sustainability concerns, as it currently is not recyclable on a large scale with the existing mechanical and chemical recycling technologies (Ragaert et al., 2017; Horodytska et al., 2018). EU is advancing toward improved packaging recyclability; however, plastic multi-material solutions are still far from the European strategies due to the challenges posed by their layered composition (European Union, 2018; European

Commission, 2018; European Commission, 2020; Soro et al., 2021). As a result, cured meat producers have started exploring alternative materials, such as paper, to align with PPWR sustainable objectives due to the possible recyclable end-of-life of this material.

The first packaging solution to reach the market features hybrid systems comprising a paper-based tray and a plastic multi-material lid. More recently, fully paper-based tray and lid systems have become available on supermarket shelves, demonstrating promising performances for cured meat products packed in a modified atmosphere. These packaging solutions typically include thin laminated multi-material plastic layer to provide the necessary barrier properties for perishable products like cured meats. Despite containing plastic, these paper-based films are compatible with the paper recycling stream in EU facilities (CEPI, 2019).

In addition to the circularity and recyclability, the primary function of packaging is to protect and preserve the food product (Verghese et al., 2013). The shelf-life provided by packaging can indirectly affect the overall environmental impact of packaged food by either reducing or increasing the generation of potential food waste (PFW). Food losses and waste have a greater environmental impact than packaging itself (Wohner et al., 2020; Arfelli et al., 2024). Therefore, food losses and waste issues have become key topics of discussion in recent decades, representing significant sustainability challenges in the food sector (Cattaneo et al., 2021). Food waste differs from food losses since it refers to those losses that take place at the end of the food supply chain, i.e., during retail, distribution, and household (FAO, 2019). In 2022, the total amount of food losses and waste generated in Europe, accounting for slightly more than 59 million tons (of fresh mass), was more than half of food waste, with 54% occurring at the household level and 8% at the retail-distribution level (EUROSTAT, 2023). Food waste at the retail level is mainly driven by the limited expected shelf-life of products, while at the consumer level, besides the shelf-life, it results from factors such as inadequate meal planning, overbuying influenced by large portions and package sizes, misunderstanding of labels, and improper storage practices at home (FAO, 2019; Quested et al., 2013). Therefore, it can be inferred that improving shelf-life is a key strategy to reduce food waste at both the retail/distribution and consumer levels, as much of the waste stems from food not being consumed before its expiration date, particularly in the case of perishable products (WRAP, 2008; Tetteh et al., 2024; Conte et al., 2015; Gutierrez et al., 2017).

Life cycle Assessment (LCA) is the most widely used tool for assessing the environmental impact of food packaging (Desole et al., 2021; Bishop et al., 2021), and in particular, meat packaging regarding bioplastic and several types of plastic packaging (multi- and mono- materials) (Maga et al., 2019; Marcos et al., 2024). LCA considers all stages of a product's life, from the extraction of raw materials and manufacturing processes to distribution, use, and eventual disposal or recycling (ISO, 2006a, b).

A growing number of studies, such as the conducted by Tetteh et al. (2024) and Casson et al. (2022) regarding fresh meat and Gutierrez et al. (2017) regarding packaged cheesecake, assessed not only the food packaging life cycle (direct effects) but also the PFW environmental burdens correlated to the packaging shelf-life (indirect effects). These authors highlighted the importance of incorporating the impact of the PFW related to the packaging shelf-life into the whole environmental evaluation of a food-packaging system, significantly influencing and guiding the impact results.

However, to our knowledge, there are no LCA studies that investigate and compare multi-material and paper-based packaging specifically designed for cured meat products.

The objective of this study is to evaluate and compare the environmental performance of three different types of sliced cooked ham packaging systems: i) a plastic multi-material system; ii) a paper-based system, and; iii) a hybrid system (composed of plastic and paper). The study investigates the relationship between the packaging effective shelf-life and PFW production, incorporating the indirect effects of food packaging into the environmental assessment.

2. Materials and method

The LCA was performed following ISO 14040 and 14044 standards (ISO 2006a, b).

2.1. Systems analyzed, functional unit, and system boundaries

Three cooked ham-MAP packaging systems (Table 1) were studied as follows:

1) MM - multi-material, tray and lid film, consisting of polyethylene terephthalate (PET), polyethylene (PE), and ethylene-vinyl-alcohol (EVOH), with an effective shelf-life of 35 days;
2) PA - paper-based tray and lid, both featuring a multi-material plastic barrier made of PE and EVOH, with an effective shelf-life of 31 days;
3) HY - hybrid packaging, combining the paper tray of the PA packaging and the multi-material lid of the MM packaging, with an effective shelf-life of 31 days.

The functional unit (FU) is defined as a single packaging unit containing 100 g of sliced cooked ham, considering the specific effective shelf-life of each packaging presented in Table 1, as well as the losses and potential waste of both cooked ham and packaging throughout the supply chain. The three cooked ham-MAP packaging systems under study required the same type of modified atmosphere composition (O_2: CO_2: N_2), with the effective shelf-life varying due to the different permeability characteristics of the packaging films.

The expected shelf-life of cooked ham was 31 days for two paper-based packaging and 35 days for the multi-material packaging. During the shelf-life test, microbiological and quality parameters of both packaging systems were monitored while stored at 4°C (simulating the same lighting conditions as a supermarket shelf). The results indicated that, in the two paper-based packaging, the primary factor limiting shelf-life was a decline in ham quality, with dehydration and the release of exudate occurring after 31 days. In contrast, the ham in the multi-material packaging maintained its quality attributes for 35 days (data not shown).

Table 1. Packaging layers composition, gas mixtures, and dimension of the three cooked ham-MAP packaging systems.

	Unit	MM	PA	HY
Tray film	-	APET/PE-EVOH-PE	Paper/PE-EVOH-PE	Paper/PE-EVOH-PE
Lid film	-	PET/PE-EVOH-PE	Paper/PE-EVOH	PET/PE-EVOH-PE
Gas mixture	%	45:55 (CO_2: N_2) (residual O_2 < 0.1)	45:55 (CO_2: N_2) (residual O_2 < 0.1)	45:55 (CO_2: N_2) (residual O_2 < 0.1)
Weight	g	16.4	20.5	20.3
Dimensions (L x W x H)	cm	23.5 x 20 x 1.2	23.5 x 20 x 0.5	23.5 x 20 x 0.5
External volume	cm^3	564	235	235
Effective shelf-life	day	35	31	31

APET; amorphous polyethylene terephthalate; PET: polyethylene terephthalate: PE polyethylene; EVOH: ethylene vinyl alcohol; AlOx: aluminum oxide.

The system boundaries (Figure 1) encompassed six stages as follows: (1) film production; (2) sliced cooked ham production – considering only the production of cooked ham losses and potential waste generated throughout the supply chain (3) sliced cooked ham packing; (4) retail/distribution; (5) household; (6) packaging end-of-life (EoL).

