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Environmental comparison of food-packaging systems: The significance of shelf-life extension

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ABSTRACT

Consumer-level food waste has considerable environmental consequences and is related to packaging and its impact on product shelf life. This study uses the life cycle assessment methodology to compare food packaging systems with similar or varying shelf life. When comparing packaging with different shelf life, estimating food waste from retail to consumer related to shelf life becomes crucial. Currently, no validated models exist for this purpose, and this paper contributes, for the first time, to a critical comparison of existing models. Key findings from a case study on chicken meat packaging reveal that extending the shelf life from 6 to 15 days in a PET tray, employing a modified atmosphere (with the highest packaging-to-food ratio), led to an average reduction in food waste from 47% to 15% of the total chicken meat produced at the slaughterhouse, consequently reducing Climate Change by approximately 78%. The range of food waste estimate was 24–66% using 5 different models. Despite this variation, a sensitivity analysis demonstrates that the comparison results remain consistent, emphasising the significance of food waste in the environmental impact. This underscores the crucial need for a validated method to assess food waste based on shelf life in food packaging ecodesign.

1. Introduction

Food packaging has many functions, some of which include to contain, protect and communicate. However, its primary function is to protect and preserve, especially perishable products (Heller et al., 2019). This protection and preservation function allows it to extend the shelf life of food products and thereby helps to reduce food loss and food waste.

The environmental and socio-economic impacts of food loss and waste (FLW) along agri-food supply chains (see Fig. 1) have been published in the scientific literature (Kummu et al., 2012). FLW is the disposal of food originally meant for human consumption. In this paper, the distinction between 'food loss' and 'food waste' is made according to the definition by FAO (2019). Food loss refers to losses occurring throughout the food supply chain, starting from harvest, slaughter, or catch, up to, but excluding, the point of retail, while food waste refers to losses occurring at the end of the food supply chain (mainly retail and consumption). Furthermore, a distinction is also made between avoidable food waste and unavoidable food waste. Avoidable food waste encompasses discarded food resulting from consumer attitudes, spoilage, or surpassing its use-by or expiry date. Conversely, unavoidable waste refers to food preparation residues like tea bags and inedible fruit and vegetable peelings, which were never intended for consumption. Throughout this paper, any mention of food waste specifically refers to 'avoidable' food waste.

In industrialised nations, food waste at both the retail and consumption stages of the food supply chain is a major concern (De Laurentiis et al., 2023; FAO, 2019). For example, in 2021, within the European Union, the consumer and retail segments collectively accounted for 70% of the total food waste in the supply chain. This breakdown comprised 54% from households, 9% from restaurants and food services, and 7% from retail and other food distribution services (Eurostat, 2023) (see also Fig. 1(a)). A leading cause of food waste at retail is due to food not being sold before it reaches its shelf life or use-by date (Spada et al., 2018).

A recent study conducted in Sweden by Williams et al. (2020) aimed

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to quantify the correlation between packaging functions and food waste at the consumer level. Among the 37 surveyed households in Sweden, the study revealed that 'food going bad in opened packaging' was the primary cause of food waste at 43.3%, while 'food passing its best-before date' accounted for 24.4%, ranking as the second leading cause. Consequently, both packaging challenges and consumer behaviour play a role in contributing to food waste at the downstream end (retail and consumption) of the food supply chain.

In their examination of various food product categories, Williams et al. (2020) discovered that fish and meat products represented 6.4% of total food wasted at households. Within fish & meat category, chicken meat emerged as the most wasted food type, representing 54.5% of the total in this category being discarded at the household level (equating to 3.27% of total household food waste, see Fig. 1(b)). Packaging design and attributes were identified as significant contributors to the waste of fish and meat products, with 50% of waste directly linked to packaging challenges such as difficulty in emptying or resealing, as well as considerations of shelf life (1.75% of total household food waste). Notably, focusing on chicken meat, the authors identified that 69.2% of the wasted meat was attributed to being 'past its best-before date,' a factor associated with the product's shelf life. Therefore, packaging, and particularly its relation to product shelf life, may play a significant role in food waste prevention.

