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Beyond the eco-design of case-ready beef packaging: the relationship between food waste and shelf-life as a key element in life cycle assessment

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Abstract

This study aims to compare the environmental impact of three food packaging systems (Overwrap: OW, High Oxygen Modified Atmosphere Packaging: MAP and Vacuum Skin: VS) currently used in beef meat market, including the potential waste effect that derives from shorter shelf-life in the inventory and assessment. The Life cycle Assessment method was used, and a “cradle-to-grave” approach was applied for both packaging and meat chains. The functional unit was defined as one unit of packaging containing 500 g of sliced beef.
Considering only the packaging life cycle, the OW system has the best environmental performance in most of the environmental impact categories, while considering the potential food waste effects, results showed that the packaging system with the longest shelf-life (VS) represents the best environmental solution.
Future eco-design approaches for packaging solutions for food products should consider the ability of reducing potential food waste, as a direct consequence of improved shelf-life.

Keywords: circular economy, sustainability, meat, food packaging, LCA, consumer habits

1. Introduction

Food packaging has been seen for a long time as an additional environmental cost within a packaged food life cycle. It is a common belief that packaging production and particularly packaging waste strongly affects the overall environmental performance of packaging products (Gallucci et al., 2021; Sazdovski et al., 2021). As a result, both policy and research realities have focused their attention on developing innovative sustainable packaging sources and on preventing package waste. In this uneasy scenario, recent scientific research state that food packaging has positive aspects that depends on its inherent properties and could prevent and reduce food waste at different levels of the supply chain (Verghese et al., 2015; Wikström et al., 2018). In particular, Wohner et al. (2019) and Gutierrez et al. (2017) have shown how the role of shelf-life in reducing potential food waste and, consequently, the overall environmental impacts of the food-packaging system need to be studied and implemented in food packaging environmental assessments. Hence, an eco-efficient food packaging solution should balance and reduce both food waste and packaging waste (Coffigniez et al., 2021; Verghese et al., 2015).

Considering the complex relationship between food packaging eco-profile and food waste reduction due to technical performances of the packaging, it must be taken into consideration that such balances highly depend on the food contained in the packaging. Williams and Wikström (2010) demonstrated that depending on the nature of the food product, the potential reduction of the overall environmental system could be highly variable. Generally, for animal-based products such as beef meat, the potential impact of food waste reduction using innovative packaging designs or systems is higher than for vegetable products.

With particular regard to meat products, they represent one of the food products with the greatest environmental impact due to the inherent inefficiency of animals in converting feed to meat (Springmann et al., 2018). It is assumed that 75-90% of the energy consumed by livestock is needed for body maintenance or lost in manure and by-products such as skin and bones rather than for actual meat production (Djekic, 2015). Some of the environmental effects associated with meat production are pollution through fossil fuel usage, water use and land occupation (Ferronato et al., 2021). Furthermore, methane (CH_4) generated by ruminant production systems and its effects on global climate change is of major concern worldwide (Petrovic et al., 2015). The entire meat supply chain shows high environmental impacts coming both from breeding activities and from the other phases of the supply chain such as processing, packaging, distribution, consumption that must be taken into consideration for an overall environmental view (Casson et al., 2019; Singh et al., 2015). This situation is getting even worse taking into consideration that global meat production has tripled over the last four decades and increased 20 % in just the last 10 years (Stoll-Kleemann and O’Riordan, 2015). Packaging can potentially represent a strategy to minimize food waste and consequently the overall impacts of the food system under study (Pauer et al., 2019).

Numerous food packaging materials, solutions and systems are currently available on the market. All are characterized by different material compositions, properties and characteristics that lead to different expected shelf lives and eventually potential food waste reductions (Gogliettino et al., 2020; Sumrin et al., 2021).

Nowadays, Life Cycle Assessment (LCA) methodology is widely applied in the packaging field with both the aim of highlighting environmental hotspots and of identifying the more eco-compatible solutions through comparison analysis (Molina-Besch et al., 2018; Vendries et al., 2020; Wohner et al., 2019).

Despite numerous food-packaging LCA studies have been conducted in recent years, only a few studies have consistently investigated and compared the influence of different packaging systems, as well as different packaging compositions, on the potential reduction of food waste, a variable that plays a decisive role in the real evaluation of the environmental impacts generated (Maga et al., 2019).