The film production (both tray and lid) considered all operations from raw materials extraction and processing, fossil resources for plastic films and forest trees for paper films, up to film manufacturing. The paper film production stage included manufacturing from the trees growing and cutting, kraft pulp production, and effective paper film production. Thermal lamination was used to produce all the films that composed MM, PA and HY packaging except for the lid that composed the PA packaging, which was produced by co-extrusion. The produced films were then transported to the cooked ham company packing and logistic site.

The cooked ham production stage included pig farming and meat slaughtering operations and refrigerated transport of pork meat to the cooked ham company production site. The cooked ham manufacturing steps comprised brining, molding, cooking (at a temperature ranging between 65°C – 75°C for 15 – 18 h), cooling, and storage. After production, the entire cooked ham piece was transported to the cooked ham company packing and logistic facility. All the operations related to the cooked ham packing stage (i.e., cooked ham slicing, thermoforming of the tray film, MAP gases mixture injection, the sealing with the lid film) were carried out consecutively in an operating line inside a refrigerated (+ 4°C) and aseptic room. This stage also included refrigerated storage (+ 4°C) in the logistic warehouse before cooked ham-MAP packaging systems shipping. The solid losses generated during the cooked ham packing stage - unpackaged cooked ham, packaged cooked ham and packaging - were subjected to external waste treatment (incineration). The retail/distribution stage included the refrigerated distribution of the cooked ham-MAP packaging system to the large-scale retail trade across the Italian territory (islands excluded), the final product at the retail (i.e. sale points) and the management of the resulting potential cooked ham-MAP packaging system waste. The household stage included the refrigerated storage and the disposal of potential cooked ham and packaging waste generated during this stage.

The packaging EoL stage considered the disposal and treatment of empty packages (Figure 1); a mix of incineration, landfill and open burning for MM and HY systems (only the lid) and recycling for PA and HY (only the tray) systems.

The consumption phase was excluded from the system boundaries due to its significant variability influenced by consumer behaviour, such as habits, cooking/heating methods, and geographical factors. The transportation of workers and machinery, as well as the production of capital good (e.g., buildings, machinery, and equipment), were also excluded from the analysis.

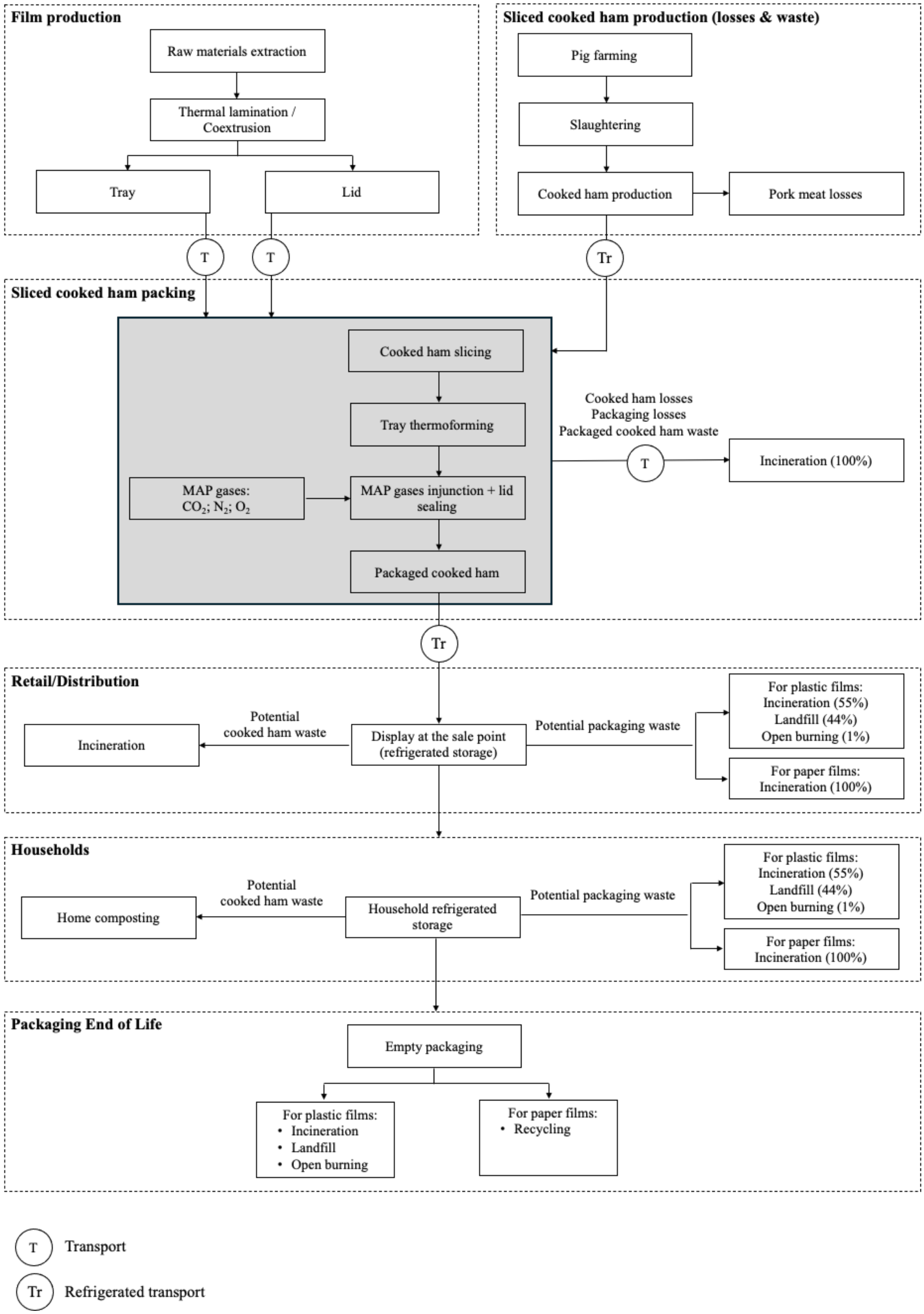

Figure 1. System boundaries.

2.2. Inventory analysis

2.2.1. Cooked ham-MAP packaging systems data

Table 2 provides detailed inventory data for the three cooked ham-MAP packaging systems under study.

For the film production stage, data on the quantities of input polymers and paper films, gas mixtures, electricity consumption, and generated cooked ham and packaging losses were gathered from a representative Italian company of cooked ham for the year 2023. This survey was complemented with information from the Ecoinvent v3.9.1 database (Wernet et al., 2016), particularly concerning the co-extrusion of the paper-based lid film of the PA packaging, which included a loss percentage of 3% of the total material. Regarding the thermal lamination of the MM and HY packaging system and the tray of the PA packaging, the data were sourced from He et al. (2021).

For the MM packaging films, transportation distances of 357 km and 205 km (Euro 5 truck) were considered for the delivery of the tray and lid film from their respective producers to the sliced cooked ham packing and logistic facility. For the PA packaging films, transportation distances of 205 and 645 km (Euro 5 truck) were considered for the tray and lid, respectively. For the HY packaging films, a transportation distance of 205 km (Euro 5 truck) was considered, as both the tray and lid were sourced from the same producer.