Life cycle assessment (LCA) (ISO 14044 (2006)) is the most commonly used tool for evaluating the environmental impact of food-packaging systems (Heller et al., 2019; Wohner et al., 2019). LCA has also been used to evaluate and compare the environmental impact of meat packaging (Maga et al., 2019; Wikström et al., 2016). UNEP--SETAC Life Cycle Initiative (2013) published a comprehensive material that conducted an analysis of LCA to be applied in packaging for food and beverage. An important conclusion from this publication was that "including product losses within system boundaries will be important if loss rates are expected to differ among alternative packaging designs". Some studies have also highlighted the need to incorporate the impact of food waste into the environmental impact evaluation of food-packaging systems (Heller et al., 2019; Wikström et al., 2016) by showing that including this impact could significantly influence the results of the food-packaging system. However, determining the food waste associated with various packaging systems poses a challenge. Conducting a comparative market study to explore different alternatives would likely incur significant expenses. Therefore, offering a cost-effective alternative through calculation methods (e.g., models based on shelf life) would be highly appreciated.

Although there is evidence that extending the shelf life of a food product may reduce food waste (Settier-Ramirez et al., 2022), to date, the relationship between shelf life and food waste remains unclear (Williams et al., 2020). Various researchers have sought to establish this relationship, with approaches ranging from utilising real market and consumer data for specific food products to proposing theoretical relationships or a combination of both. Only two studies (Conte et al., 2015; Matar et al., 2020) have formulated theoretical/mathematical models that are applicable to both retail and consumer contexts. The remaining studies either focus exclusively on retail applications (Spada et al., 2018; Westergaard-Kabelmann and Olsen, 2016) or are specifically designed for consumer contexts (Zhang et al., 2019). An empirically accepted relationship between shelf life and food waste is crucial, yet it is currently absent in the existing literature (Coffigniez et al., 2021). Therefore, additional research is required in this area to address and fill this gap in the current body of knowledge.

The objectives of this study were twofold: (i) to employ the LCA methodology for comparing various chicken packaging systems under varying amounts of food waste due to differing shelf lives, and (ii) to evaluate different models from existing literature that estimate food waste (from retail to consumer) based on shelf life.

2. Materials and methods

This section includes a depiction of the examined packaging systems, along with two subsections detailing the methodology employed to compare packaging systems with either identical or varying shelf life.

The characteristics of the four analysed packaging systems outlined in this paper were obtained in 2012 from a chicken meat producer in