As for meat packaging LCA studies, Ingrao and colleagues (2017, 2015) mainly focused on identifying hotspots in the production and disposal of different packaging solutions; they stated that the greatest impacts derive from polymer extraction and granule production and suggesting moving forward innovative and bio-based polymers. Maga et al. (2019) determined the environmental impacts generated by different tray solutions for meat packaging. A comparative environmental assessment was conducted taking into consideration nine packaging solutions including trays based on PS, PET, PP and PLA. The scope of the LCA study included tray manufacturing and packaging end-of-life. Meat production and packaging preserving role were neglected, representing a major limitation of the study. Additional factors such as expected shelf-life, coming from different packaging designs and materials, could strongly affect the results.

Meanwhile, few research papers have focused their attention on the so-called "indirect effects" of meat packaging solutions considering the relevant environmental impacts of the packaged products. For example, Wikström et al. (2016) demonstrated through a comparative LCA study, that consumers' behaviour greatly influences the results in terms of derived environmental impacts. When considering only direct effects (i.e., packaging production and end of life processes) the best environmental option is the packaging with a lighter mass and fewer materials' variety. Nevertheless, when indirect effects and user behaviour are included in the comparison, the packaging option that guarantees better performances in terms of consumers' derived food waste (i.e., ease of emptying) can result as the best choice.

Alternative applications of LCA studies considering the direct and indirect environmental effects balance between food products and packaging were proposed by Zhang et al. (2015), Settier-Ramirez et al. (2021), and Hutchings et al. (2021). The first paper proposed an LCA study of four different packaging alternatives for fresh beef (active and conventional packaging solutions) that lead to a breakeven point analysis highlighting the importance of considering the potential reduction of food waste as an input parameter in packaging development processes. The second one analysed a new approach to evaluate the environmental impact assessment of the entire life cycle of pastry cream taking the quantity actually consumed as unit to reflect the effect on food waste for the packaging system analysed. The last one proposed a new methodology for comparative LCA for packaging where the direct effects of packaging were compared based on an unchanged ratio of Shelf-life related food waste underlined the importance of the correct definition of the functional unit (e.g., the mass of film required to correctly preserve 1 kg of product).

Even if a great amount of research is currently focusing on the environmental assessment of food packaging systems, knowledge and methodological approach gaps still occur.

In this scenario, this study aimed to propose an alternative LCA approach evaluating and comparing packaging performances in terms of expected shelf-lives and related potential food waste of beef. The study compared Modified Atmosphere Packaging (MAP; gas mixture) and Vacuum Skin (VS; under vacuum) systems as innovative solutions, against Overwrap packaging system (OW; in air), identified as the conventional solution.

An approach for estimating shelf-life ratio and related probability of food waste was described and implemented in the study to take into consideration the different performances provided by the three packaging systems. Therefore, a “cradle-to-grave” approach was applied both for packaging and meat chains from raw material extraction till the end-of-life scenarios. Particular attention was paid to packaging and its role in the food waste generated throughout the supply chain.

2. Materials and methods

A comparative environmental analysis of three different packaging solutions for sliced beef was carried out using the LCA methodology. LCA was applied considering the life cycle of the packaging solutions and the life cycle of the wasted portion of sliced beef. This study was carried out following the requirements of ISO 14040:2021 and ISO 14044:2021 standards.

2.1. Goal and scope definition

Life Cycle Assessment of packaging in the meat supply chain was applied to evaluate the environmental impact of different packaging solutions, understanding, and quantifying at the same time the impact of the entire life cycle of the product, including potential food waste derived by different shelf-life performances.

The study wants to compare the current packaging solutions used in meat production and commercialization chain which are represented by three different systems:

- Overwrap Packaging (OW)
- Modified Atmosphere Packaging (MAP)
- Vacuum Skin Packaging (VS).

These packaging systems require different materials to produce both the tray and the lid film. High oxygen and vacuum packaging require materials with high gas barrier performance and excellent sealing capabilities. In fact, the aim is to avoid changes to the gas composition during shelf-life, maintaining the quality and the safety of the meat for longer times. Hence the need to use multilayer materials, as shown in Table 1. The necessity to assess the environmental impact of the packaging production system, along with the shelf-life effects on food waste, is the main driver of this study.