The inventory data for producing the cooked ham were obtained from the World Food LCA database (WFLDB) v3.5 (Nemecek et al., 2019) available through the SimaPro software (Pré Consultants, 2021) and supplemented by primary data provided by a facility in Northern Italy involved in cooked ham production. This latter data includes thawing, weighing, pressing, and kneading operations.

Concerning the cooked ham packing, all three cooked ham-MAP packaging systems considered an unpackaged cooked ham loss of 1% and a packaged cooked ham loss of 1%. These wastes were transported to incineration facilities located 15 km from the company. Packaging losses during sliced cooked ham packing consist of empty trays produced by thermoforming before the MAP gases were properly adjusted to be injected and from the clippings from spool. These losses accounted for around 23% and 30% for MM and the two paper-based packaging systems, respectively. The packaging losses derived from the paper films were also sent to incineration, for logistic issues in the company.

For the retail/distribution stage, an average transport distance of 362 km by refrigerated truck (Euro 5) was considered from the cooked ham packing and logistic facility to logistics warehouses or supermarkets. This estimate was calculated as a weighted average distance from the facility to each regional capital (excluding islands), accounting for the population size of each region (EUROSTAT, 2023).

Electricity consumption data for storing the three cooked ham-MAP packaging systems in warehouses and supermarkets were estimated using the average electricity consumption of a retail refrigerator (4.8E-06 kWh/cm^3/day) as reported by Fricke & Becker (2010), the average volume occupied by a cooked ham-MAP packaging system in the refrigerator (564 cm^3 and 235 cm^3 for MM and the two paper-based packaging, respectively) and assumed that meat products, on average, spend 20% of their effective shelf-life at retail (Roccato et al., 2017). At the household stage, electricity consumption data for the refrigerated storage of the three cooked ham-MAP packaging systems were estimated using the average energy usage of a consumer refrigerator (300 kWh/year) with a total capacity of 250 L (International EPD® System, 2021), and the average time that the meat products spend a household, i.e., 80% of the total shelf-life (Roccato et al., 2017).

Inventory data for electricity generation in Italy were sourced from the Ecoinvent database.

At the retail/distribution and household stages, the potential packaging waste treatment was assessed as follows: 1) for MM packaging system and the lid of the HY packaging system, it was considered the specific share of packaging waste management in Italy, comprising incineration (44%), landfill (55%), and open burning (1%) from Ecoinvent database, and; 2) for PA packaging and the tray of HY packaging, 100% incineration was considered.

Regarding the packaging EoL, different modeling were considered. Concerning the MM and the HY (lid) systems, the effects of empty packaging EoL were evaluated following the cut-off method, as currently, this packaging cannot be mechanically recycled due to the incompatibility of the different layers. The specific share of packaging waste management in Italy, comprising incineration (44%), landfill (55%), and open burning (1%) was also considered.

Regarding the PA and HY (tray) systems, the tray composition is around 90% paper and 10 %. plastic, while the lid film consists of approximately 62% and 38% plastic. The paper component of PA packaging and the tray of the HY packaging can be recycled, then its EoL modeling was performed based on the material component of the Circular Footprint Formula (CFF) from the Products Environmental Carbon Footprint (PEF) directive (European Commission, 2021). It was considered that the paper films are recycled to produce pulp, and that this recycled pulp that substitutes virgin pulp to produce other products rather than food packaging (European Commission, 2007). Following CFF modeling, it was considered that: 1) the quality of the recyclable material at the point of substitution is equal to the quality of the virgin pulp because the paper recycling process considers fiber losses, and 2) a default allocation factor packaging of 0.2, based on supply and demand of recycled material (a parameter from CFF); and 3) impacts related to inspection, collection, sorting and recycling of PA packaging. For plastic components (10 and 38 %) waste, it was considered the above-mentioned share of waste management.

2.2.2. Shelf-life and cooked ham potential waste

The estimated potential waste of cooked ham generated during the retail/distribution and household stages, based on the effective shelf-life of each cooked ham-MAP packaging system under study (Table 1), was based on the method developed by Casson et al. (2022). This potential waste considered the shelf-life ratio (SLR) for each cooked ham-MAP packaging system, the weight of the cooked ham per FU (100 g), and the probability percentage of food waste (PPFW) occurring during the retail/distribution and household stages. The shelf-life ratio was defined based on the worst-case shelf-life scenario and the effective shelf-life of each cooked ham-MAP packaging system, as detailed in section 2.1.

The worst-case shelf-life scenario assumed a shelf-life of 31 days for the PA and the HY packaging, as a shorter shelf-life increases the probability of food not being consumed and ultimately turning into waste. The SLRs were calculated as 1 and 0.89 for the multi-material and the two paper-based packaging, respectively.

For the retail/distribution and household stages, a probability percentage of food waste of 2.8 and 12 %, respectively, were considered for the three-cooked ham-MAP packaging system (Caldeira et al., 2019).

By applying the SLR, the FWPP, and the cooked weight of the FU, the potential food waste for each packaging solution was quantified as follows:

$$PFW = \text{Cooked ham} \times SLR \times FWPP$$

The potential packaging waste generated during the retail/distribution and household stages was calculated using the same waste probability (2.8 and 12 % retail/distribution and household stages respectively) applied to the three cooked ham-MAP packaging system. This calculation was based on a proportional relationship between the amount of PWF and the packaging material used for cooked ham.

The end-of-life of potential cooked ham waste generated at retail/distribution, for all three cooked ham-MAP packaging systems, was modelled based on the Ecoinvent dataset considering incineration as the waste management operation. On the other end, the end-of-life of potential cooked ham waste generated during households was assumed to undergo biowaste treatment through composting, and the related impacts were sourced from the Ecoinvent database.

Table 2. Inventory data per FU for the cooked ham-MAP packaging systems.

			Cooked ham-MAP packaging systems		
Supply chain step		**Unit**	**MM**	**PA**	**HY**
Film production	**Inputs**				
	Tray	g	19.26	28.13	26.01
	Lid	g	5.42	6.60	5.61
	Electricity (tray + lid)	kWh	0.0024	0.0058	0.0022
	Outputs				
	Tray film	g	19.26	28.13	26.01
	Lid film	g	5.42	6.40	5.61
	Losses	g	-	0.20	-
Cooked ham production	**Inputs**				
	Meat pork	g	15.42	17.09	17.09
	Electricity	kWh	0.64	0.64	0.64
	Water	m^3	0.0032	0.0032	0.0032
	Outputs				
	Cooked ham	g	14.92	16.59	16.59
	Pork meat losses	g	0.5	0.5	0.5
Cooked ham packing	**Inputs**				
	Tray film + lid film	g	24.68	34.54	31.62
	Cooked ham	g	14.92	16.59	16.59
	Gases MAP:	g	0.45	0.45	0.45
	CO_2	g	0.27	0.27	0.27
	N_2	g	0.14	0.14	0.14
	O_2	g	0.04	0.04	0.04
	Electricity	kWh	0.07	0.07	0.07
	Outputs				