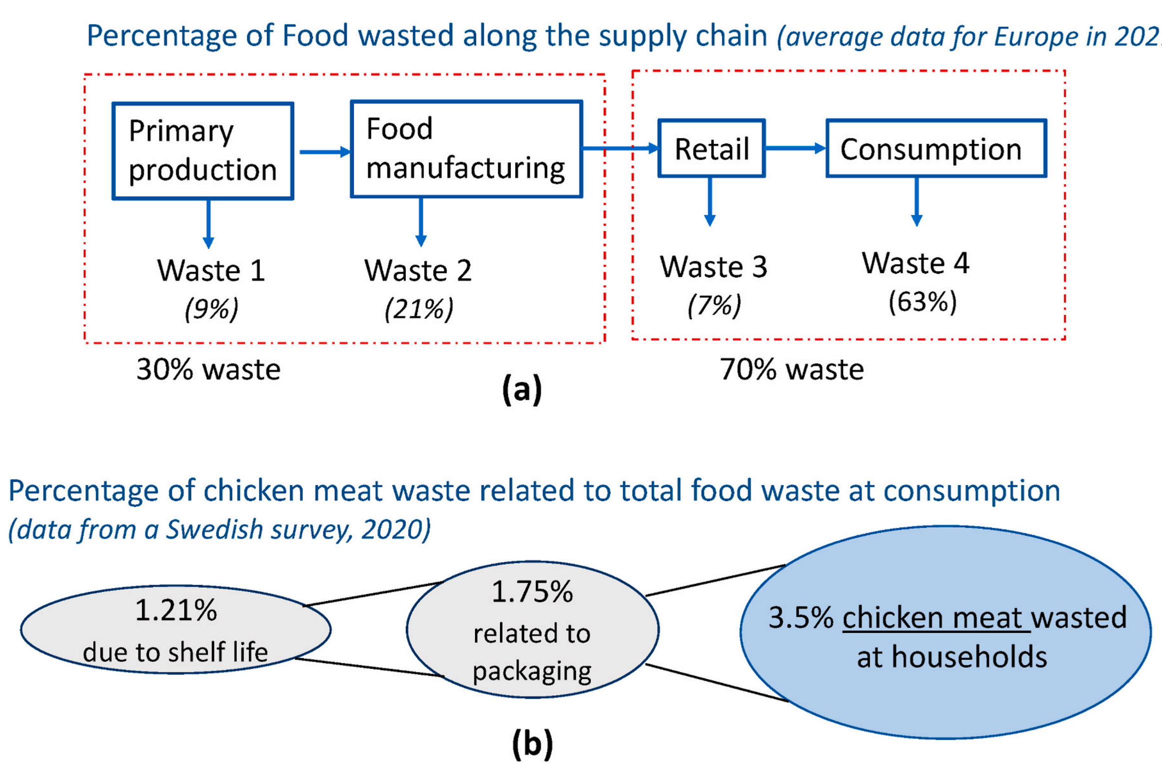


Fig. 1. Percentage of food waste in the last steps of the food supply chain and its relation to packaging. Data from (Eurostat, 2023; Williams et al., 2020).

Spain and are summarised and presented in Table 1 and Fig. 2. All these systems include air in their headspace, except for PK3-MA, which incorporates a modified atmosphere. PK1 (polyethylene (PE) bag), PK2 (multilayer polystyrene (PS)/polyvinyl chloride (PVC) tray) and PK3-MA (polyethylene terephthalate (PET) tray with modified atmosphere) were real commercial products in 2012, when data was gathered. PK3 (PET tray) (see Table 1) is a hypothetical product using the same packaging materials and meat content as PK3-MA, but without modified atmosphere. Data for these packaging systems (Table 1) were obtained from the second biggest chicken meat producer in Spain (Tetteh et al., 2022). It should be noted that chicken meat packaging has undergone significant changes in recent years in Europe, primarily due to new requirements aimed at preventing the migration of substances from the packaging to the food (EFSA (European Food Safety Authority) et al., 2023) (ie., PVC might be removed from the market for many food contact applications). Additionally, for Modified Atmosphere (MA) applications, barriers have been introduced to reduce the gas permeability of packaging materials (Han, 2013). Therefore, the packaging types discussed here may not be current; however, they are still valuable for comparison in academic contexts, such as the present study.

The meat content of the packaging types is an average obtained out of 50 samples and the maximum deviation from this average is also presented in Table 1. Information regarding the shelf lives was obtained from current literature data, as shown in Table 2.

Meat packaging types that fall into Comparison-Category 1 (the same shelf life) had air in their headspace and correspond to PK1, PK2 and the hypothetical PK3. PK1 (PE bag) is included in the comparison, even though its function differs from that of PK2 and PK3 (trays), because it is the simplest packaging possible for this type of product and it is helpful to have it as a baseline. PK1 is designed solely for packaging the whole chicken, without accommodating its distinct portions such as breasts, leg quarters, or wings. Nonetheless, the comparison remains relevant since PK2 and PK3 could also serve the purpose of packaging the whole chicken carcass.

On the other hand, the meat-packaging systems that fall into Comparison-Category 2 (different shelf lives) include the previous three packaging (having air in their headspaces), and PK3-MA (with modified atmosphere). Given the variations in headspace composition among the aforementioned packaging types—specifically, air and modified atmosphere—it is anticipated that they will exhibit distinct shelf lives and, consequently, varying percentages of food waste (see also Section 2.2).

Literature data were gathered to support shelf-life information as it will be significant in the results obtained. Table 2 presents a summary of six earlier studies that investigated the influence of chicken meat packaging methods, and headspace composition, on shelf life. As can be deduced from the studies presented, the average shelf lives for chicken meat packaged with air and modified atmosphere are 6 and 15 days respectively. Thus, these values were used to estimate the food waste associated with each meat packaging.

2.1. Comparison-category 1: packaging systems having the same shelf life

In this section, the environmental performances of three packaging systems that share identical shelf life durations and percentages of food waste are compared. To this end, the functional unit (FU) selected for the study was primary packaging required for 1 kg of chicken meat.