2.1.1. Functional unit and reference flow

The functional unit (FU) identified as the reference unit of the system analysed (ISO 14040, 2021; ISO 14044, 2021), was defined as one packaging unit which contains 500 g of sliced beef in relation to the expected shelf-life for each packaging system as stated in Table 1. All the shelf-life values are referred to 4-5°C of storage.

For MAP and VS technologies, different packaging solutions were analysed (4 and 2 types, respectively) and averaged results for every single system (i.e., MAP and VS) were proposed in this study.

2.1.2. System boundaries

The system boundaries, presented in Figure 1 show all the processes involved in the life cycle of the systems. A "cradle-to-grave" approach was used to evaluate the environmental profiles of the different system. The life cycle includes (i) breeding, slaughtering and commercialization and End-of-Life (EoL) related to the beef system, (ii) packaging production, commercialization, and EoL processes related to the packaging system.

The consumption phase of the product depends highly on the consumer behaviours (i.e., habits, cooking/heating processes and geography) and for this reason, the "consumer phase" analysed included only the storage at consumer level not considering the food preparation (out of the scope of the study).

2.1.3. Life Cycle Inventory modelling framework

The LCA study required the application of allocation procedures for the distribution, energy and water consumption, and storage at different points of the analysed system which have been solved using mass allocation criteria. Moreover, time-related coverage of a maximum of 10 years for data and geographical coverage within Europe were set as specific requirements during the study.

2.2. Life Cycle Inventory (LCI)

2.2.1. Packaging Life Cycle Inventory

The three different packaging compositions, volumes and average volume occupied by meat have been evaluated with the support of Sealed Air Corporation to reflect representative average data of European solutions available in the market. Detailed description of materials and percentage weight composition used for the different packaging solutions are reported below.

2.2.1.1. Modified Atmosphere Packaging (MAP) LCI

The high oxygen MAP system analysed is represented by four packaging solutions composed by the merge of two multi-material bottoms and three multi-material top lids (as described in Table 1), an absorbent pad (2 g) to absorb the exudates of the beef and an adhesive label (0.5 g).

The first bottom tray considered in the study was a 18×12×7.5 cm coextruded and thermoformed bottom with high barrier layer film (PP/EVOH with percentage weight composition of 96/4) with an overall weight of 20.2 g (MAP1 and MAP2 solutions). The second bottom tray considered in the study was a 25×18×5 cm extruded foamed bottom laminated with high barrier multilayer film (XPS/EVOH/PE with percentage weight composition of 92/1/7) and an overall weight of 14.1 g (MAP3 and MAP4 solutions). Both the bottom tray models created consider all the production phases starting from the extraction of polymers and accounting 2% of loss during production processes.

Regarding the films used as lid, four types of multilayer plastic materials have been modelled:

- MAP1: a multilayer coextruded film of PE, EVOH and PP laminated with a film of PP using PU as adhesive (multilayer/PU/PP with percentage weight composition of 60/4/36 and 9.2% EVOH);
- MAP2: a multilayer coextruded film PE/PP/EVOH/PA (multilayer/PA with percentage weight composition of 97/3 and 14.8% EVOH);

- MAP3: a multilayer coextruded film PE/PP/EVOH/PA (multilayer/PA with percentage weight composition of 97/3 and 14.8% EVOH);
- MAP4: a multilayer coextruded film of PE, PP and EVOH laminated with a film of PET using PU (multilayer/PU/PET with percentage weight composition of 60/4/36 and 7.9% EVOH).

The relative weights of the film analyzed were 0.93 g, 0.52 g, 1.09 g, and 2.27 g respectively. To model the absorption pad, a composition of 69% cellulose and 31% PE film was considered following Maga et al. (2019). For the label, bleached kraft paper was considered representative of the material used. Considering that the inks and glues for the label represent, in terms of weight, values lower than 1%, these components were neglected.

Considering the modified atmosphere, the gas mixture inside the package was quantified in 20% carbon dioxide and 80% oxygen, commonly used for beef meat storage (McMillin, 2008). Considering the average volume occupied by 500 g of meat (484 cm^3) and the averaged volume of the three MAP solutions (1448 cm^3), the gas composition was modelled on the resulting headspace of the package (964 cm^3 headspace).

The MAP technology requires an average consumption of 0,008 kWh/pack, due to sealing and gases inflation operations.