	Packaged cooked ham	g	32.15	38.92	38.71
	Cooked ham losses	g	2	2	2
	Tray film + lid film losses	g	5.90	10.63	9.34
Retail/distribution	**Inputs**				
	Packaged cooked ham	g	32.15	38.92	38.71
	Electricity	kWh	0.019	0.007	0.007
	Outputs				
	Packaged cooked ham	g	29.25	35.50	35.53
	Potential cooked ham waste	g	2.44	2.76	2.76
	Potential packaging waste	g	0.46	0.66	0.65
Households	**Inputs**				
	Packaged cooked ham	g	29.25	35.50	33.90
	Electricity	kWh	0.052	0.019	0.019
	Outputs				
	Packaged cooked ham	g	16.85	20.95	20.75
	Potential cooked ham waste	g	10.48	11.83	11.83
	Potential packaging waste	g	1.92	2.75	2.72
Packaging End of life	Emissions to air:				
	CO_2	g	0.27	0.27	0.27
	N_2	g	0.14	0.14	0.14
	O_2	g	0.04	0.04	0.04
	Empty package waste	g	16.4	20.5	20.3

2.3. Impact assessment

The environmental impact assessment was performed for seven impact categories – global warming (GW), ozone formation (terrestrial ecosystem) (OF-TE), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), mineral resource scarcity (MRS) and fossil resource scarcity (FRS), applying the ReCiPe 2016 midpoint v.1.01 method (Huijbregts et al., 2016). GW was selected due to its significance in the context of climate change. However, to ensure a thorough and consistent environmental evaluation with reliable conclusions, it is essential to consider additional impact categories. Consequently, the other impact categories were included because they are frequently reported in LCA studies of packaging systems.

3. Results and discussion

3.1. General environmental assessment

The comparative environmental performance obtained per FU of the three cooked ham-MAP packaging systems under study are shown in Table 3 and Figure 2. In particular, figure 2 showed the relative contribution of each stage within the system boundaries to the total impact per FU of three cooked ham-MAP packaging systems under study.

Table 3. Impact assessment results per FU of three cooked ham-MAP packaging systems under study.

Impact category	**Unit**	**Cooked ham-MAP packaging systems**		
		MM	**PA**	**HY**
GW	kg CO_2 eq	4.76E-01	4.31E-01	4.37E-01
OF-TE	kg NOx eq	1.02E-03	1.03E-03	1.03E-03
TA	kg SO_2 eq	1.37E-03	1.40E-03	1.40E-03
FE	kg P eq	9.13E-05	1.26E-04	1.17E-04
ME	kg N eq	1.55E-04	1.65E-04	1.65E-04
MRS	kg Cu eq	4.04E-04	4.14E-04	4.18E-04
FRS	kg oil eq	1.22E-01	1.08E-01	1.11E-01

GW: global warming; OF-TE: ozone formation (terrestrial ecosystem); TA: terrestrial acidification; FE: freshwater eutrophication; ME: marine eutrophication; MRS: mineral resource scarcity; FRS: fossil resource scarcity.

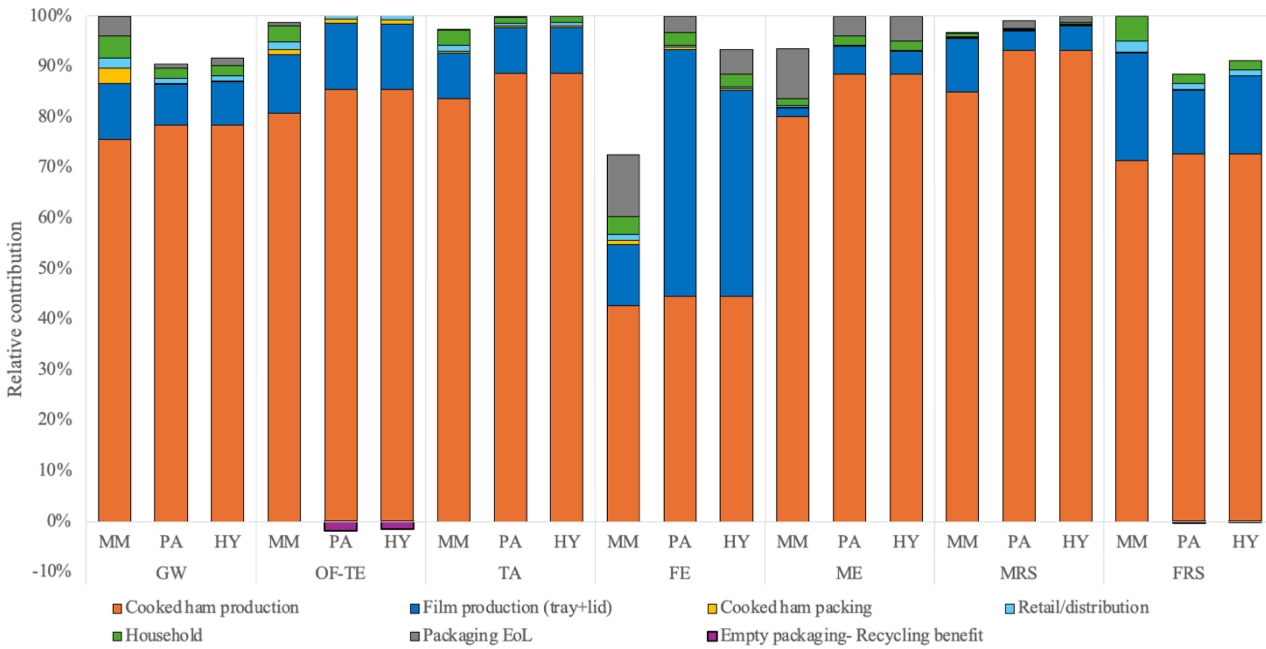

Figure 2. Relative contribution of the environmental impact considering the life cycle of the three cooked ham-MAP packaging systems under study.

The MM presented the best environmental performance for almost all the impact categories (5 out of 7), followed by, in this order, the PA (2 out of 7) and HY (0 out of 7). For GW and FRS, the MM showed the highest impact (Table 3), mainly due to the film production stage. This is largely attributed to PET manufacturing, the main polymer in both tray and lid films. PA showed the highest environmental impact for FE and ME, representing the overall worst environmental outcome. In particular, regarding FE, the highest impact of PA was mainly due to the impactful contribution of the paper film production stage, which had a percentage of 48% representing the main hotspot, mainly caused by the leaching phenomenon of ashes deriving from the landfill treatment of the sludge produced during pulp manufacturing.

Lastly, the HY packaging presented the highest environmental for OF-TE, TA, and MRS, even if PA showed similar impacts, with differences lower than 1%.

Overall, it should be noted that HY and PA had similar environmental impacts in all the impact categories, with differences lower than 5% among impact categories. The exception was FE (7%), in which the PA had the highest impact, mainly due to the film production stage, as mentioned above.