2.2.1.2. Overwrap (OW) LCI

The OW system is made by an expanded polymer (EPS) bottom tray (25×18×5 cm) (12.26 g), wrapped with a cling PVC film (2 g); an absorbent pad (2 g) to remove the exudates is included in the tray and an adhesive label is applied on the surface of the cling film (0,5 g).

The model of the bottom considered the polystyrene polymer extraction and the expansion of the polymer via a foaming process. According to the Ecoinvent dataset, a 2% of production loss was considered during production processes. The stretch film used in the study was a mono-material PVC film; the model considered the extraction of polymer and its extrusion. The pad consists of a cellulose-based product that absorbs the exudates and moisture. To model the absorption pad, a composition of 69% cellulose and 31% PE film was considered (Maga et al., 2019). For the label, bleached kraft paper was considered as representative of the material used. Considering that the inks and glues for the label represent, in term of weight, values lower than 1%, these factors were neglected.

The overwrap packing operation can be performed directly at the retailers and using automatic machinery or operators. The energy consumption of this operation has been quantified in 0.001 kWh/pack.

2.2.1.3. Vacuum skin (VS) LCI

Two bottoms (both 19×19×2 cm) were considered for the VS solutions (coded as VS1 and VS2). The first one was a coextruded and thermoformed PET/EVA/PE (17/42/41) sheet with a relative weight of 14.2 g. The second bottom considered in the study analysed a substitution of the PET layer with a PP matrix; in this case, an addition of a gas barrier layer of EVOH is fundamental to obtain the multilayer structure PP/EVOH/PE/EVA (12/12/38/38) with a final weight of 13.8 g.

Regarding the film, only one type of layer has been modelled analysing a coextruded PE/EVA/EVOH (42/43/15) multilayer film (4.34 g).

The vacuum skin technology is the most energy-consuming due to the thermoforming and vacuuming of the pack. The energy consumption of this operation was quantified in 0.016 kWh/pack.

2.2.1.4. End-of-life (EoL) processes of packaging waste

The different packaging solutions analysed do not present recyclability characteristics. Eurostat (2021) database has been used to quantify the share of current waste management system related to food packaging, two types of waste treatment have been identified and the relative share are reported below:

- Incineration with energy recovery: 65.7%
- landfill: 34.3%

According to the polluter pays principle (PPP), for the calculation of impacts related to incineration with energy recovery, as a default option suggested by International EPD® System (2019), 50% of the impacts of the waste incineration plant have been attributed to packaging waste treatment and 50% to the energy recovery for the next product life cycle.

2.2.2. Beef LCI

2.2.2.1. Beef production and distribution to transformation point

The breeding activities were selected from secondary data available in Agrifootprint 5.0 database. Beef meat, at slaughterhouse/IE Economic, was selected as the reference process for meat at the slaughterhouse.

The inventory includes the processes for beef cattle slaughtering, namely energy carriers, tap water, packaging film, chemicals, transport from the farm to the slaughterhouse and slaughterhouse infrastructure.

An average distance of 500 km from the slaughterhouse to the transformation site was considered in the study (Coop, 2013; International EPD® System, 2021a). The share of transport via road and rail was defined as 81% road and 19% rail (ANFIA, 2020).

2.2.2.2. Refrigeration of the product at retail

According to Fricke and Becker (2010), the average dimension of a retail refrigerator was considered equal to $730 \times 100 \times 150$ cm (W×L×H) and an average consumption equal to 4.8×10^{-6} kWh/cm^3/day. Considering the average volume of the packaging among the different system analysed equal to 1.43 cm^3, the allocated energy consumption per day was quantified in 0.0096 kWh/day.

Considering the shelf-life of every single packaging system and the average time the packaging spends at the retail, 20 % of the shelf-life was allocated at the retail stage (Roccato et al., 2017).

2.2.2.3. Household refrigeration

The energy consumption and the average volume of a consumer refrigerator was quantified equal to 300 kWh/year and 250 l respectively (International EPD® System, 2021b). According to the average volume of the packaging and the average energy consumption per day of the refrigerator, the average energy consumption per packaging was quantified in 0.0047 kWh/day.

According to the shelf-life of every single packaging solution and the average time the packaging spends at retail, 80 % of the shelf-life was allocated to home preservation (Roccato et al., 2017).

2.2.2.4. Meat Beef waste EoL

Considering the current scenario in European countries, the potential food waste deriving from the shelf-life of the different packaging systems was modelled using the dataset available in Ecoinvent for the treatment of biowaste.

2.2.3. Shelf-life related to potential food waste

Few studies considered the potential food waste and the shelf-life correlation, but its definition is still discussed due to the different approaches proposed. In fact, Quested (2013) analysed and reported a trend between shelf-life increase and food waste reduction for milk products. Manfredi et al. (2015) instead analysed and directly measured the effects of innovative solutions applied to open fresh milk and defined the impact of food durability after opening on food waste production at household level on the basis of consumer behaviour. Moreover, considering the lack of experimental data available in the literature about the relationship between the food loss probability (FLP) and the shelf-life, Conte et al., (2015) proposed three different empirical equations to calculate the FLP.

Based on the above-mentioned considerations, and on the limited experimental available data referable to the product under study, a potential food waste (PFW) quantification equation was proposed considering both shelf-life parameter and available literature data. Therefore, a shelf-life ratio equation was developed to correlate shelf-life parameter to the packaging solution analysed and to compare their performances:

Equation 1

$$SLR = \frac{RSL}{SSL}$$

Where:

SLR: Shelf-life ratio
RSL: Reference Shelf-life (days)
SSL: Studied Shelf-life (days)

The reference shelf-life (RSL) was defined by the worst-case scenario represented by the OW (2.5 days). Applying the equation to each system, the following SLRs were obtained: $SLR_{OW}=1$, $SLR_{MAP}=0.31$ and $SLR_{VS}=0.12$.

Starting from the shelf-life ratio identification and according to Mena et al. (2014), which identified a food waste equal to 3.90 % from retail, the potential food waste for every single packaging solution has been quantified following equation 2:

Equation 2 $$PFWR = Meat \times SLR \times FWR$$

Where:

PFWR: Potential food waste at the retail (g)
Meat: weight of meat (g)
SLR: Shelf-life ratio (adimensional)
FWR: Food waste at the retailer (%)

Results from equation quantified a PFWR equal to:

- MAP: 6.1 g (1.22 %)
- OW: 19.5 g (3.90 %)
- VS: 2.3 g (0.46 %)

Starting from the shelf-life ratio identification and according to Caldeira et al. (2019), which identified a food waste equal to 14.5 % at the consumer level, the potential food waste for every single packaging solution has been quantified.

Equation 3 $$PFWC = Meat \times SLR \times FWC$$

Where:

PFWC: Potential food waste at the consumer (g)
Meat: weight of meat (g)
SLR: Shelf-life ratio (adimensional)
FWR: Food waste at the consumer (%)

Results from equation quantified a PFWR equal to:

- MAP: 22.6 g (4.53 %)
- OW: 72.5 g (14.5 %)
- VS: 8.6 g (1.73 %)

The calculations were made taking into consideration that the shorter the shelf-life the more likely it is that a food is not consumed and therefore becomes waste. Based on this, it was assumed that the maximum food waste probability is referred to the worst-case scenario, thus OW. Following this assumption, a shelf-life value of 2.5 days accounts for 3.9% of probable waste at the retailer and 14.5% of probable waste at household, given the fact that the SLR for OW is 1. The remaining systems account for a part of the maximum food waste probability in relation to their SLR.

Results from equations 2 and 3 have been summed and total potential food waste for every single system was quantified in:

- MAP: 28.7g/500g
- OW: 92g/500g
- VS: 10.9g/500g

2.2.4. Alternative scenario for packaging materials EoL

Alternative scenario was modelled to evaluate the potential reduction of environmental impacts of the different systems analysed considering the possibility to manage the packaging waste as recyclable plastic packaging. To identify the share of waste management operations in Europe, Plastic Europe (Plastics Europe - Association of Plastics Manufactures, 2020) set the following waste scenario:

- recycling: 40.8%
- incineration with energy recovery: 38.8%
- landfill: 20.4%

Concerning the recycling waste management, the recycling activities were not allocated to the packaging which ends its life cycle at the gate of the recycling plant. According to the polluter pays principle (PPP), for the calculation of impacts related to incineration with energy recovery, as a default option suggested by International EPD® System (2019), 50% of the impacts of the waste incineration plant have been attributed to packaging waste treatment and 50% to the energy recovery for the next product life cycle. Landfill operations have been completely allocated to the packaging.