Comparing the PA and MM, the PA presented lower impacts for GW and FRS because of the low impactful paper production compared to the plastic polymer production. However, PA showed higher impacts compared to MM for OF-TE (+ 1%), TA (+ 2%), ME (+ 7%), and MRS (+ 3%), mainly because of the higher impact of cooked ham production. Moreover, in FE (+ 28%), the greatest difference between MM and PA was related to the higher impacts of paper film production than plastic film production.

The environmental impact of the three cooked ham-MAP packaging systems under study was primarily driven by the cooked ham production stage, which emerged as the main hotspot across all impact categories. Its contribution ranged from 44% for FE and 93% for MRS.

The impacts of cooked ham production for PA and HY are identical in all the impact categories, as both were characterized by the same effective shelf-life (31 days). However, their shorter shelf-life compared to the MM of 35 days results in increased PFW. This, in turn, contributes to a higher production of cooked ham, affecting the environmental impact of the entire food-packaging unit life cycle. The shorter shelf-life of PA and HY is due to the inferior barrier properties of paper-based films compared to plastic films of MM, which allow gases and water vapor to permeate through the packaging, ultimately compromising the quality of the cooked ham. Most of the environmental impacts associated with pork meat production stem from animal feed, with grain and soybean cultivation being the main contributors. These impacts are mainly due to fertilizers application during crop cultivation (such as nitrogen, nitrate, phosphorus, and phosphate) and tillage activities, which also entail fossil fuel consumption for machinery operations.

Overall, the film production stage was identified as the second-largest contributor across all impact categories for all three cooked ham-MAP packaging systems, ranging from 2% (ME) to 40% (FE). Exceptions were observed for the PA packaging system in the FE impact category, where film production accounted for up to 48%, respectively, representing the first hotspot, mainly due to impacts associated with pulp production. In the film production stage, tray films showed the highest contribution to environmental impacts compared to lid films across all the packaging analyzed, with contributions ranging between 63 and 85% for the MM, 62 and 83% for PA, and 47 and 94% for HY packaging, relative to the total impact of film production stage. Regarding the EoL packaging stage, the contribution to all impact categories was lower than 5% except for MM in FE and ME, where the contributions were 12% in FE and 10% in ME. The contributions of the EoL packaging in the MM were higher compared to the PA and HY (0.10 – 7.5 %), mainly because of landfill leachate, mainly chemical oxygen demand (COD) (FE) and nitrogen (ME).

3.2. Environmental impact comparison considering only the packaging life cycle

Figure 3 shows the relative contribution of each packaging stage to the total packaging environmental impact per FU for the three packaging under study.

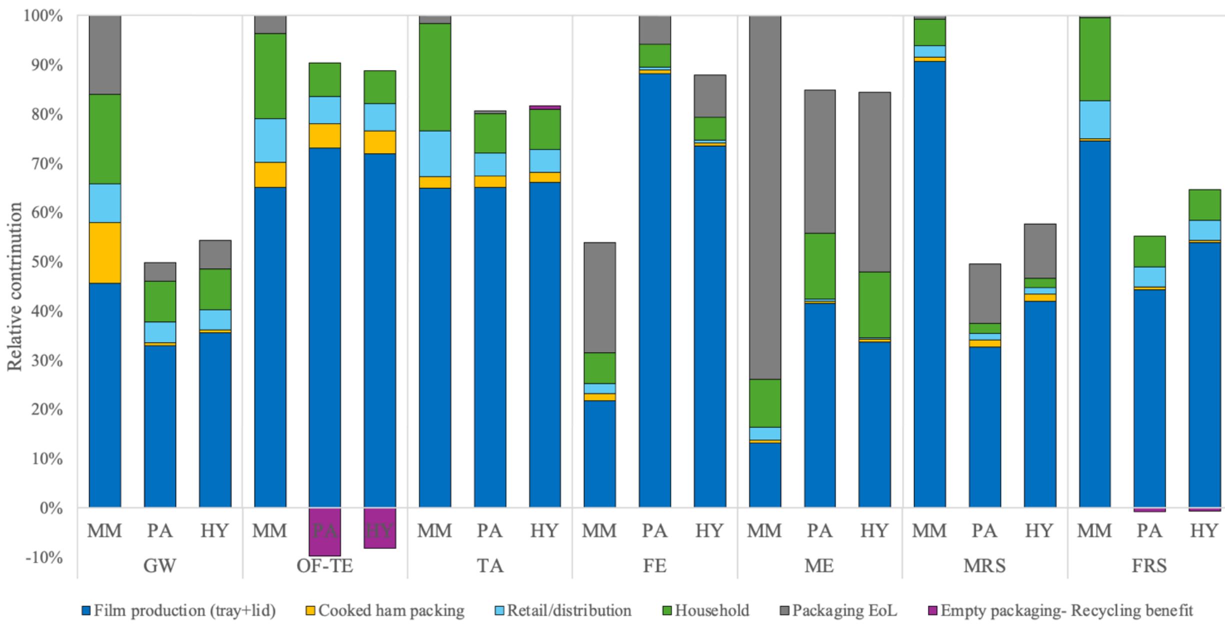

Figure 3. The relative contribution of the packaging environmental impact of the three packaging under study.

Focusing on the packaging life cycle of the three packaging under study, the PA presented the best environmental performance in 4 out of 7 impact categories, i.e., GW (49%), TA (88%), MRS (49%), and FRS (54%). Moreover, in OF-TE and ME, the PA packaging's environmental impact was slightly higher than that of HY packaging, with a difference of approximately 1%. In the FE impact category, the PA packaging presented the highest environmental impact, mainly due to the production of paper film. Specifically, the landfill of the ashes deriving from the kraft pulp sludge contributes to this impact, leading to leaching into groundwater (Section 3.1.).

Comparing PA and HY packaging, the HY had a higher impact compared to PA in 4 out of 7 impact categories i.e., GW, TA, MRS, and FRS. Although the difference between PA and HY packaging was relatively small, the HY packaging had a higher overall impact in 4 impact categories out 7, i.e., GW (+ 6%), TA (+ 1%), MRS (+ 8%) and FRS (+ 10%). This was mainly due to the higher contribution of the film production stage, which included the production of plastic multi-material lid. This lid has a higher environmental contribution compared to the paper lid, leading to an increased overall impact on the HY packaging.

The MM packaging presented the highest environmental performance across all the impact categories except for FE, where the PA represented the highest environmental impact. For GW, MRS, and FRS, the MM packaging had the highest overall environmental impact due to the contribution of film production. Specifically, film production accounted for 75% and 90% of the environmental impact in MRS and FRS, respectively, mainly due to the production of terephthalic acid from crude oil extraction for the manufacturing of PET, the main plastic polymer of the MM packaging (Section 3.1.). In OF-TE and TA the main hotspot for the MM packaging was the household stage, mainly due to the electricity consumption. This is particularly significant in Italy, where electricity is largely generated from fossil fuels (European Union Council, 2024). The households' stage is also relevant for GW (8 – 1 %) and FRS (6 – 17%) impact categories. For ME, the highest environmental impact of the MM packaging was mainly related to the packaging EoL stage, which contributes 73% of the total ME impact. This is largely due to the disposal of MM packaging waste (55%) in landfills, leading to nitrogen leaching into groundwater.

Film production is the primary contributor to the environmental impact across all packaging, with contributions ranging from 13% in ME to 90% in MRS. The exception is the ME category for the MM and HY packaging, where the EoL stage is the main hotspot, accounting for 73% and 36% of the total impact, respectively, largely caused by the landfill disposal of plastic (Section 3.1.).

It should be noted that in the OF-TE and FRS impact categories, the recycling of paper in the HY and PA packaging provides an environmental benefit as the production of virgin materials is avoided. The paper recycling process, in both HY and PA packaging, provides an environmental benefit of 9% (PA) and 8% (HY) for OF-TE and approximately 1% for both PA and HY for FRS.

4. Conclusions

This study evaluated the environmental performance of three different packaging systems (MM, PA and HY) used for cured meats by considering direct and indirect effects that contribute to their total environmental profiles.

When assessing the entire packaging-food unit life cycle, the cooked ham-MAP MM packaging system emerged as the best environmental system across most impact categories. Its expected shelf-life (35 days) enhances environmental sustainability by reducing PFW. In contrast, the cooked ham-MAP HY packaging system was found to have the highest environmental impact, mainly because of its shorter shelf-life (31 days), which results in increased cooked ham waste. Additionally, the combination of paper and plastic film required for the production of tray and lid further contribute to its environmental burden. When focusing solely on the packaging life cycle, the two paper-based packaging systems (PA and HY) demonstrated a lower environmental impact than the MM packaging system. This is largely attributed to the lower environmental burden of paper production and the recyclability of paper-based materials at the EoL stage.

The findings highlight the complexity of assessing food packaging systems' environmental impacts, as results are affected by whether the analysis includes only the packaging life cycle (direct effects) or the entire packaging-food system (indirect effects). Although MM packaging shows advantages in reducing overall impacts by extending the expected shelf-life and reducing food waste, it had higher environmental burdens when its packaging life cycle is considered in isolation. To advance sustainable packaging solutions, particularly for paper-based systems, efforts should prioritize improving barrier properties to enhance food preservation and extend shelf-life, ensuring compatibility with perishable products.

These results highlight the importance of adopting a holistic approach to packaging design, considering raw materials, recyclability, manufacturing impacts, and the role of packaging in reducing food waste. Future LCA of cured meat packaging should prioritize the evaluation of alternative materials, considering the interlink between packaging properties and PFW generation. This approach optimizes packaging systems that effectively preserve food quality and safety while reducing environmental impacts.

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Chapter 5

General discussion and conclusions

1. General discussion

Cured meats are more and more present in the supermarket as packaged food and the most commonly used packaging solutions rely on multilayer, multi-materials structure systems mainly constituted by different plastic polymers (i.e., PET, PE, PP, PA, EVOH, PVC, or PVDC) (McMillin, 2017). These materials pose serious sustainability concerns due to their origin from non-renewable sources and the non-possibility of mechanical recycling caused by challenges with layer separation (Horodytska et al., 2018) (**Chapter 1**). Early-stage technologies for recycling this multilayer, multi-material packaging demonstrate promising potential for the future (i.e., thermochemical, and chemical recycling and use of compatibilizers); however, additional research is needed to confirm their effectiveness (Tito et al., 2023; Laredo et al., 2023). Therefore, a substantial transition must take place, requiring a redesign of the packaging to ensure a balance between packaging functionality, food quality and safety, and sustainability.

As discussed in **Chapter 1**, the European Strategy for Plastics, the Circular Economy Action Plan, and the Packaging and Packaging Waste Regulation have set guidelines and goals for more sustainable packaging systems by requiring recyclability, reducing over-packaging, enhancing recycled content, and also increasing the reuse, return and refill systems, and finally implementing the bio-based materials with compostable or biodegradable end-of-life (European Union, 2024; European Commission, 2018; European Commission, 2020).

Vacuum and MAP are the most used technologies capable of decreasing, at the required levels, the oxygen in the headspace of the packaging. Only a few studies have focused on the quality attributes of cured meat products packaged with more sustainable solutions, including multilayer, multi-material packaging with less material weight, mono-material and bioplastic packaging (Peelman et al., 2014; Kurek et al., 2021; Nobile et al., 2024; Korte et al., 2023) (**Chapter 1**). These few articles underline how these more sustainable materials were not as effective in keeping the quality of cured meats during storage as the conventional multilayer, multi-material packaging. In brief, when developing new packaging materials for perishable products, it is essential to examine the functional properties of packaging, particularly barrier properties and properly tailored sealing settings that are the most important (Korte et al., 2023). In addition, the literature review highlights the current practice of packaging disposal management and examines and synthesizes advances and potential practices in sustainable packaging **(Chapter 1)**. In particular, multilayer, multi-material packaging poses significant recycling challenges due to its complex composition. Current recycling technologies, such as mechanical recycling, struggle to handle such materials, leading to incineration or landfilling. Chemical recycling, including emerging methods like hydrothermal liquefaction and solvent-based recycling, has shown to be a promising option but remains in its early stages, requiring further research to address scalability, efficiency, and environmental impact. On the other side, compostable bioplastics offer an opportunity to reduce waste by diverting it from landfills to composting, generating biogas and nutrient-rich compost. Current biodegradability assessments often fail to replicate real-world conditions, necessitating further research on degradation processes in industrial settings. Expanding the use of bioplastics in organic waste management will require updated systems and further research to address technological, economic, and safety challenges.

In this context, **Chapter 2** investigates the most important functional properties between several types of industrial-level packaging solutions for fresh, chilled MAP products (as cured meats), from conventional to alternative solutions, selected based on previous literature research that explored both functional and environmental legislation aspects (**Chapter 1**). The alternative solutions analyzed in **Chapter 2** were multilayer, multi-material with plastic weight reduction, potentially recyclable mono-material (i.e., mono-PET and paper), and bio-based materials. The chapter aimed to identify if the alternative packaging solutions were comparable to the conventional multilayer, multi-material structures in terms of functional efficiency and thus suitable in the application for perishable products, such as chilled and MAP foodstuffs. Based on the results, mono-material solutions (i.e., mono-PET and paper) showed a strong potential for cured meats packaging applications, presenting the best compromises between the analyzed techno-functional properties, in particular oxygen, carbon dioxide and water vapor transmission rate, and the European legislative recommendations and goals.

After the investigation of the functionality of specific industrial-level packaging for fresh, chilled MAP products in **Chapters 3 and 4**, the effective sustainability of the selected mono-material solutions analyzed in **Chapter 2** has been investigated. The applied LCA approach in this thesis included not only the direct effect of the packaging system related to its life cycle (i.e., from raw materials extraction to disposal) but also the so-called indirect effects related to the shelf-life packaging system and the corresponding potential food waste generation or prevention (Molina-Besch et al., 2019; Pauer et al., 2020). Including the shelf-life influence and, thus, the correlated potential food waste generation allows the evaluation of the sustainability of the packaging system entirely. This approach considers not only the environmental impact of the packaging's manufacturing and disposal, the primary sustainability burdens associated with the package but also its protective performance in preventing or contributing to food waste, which has been estimated to possess a greater impact compared to the packaging life cycle (Arfelli et al. 2024).