3. Life cycle impact assessment (LCIA)

In accordance with the objective of the study, the impact assessment methodology used was CML-IA, a LCA methodology developed by the Center of Environmental Science (CML) of Leiden University in The Netherlands.

To analyse the environmental impact, the SimaPro v 9.1.1.1. (PRé Sustainability, Amersfoort, The Netherlands) software and the database Ecoinvent v 3.6., Agrifootprint 5.0 and World Food LCA Database Version 3.5 following cut-off allocation criteria were used.

The LCIA phase aims to quantify the extent of potential environmental impacts using life cycle inventory analysis data; it consists in associating inventory data on pollutants with certain categories of environmental impact. The impact categories, the relative units, and acronyms used are summarized in Table 2.

4. Results and discussions

According to the purpose of the study, packaging solutions and food waste were firstly analysed separately and then merged to evaluate the overall environmental impact of the three food-packaging systems under study. To simplify the presentation and discussion of the results, average values were proposed for complex systems as MAP and VS which involved different packaging solutions (4 types for MAP; 2 for VS), detailed results for the different packaging solutions are reported in supplementary data tables (S1).

The results proposed in the following paragraph describe the comparison of the three packaging systems under study (OW, MAP, VS) at different levels of detail. Comparison results of the three packaging solutions, comparison of three food-packaging systems and hotspot analysis are presented.

4.1. Packaging environmental impact comparison considering only packaging life cycle

Table 3 reports the environmental impact comparison results for the life cycle of the three packaging systems. In Figure 2, the 11 environmental impact categories are shown on the x-axis, while a percentage value is reported on the y-axis. For each impact category, the worst-case reaches the value of 100%, while the others are scaled relative to it.

Results reported in figure 2 show that the MAP solution represents the worst case in almost all the impact categories analysed (7 out of 11). VS and OW systems follow respectively with 2 and 2 out of the 11 worst environmental scores.

The environmental impact of the three different packaging solutions is highly dependent on their average weights, dimension, and material compositions. Complex systems as MAP and VS (which require multilayer packaging components with higher weight with respect to the OW) showed similar trends in almost all impact categories (e.g., ADF; GWP; FWE; MAE; ACID; EUT). However, for two impact categories (i.e., OLD; PO) the OW system showed the highest percentage, representing the worst solution with a recorded maximum percentage difference, calculated in respect to the other two packaging systems of 8% in OLD and of 72% in PO. To better analyse the three packaging systems, Figure 3 helps to identify the different hotspots within each packaging system and impact category, for example the two impact categories that showed OW as the worst packaging system helped to quantify the main hotspot in OLD impact category related to the production process of the top film (49%) and the main hotspot in PO impact category related to the bottom production process (95%).

Results from figure 3 showed the significant factors that should be considered when analysing the eco-profile of these packaging, allowing to evaluate the average hotspot values among impact categories and packaging systems. The bottom part is accountable for the highest impacts with an average value equal to 59.7% (maximum of 68.4% in MAP and minimum of 46.6% in OW). The second hotspot is represented by the top lid (13.2%, with a maximum value of 19% in OW and a minimum of 3.9% in MAP), followed by packaging EoL (11.1%, with a maximum value of 13.8% in OW and 9.8% in VS and MAP), adsorbent pad (11%) and the packaging creation process (5.0%). Regarding the bottom part, this responsibility is due to its high weight in each of the three packaging systems. Moreover, the extraction and processing of polymers to obtain the final bottom trays are the main source of these large impact responsibilities. Taking into consideration the Global Warming Potential category, the bottom part in MAP reaches 70.8% (0.078 kg CO_2 eq.) of the total GWP impacts, OW 6.3% (0.051 kg CO_2 eq.) and VS 59.7% (0.053 kg CO_2 eq.).

Despite the responsibility of the bottom part that is high in almost all the impact categories and packaging systems, the top represents the second overall hotspot (13.2%) even if in Figure 3 this responsibility is not so visible. In the case of VS system, the top represents the second hotspot with an average responsibility of 16.5% (with a maximum of 21.3% in ADF, and a minimum of 11.8% in FWE). This is deriving from the extraction of the main plastic polymers and the production of EVOH and EVA films as barrier polymer in the top film structure. In the case of OW, the top part reaches half of the environmental impact responsibility, the PVC production represents the main cause of these results, particularly in Abiotic Depletion (49.8%) and Ozone Layer Depletion (55.0%) impact categories.

Even if the third average hotspot among packaging systems is represented by the pad (considering also the VS system, even if it’s absent in this solution), the adsorbent represents the second hotspot in MAP and OW systems.

The second hotspot in MAP system is therefore represented by the adsorbent pad with a percentage responsibility of 13.1% while in the OW system, higher percentage values are reported reaching an average value of 19.9%. Considering these two systems that require the absorbent pad inside the packaging, the Terrestrial Ecotoxicity impact category revealed a higher dependence by the absorbent pad that reached 78.7% and 59.6% of impact responsibility for OW and MAP respectively, mainly driven by the production of the tissue paper.

If considering the EoL scenario proposed in the LCI section, the packaging systems do not present recyclability characteristics. For these reasons, EoL scenario involves only incineration and landfill operations, resulting as the third hotspot in MAP and VS system and the fourth hotspot in OW system. Since the scenario is common to the three systems under study, the variable affecting the environmental impact of packaging EoL scenario, between and within each packaging system, is the weight of the packaging solutions.

From the proposed results, it can be noticed how the packaging creation process does not represent significant environmental impacts among packaging and impact categories, representing an average responsibility always lower than 10%.

Considering results proposed in Table 3, and in Figures 2 and 3, OW system should be selected as the packaging with the best environmental profile.

According to the goal of the study, results that also consider the potential food waste generated as function of the meat shelf-life depending on the different packaging solutions, must be considered to confirm or reverse the results obtained so far.

4.2. Packaging environmental impact comparison considering meat beef waste

Results reported in table 4 show percentage environmental impacts responsibilities and total environmental impacts of the different scenario analysed considering the whole system under study: the packaging system and its potential beef waste.

In order to propose clearer results by including graphical representations, figure 4 reports the comparative results of all environmental impacts considering all the variables that occurred in the packaging life cycle (blue color) and including the potential food waste variable (orange color). Results are reported as values, where the packaging solution showing the greatest impact is represent the highest value (100%) to which impacts of the other solutions are related.

As it can be inferred from Figure 4, unlike the previous situation, considering only the packaging life cycle, the OW system generates the greatest environmental impact in terms of almost all the impact categories considered (10 out of 11).

Furthermore, it is possible to observe how the environmental impacts of OW are significantly higher than the ones generated for the other two packaging systems. On average, MAP system reported a potential environmental impact reduction of 56.5 %, while VS showed a potential reduction of 73.8% when compared to the worst case represented by OW. Only in the case of AD impact category, even if OW results to be the packaging system with the lowest environmental impacts, it showed a significant reduction of the gap between OW and the worst case (VS) passing from 64% to only 10.1%.

Apart from AD impact category, that is strongly influenced by packaging variables, all the other impact categories reported similar trends which highlighted the major influence of wasted beef, which is the variable of the whole food-packaging life cycle responsible for the greatest environmental impacts.

In this regard, the average influence of beef waste on all the impact categories is 76% for MAP, 89% for OW and 67% for VS system.

Consequently, with reference to the impact category taken into consideration, all the other components of the supply chain generate significantly lower environmental impacts, ranging between 0 and 4%, apart from the bottom which in the MAP impacts for 6% of the total while in the VS it impacts 10%.

4.3. Alternative scenario impact comparison considering only packaging life cycle

According to alternative scenario LCI, Figure 5 shows the results of the comparison of environmental effects by considering the possibility of recycling the three packaging systems without altering their compositions.

From results reported in Figure 5, no significant impact reductions can be accounted in the modification of the end-of-life scenario analysed. The only impact categories that report significant reductions of environmental impacts (variation of results higher than 10 %) are the Fresh Water Eutrophication and the Eutrophication that show similar trends and a decrease that goes from 9% in VS system to 14% in OW system. No significant reduction can be recorded if considering the whole systems analysed, as seen previously, the impacts coming from the wasted beef lead on the entire system, therefore, even if the end of life of the packaging is modified in the packaging systems, the variations are very low (lower than 1 %).

4.4. Eco-design strategies (trends of food waste environmental impact)

From results reported in section 4.2. and 4.3, the environmental impact deriving from the beef waste is the major hotspot in all the three systems even if better EoL scenario is considered for the packaging products. Considering that the environmental impact of the wasted beef is directly correlated to the protection performances of the packaging (e.g., barrier properties), a correlation between shelf-life/food waste and environmental impact deriving from the wasted beef is proposed in figure 6, referring only to GWP which is nowadays an emerging impact category. The points used to obtain the trends are represented by the three systems analyzed, the environmental impact in term of GWP are reported on the y-axis while the shelf-lives expressed in days are reported on the x-axis.