In **Chapter 3**, the LCA study investigated the environmental performances of the alternative mono-PET system with the conventional multi-material system, specifically designed for sliced cooked ham combined with a modified atmosphere. The results show that the mono-material packaging system presented the highest environmental impact for all the impact categories, both considering the whole food packaging unit (direct and indirect effects) and only the packaging life cycle (direct effects). The shorter shelf-life of the mono-material packaging system compared to one of the multi-material packaging systems led to a higher amount of PFW with a higher environmental impact. Moreover, regarding the packaging life cycle, the greater packaging weight of the mono-material packaging resulted in a higher environmental impact compared to the multi-material packaging. In the debate about multi-material versus mono-material, the focus relies on the possibility of recyclability or not. Indeed, mono-material is a non-complex solution, which could be recyclable in the future with improvement in the sorting and recycling infrastructures. However, the presence of only one material impairs the barrier properties, leading to an increase in the thickness, causing negative environmental consequences in terms of the raw materials' weight increase. Therefore, even if the multi-material is a non-recyclable complex system compared to the mono-material, the combination of several polymers leads to high-efficiency packaging with lower environmental impacts (Bauer et al., 2021). Mono-PET could offer a valuable solution in terms of sustainability and functionality, providing advancements in their barrier properties and thus, shelf-life. Additionally, its effective recyclability across Europe would significantly contribute to reducing environmental impact.

In **Chapter 4**, the LCA study investigates the environmental impacts of a conventional plastic multi-material system and two different types of paper-based packaging (a hybrid and a full paper material) designed for sliced cooked ham. Considering the whole food packaging unit (direct and indirect effects), the LCA results show that the paper-based packaging systems presented an overall higher environmental impact compared to the multi-material one. As the previous LCA study, the shorter shelf-life of the two paper-based packaging systems compared to the one of the multi-material leads to a higher amount of PFW with a higher environmental impact. On the other side, considering only the packaging life cycle (direct effects), the packaging manufacturing of the plastic polymers that composed the multi-material system resulted in a higher environmental impact compared to paper film production of two paper-based systems. These results show how paper-based packaging systems, thanks to the lower impact of the packaging production itself and the benefit deriving from the recyclability and, thus, lead to a lower overall environmental impact compared to the multi-material packaging system.

Both **Chapters 3 and 4** showed the comparison between multi-material packaging with different types of potential (mono-PET) and effective (paper) recyclable materials. These LCA studies highlighted the importance of accounting for both packaging's direct and indirect effects. Specifically, they emphasized the significance of indirect effects related to a longer or shorter shelf-life and corresponding PFW generation, which can lead to differing conclusions regarding effective packaging sustainability and packaging selection and thus strategies to pursue for an eco-design approach.

In summary, the studies reported in this thesis investigated and developed a new understanding of the knowledge required to packaging alternatives eco-design for cured meat products, highlighting circularity and sustainability aspects of commercially available plastic multilayer, multi-material and possible alternative solutions. In particular, these studies provide a deep comprehension of the most relevant key considerations in choosing packaging materials, exploring in detail the legislative, techno-functional, and sustainability aspects. Furthermore, the knowledge developed through this thesis can be exploited by the food industry as a guide to an eco-design approach to adopt and adapt in selecting more sustainable packaging for different types of food products, setting forward a better choice for the sustainability of the company and, broadly the whole food system.

2. Future perspectives

Suggestions for future research Follow-up studies that would be complementary to the work presented in this thesis include:

2.1. Active and intelligent packaging

Active and intelligent packaging systems are innovative solutions designed to enhance the functionality and sustainability of food packaging. Active packaging interacts directly with the food or its environment to extend shelf-life, maintain quality, or ensure safety through mechanisms such as oxygen scavenging, moisture control, or antimicrobial properties (Yildirim et al., 2018). Intelligent packaging, on the other hand, incorporates sensors or indicators that provide real-time information about the condition of the packaged product, such as freshness, temperature history, or gas levels (Ghaani et al., 2016). These advanced systems have not been investigated in **Chapter 1**, because the focus was on packaging for cured meat products with industrial applications. However, these types of packaging represent interesting systems for future innovation in the sector. Their potential to enhance product safety, quality, and shelf-life could address challenges specific to cured meat packaging, such as spoilage, microbial contamination, or oxidation. For instance, oxygen scavengers or antimicrobial films could mitigate the growth of spoilage bacteria, while freshness indicators could provide consumers with real-time information about the product's condition. Integrating these technologies into packaging systems for cured meats could improve sustainability by reducing food waste. Further research and development, along with cost-effective scaling and compliance with food safety regulations, are essential to advance the adoption of active and intelligent packaging in this industry.

2.2. Consumers' sustainability perception regarding food packaging

Several aspects of the cured meat packaging sector such as functional properties, legislation and end-of-life disposal have been explored in **Chapter 1**, but no investigations regarding the consumers' sustainability perception of meat packaging have been examined. The consumers' perception regarding food packaging sustainability is crucial for shaping purchasing decisions that can drive demand for alternative packaging solutions. Increasing environmental awareness has driven many consumers to prefer unpackaged food (Otto et al., 2021), recyclable packaging (paper or glass) (De Feo et al., 2022; Oloyede and Lignou, 2021), and biodegradable and/or compostable/biodegradable materials (Otto et al., 2021). However, several studies underline the gap between sustainability consumers' perception and reality since consumers' knowledge regarding sustainable packaging is often limited and misleading (De Feo et al., 2022). As a result, consumers mainly prioritize visible attributes, like minimal or plastic-free designs, over less relevant and effective factors like the energy efficiency of production, renewable sources origin, or protection performances of the package (shelf-life) (De Feo et al., 2022: Ketelsen et al., 2020). Therefore, educating consumers about the full life cycle of packaging materials is essential to align perceptions with the effective sustainability of food packaging, encouraging conscious choices. Consumer understanding of what constitutes "sustainable" packaging is often inconsistent, influenced by cultural influences, education, marketing strategies, and communication. To the authors' knowledge, no studies have been carried out on the consumer perception of more sustainable packaging for cured meat products. Exploring this complex topic requires diverse research approaches, including qualitative methods like surveys, interviews, and focus groups, capturing insights into consumer attitudes, motivations, and preferences (Herrmann et al., 2022). Such research could provide valuable insights into bridging the gap between consumer perception and effective sustainability in cured meats packaging to understand the purchasing decisions regarding alternative packaging solutions.