From Figure 6, if the shelf-life increases, a potential reduction in food waste can be identified. The reduction correlation between these two factors can moreover be identified in a trend that shall be considered when eco-design activities are required. From the obtained results the following equation is derived, describing the relationship between the food waste and the environmental impact, expressed as GWP in this specific case.

Equation 4. $$GWP = 8.2109(SL)^{-0.998}$$

Where:

GWP: Global warming potential impact deriving from beef waste
SL: days of shelf-life (specific per each packaging solution under study).

The model proposed can be used to set an acceptance threshold level in terms of overall environmental impacts of packaging solutions. If the packaging developed following an eco-design approach includes also potential environmental impact coming from shelf-life related food waste, a complete environmental profile could be analysed and consequently a holistic eco-design approach could be implemented.

From the results proposed above, it can be noticed how the potential food waste cannot be neglected: it shall be considered as a direct consequence of packaging technological performance (protection), and as an indirect cause of the packaging environmental performances. The definition of a curve, describing the impacts of potential beef waste in relation to the shelf-life, should help fostering eco-design approaches to evaluate a priori the environmental indirect performance of the packaging systems.

5. Conclusions

When talking about shelf-life, packaging plays a fundamental role in protecting the safety and quality of food until a suitable level for consumption. Furthermore, by increasing the shelf-life of a product, the share of food waste generated along the supply chain can be significantly decreased. To reduce the total environmental impact of the packaging system, it is important to consider the connection among the type of packaging, shelf-life, and potential food waste (Gutierrez et al., 2017). In this regard, the packaging that can provide the longer shelf-life will certainly be the one that will generate less food waste and consequently also less environmental impact, if the food product is accountable for higher environmental impact as in the case of beef meat (Heller et al., 2019).

In this study, three different packaging systems (Overwrap, Modified Atmosphere Packaging and Vacuum Skin), used in meat production, were compared in terms of their environmental responsibility by examining in depth different scenarios by including all the variables that contribute to define the environmental profile of the packaging. The first comparison considered only the packaging life cycle: the results showed that MAP represented the worst solution in terms of impact in almost all the impact categories analysed, therefore OW system should be selected as the packaging with the best environmental profile. MAP's high impact task was due to its bottom part, especially its high weight and the processing of polymers to obtain it.

The second comparison was made considering both the packaging solution and the potential beef waste coming from different shelf-lives of the three solutions: in this case, completely reversed results were obtained showing OW packaging as the system that generates the greatest environmental impact.

Even if a packaging system seems to be the best solution in terms of its direct effects (i.e. material choice, packaging production and EoL), when its indirect effects are considered the final results could change. The indirect effects related to the extension of shelf-life and relative food waste reduction, could lead to different conclusion and thus strategic strategies for the packaging choice. This paper demonstrated this theory, by concluding that even if a lighter and simpler (in terms of materials and technology) packaging system for beef meat, such as overwrap in air, is preferable when accounting only the impacts deriving from packaging life cycle, the most complex packaging systems is eventually the overall best solution if considering beef waste in the life cycle.

The high environmental responsibility of the product under study (beef meat) can justify the need to consider food waste as an additional variable when developing innovative packaging solutions in the context of eco-design, as previously demonstrated by Wikström et al. (2016).

Nevertheless, such conclusions need to be critically reviewed for case specific LCA studies. Depending on the type of food product and packaging systems, the major conclusions draw for this paper could not be generally applied to all food-packaging systems (Williams and Wikström, 2010).

However, taking into account that food waste is a major problem in modern food systems, in the near future it is advisable that eco-design approaches for food packaging will consider at least three points of interest: packaging materials and production (i); packaging end of life (ii) and packaging-related food waste (iii).

Further research is needed to provide a broader knowledge on how these three aspects should be considered and balanced for different product categories and packaging systems, also considering consumers' behaviour and secondary shelf-life (Matar et al., 2021; Verghese et al., 2015). Moreover, harmonization among the scientific community should be reached to consider these aspects in LCA studies for food packaging.

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