2.3. Cost evaluation of alternative packaging solutions

As the demand for sustainable packaging solutions grows, the food industry, besides effective sustainability (discussed in **Chapters 3 and 4**), should also investigate the economic aspects related to sustainable packaging (Albuquerque et al., 2019). Alternative packaging, such as mono-materials, plastic-reduced solutions, and bio-based materials are the main options named by European guidelines (**Chapter 1**). However, the transition to sustainable packaging often presents financial challenges, as these materials could be more expensive to produce and implement compared to conventional options like fossil-fuel polymers (Afif et al., 2022). Cost evaluation plays a critical role in determining the feasibility and scalability of adopting sustainable packaging. The companies by analyzing factors such as production costs, supply chain impacts, and potential savings from waste reduction, can assess the economic implications of their sustainable packaging selection (Svanes et al., 2010). Comprehensive cost evaluations also help identify opportunities for innovation and optimization, balancing environmental goals with financial sustainability.

2.4. Estimation of food waste from the shelf-life

Shelf-life plays a critical role in reducing food waste, which is essential for enhancing the sustainability of the food sector. This waste reduction directly addresses environmental and economic concerns, as food production and disposal contribute significantly to greenhouse gas emissions, resource depletion, and financial losses. In this thesis, the shelf-life evaluation was conducted by the collaborating company that was integral to assessing the performance of packaging solutions under real-world conditions. Using industry-standard methodologies, the company tested the ability of alternative packaging materials to preserve product quality, safety, and sensory characteristics over time. In **Chapters 3 and 4**, the method of Casson et al. (2022) has been applied to calculate the amount of potential food waste generation during the retail/distribution and households stages relating to the shelf-lives of each packaging. While evidence suggests that extending the shelf-life of food products can potentially reduce food waste based on the assumption that a shorter shelf-life leads to a higher probability of food waste, the precise relationship between shelf-life and food waste remains ambiguous (Williams et al., 2020). Researchers have explored this relationship using various approaches, including real market and consumer data for specific food products, theoretical models, or a combination of both. However, only a few studies (Conte et al., 2015; Tetteh et al., 2024; Coffigienz et al., 2021) have developed theoretical or mathematical models applicable to both retail and households contexts. Despite these efforts, an empirically validated relationship between shelf-life and food waste has yet to be established (Coffigniez et al., 2021), in order to bridge this critical gap in the literature and to harmonize this calculation in LCAs.

2.5. Technology transfer

The findings of this PhD research offer significant potential for technological transfer within the food packaging industry, particularly for chilled-MAP products. By addressing the balance between functionality, and environmental impact, our research provides a framework for developing and implementing sustainable packaging solutions that adhere to European environmental policies. The insights gained through detailed Life Cycle Assessments can be used to inform and communicate scientific information on sustainability to the consumers on the packaging. Furthermore, the eco-design strategies proposed in this research, also supported by LCA, can serve as a practical guide for food manufacturers to redesign packaging systems, ensuring both product preservation and sustainability and thus directing to more conscious choices. The transfer of these innovations could drive widespread adoption of packaging investigation and selection, paving the way for a more sustainable and responsible food system.

3. Main conclusion

Common packaging for cured meat products dramatically affected sustainability, in terms of used raw materials and plastic waste pollution. Thus, designing packaging with higher sustainability and circularity is one of the main goals of environmental European policies regarding packaging. This research explores the potential sustainability in packaging for cured meats, balancing functionality, food preservation, and environmental impact. It highlights the challenges of transitioning from conventional plastic multi-material to potential recyclable mono-materials, focusing on legislative, technical, and sustainability considerations. Life Cycle Assessments (LCA) demonstrated that while mono-material and paper-based packaging could offer recycling benefits, they lead to shorter shelf-lives, increasing food waste and overall environmental impact compared to conventional systems. The findings emphasize the need for packaging designs that align with circular economy principles while maintaining essential barrier properties to reduce food waste, especially for perishable food products, such as cured meats. These insights aim to guide the food industry toward adopting more sustainable packaging with a specific eco-design approach.

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Overview of completed training activities

Courses (disciplinary and interdisciplinary)

"Academic writing & public speaking" 2024
12 hours
(Food and Drug Science Department, University of Parma)

"Life Cycle Assessment Course 2024" 2024
8 hours
(Aachen-Maastricht Institute for Biobased Materials (AMIBM), Maastricht University)

"The Role of Microbes in Food Industry" 2024
6 hours
(Food and Drug Science Department, University of Parma)

"Application of in vitro digestion method of food matrices" 2023
6 hours
(Food and Drug Science Department, University of Parma)

"Multivariate analysis with R" 2023
12 hours
(Food and Drug Science Department, University of Parma)

International Summer School on FOOD SUSTAINABILITY ON-LINE (III°Edition) 2022
24 hours
(School of advanced Studies on Food and Nutrition, University of Parma)

"Tecnologie di condizionamento e shelf-life dei prodotti confezionati" 2022
14 hours
(Master in Packaging, University of Parma)

"Packaging e sostenibilità" 2022
7 hours
(Master in Packaging, University of Parma)

"Scientific English" 2022
20 hours
(Chemistry Department, University of Parma)

"Introduction to Scientific Communication" 2022
12 hours
(Food and Drug Science Department, University of Parma)

"DSC and low-resolution NMR for studying food quality" 2022
6 hours
(Food and Drug Science Department, University of Parma)

Conferences

28th Workshop on Developments in Italian PhD Research on Food Science, Technology, and Biotechnology 2024

"Packaging materials designed for cured meat products: a sustainability issue"
Anna Mengozzi, Francesca Bot, Emma Chiavaro
Food and Drug Science Department, University of Parma

4th Circul-a-bility Conference – Cost Action 19124 2024

"Life cycle assessment of cured meat product packaging: integrating the potential food waste related to the shelf-life"
Anna Mengozzi[a], Francesca Bot[a], Paula Quinteiro[b], Emma Chiavaro[a]
[a]Food and Drug Science Department, University of Parma
[b]Department of Environment and Planning, University of Aveiro

11° Shel Life International Meeting 2024

"Packaging materials designed for cured meat products: conventional and alternative solutions"
Anna Mengozzi[a], Daniele Carullo[b], Francesca Bot[a], Emma Chiavaro[a], Stefano Farris[b]
[a]Food and Drug Science Department, University of Parma
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3rd CIRCUL-A-BILITY CONFERENCE – Cost Action 19124 2023

"Packaging materials designed for cured meat products: a comparison between conventional and more sustainable solutions"
Anna Mengozzi[a], Daniele Carullo[b], Francesca Bot[a], Emma Chiavaro[a], Stefano Farris[b]
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"Current status of food packaging for cured meat product"
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26th Workshop on the Developments in the Italian PhD Research on Food Science, Technology and Biotechnology **2022**

"Improvement and optimization of eco-friendly and sustainable packaging materials for cured meat products"

Anna Mengozzi, Francesca Bot, Emma Chiavaro

Food and Drug Science Department, University of Parma

2nd CIRCUL-A-BILITY CONFERENCE – Cost Action 19124 **2022**

Designing sustainable packaging materials for cured meat products

Anna Mengozzi, Francesca Bot, Emma Chiavaro

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