2.1.1. LCA methodology: system boundaries, inventory and impact categories

The LCA study was performed according to the ISO 14044, 2006. Nevertheless, it is a simplified/streamlined LCA, as not every question requires a detailed LCA to answer. In this case, the system boundaries include packaging production (i.e., raw material acquisition and pre-processing, and packaging manufacturing) and packaging waste end-of-life (EoL) management (see Fig. 3). Common processes such as packaging filling and sealing and retail and consumption were assumed to not result in significant differences in the comparison, and therefore excluded. Transport and distribution were excluded from the system boundaries due to a lack of data on distances, representing a limitation of this study. This limitation arises from the varying weight of packaging per functional unit (1 kg of meat) across different packaging types, with weight being a crucial factor in transport and distribution considerations. However, it is not expected that transport will significantly impact the comparison results. This expectation is consistent with findings from previous literature on food packaging studies (Humbert et al., 2009; UNEP-SETAC Life Cycle Initiative, 2013), which indicate that transport typically plays a minor role in the life cycle of food packaging due to its correlation with weight, similar to the raw material acquisition stage. In the majority of impact categories, the latter remains much more significant than transport.

Also, since the packaging systems have the same shelf life and percentage of food waste, the impact of wasted meat production was excluded.

The modelling of the meat-packaging systems was done using GaBi 2022 software (Sphera). Unless otherwise stated, all datasets used to model the packaging systems were from GaBi database. All data used in this study were modelled using European energy and material processes—Spanish datasets were a priority, if available. Data for recycling of PK1 (PE bag) and PK3 (PET tray) were obtained from a study by Martín-Lara et al. (2022). PK2, a multilayer tray made of polystyrene (50%, as assumed in this paper) and polyvinyl chloride (50%), is currently not recyclable, considering the current recycling infrastructure in Spain (Lopez-Aguilar et al., 2022). Therefore, the waste management options considered in this study for PK2 were only incineration (with energy recovery) and landfilling. Data on the shared percentage of incineration and landfilling of plastic packaging in Spain for the year 2020 was obtained from (MITECO, 2023).

The life cycle impact assessment results presented in this paper include 16 impact categories calculated using the Environmental Footprint (EF 3.0) method (European Commission, 2017) (see Table S1 of the supplementary material).

2.1.2. End-of-life (EoL) allocation approach

The circular footprint formula (CFF), recommended by the European Commission (EC) as an EoL allocation approach (European Commission, 2017), incorporates the impacts (both burdens and credits) associated with recycled content and EoL processes, including recycling,

Table 1
Properties of chicken meat packaging systems evaluated in this study.

Packaging	Material type	Tray/bag (g)	Lidding film (g)	Modified atmosphere gas (g)	Meat (g)	Packaging/food ratio	Shelf life (days)
PK1	PE (bag)	11.0	NA	NA	1880 ± 18%	0.0059	6
PK2	PS/PVC (tray); PVC (film)	22.0	5.00	NA	1950 ± 14%	0.014	6
PK3	PET (tray and film)	22.0	5.00	NA	926 ± 9%	0.029	6
PK3-MA	PET (tray and film)	22.0	5.00	0.00167	926 ± 9%	0.029	15

PK1: polyethylene (PE) bag, air in headspace; PK2: multilayer polystyrene (PS)/polyvinyl chloride (PVC) tray with PVC lidding film, air in headspace; PK3: polyethylene terephthalate (PET), air in headspace; PK3-MA: PET tray and lidding film, modified atmosphere (MA) gas in headspace; NA: not applicable. Packaging/food ratio is the ratio of the mass of packaging to the mass of meat.

Fig. 2. Chicken meat packaging systems evaluated in this study.

Table 2
Summary of some previous studies that investigated the influence of chicken meat packaging headspace composition on shelf life.

Reference	Packaging method shelf life (days)			Meat type	Storage (°C)	Trial days
	Normal (air)	Vacuum	MAP			
Gurunathan et al. (2022)	6	NS	15	Chicken leg quarters	4 ± 1	21
Guo et al. (2018)	8	NS	16–22	Roasted chicken	4	28
Chmiel et al. (2018)	7	NS	9	Chicken breasts	<4	9
Dogu-Baykut and Gunes (2014)	8	15	15	Marinated chicken drumsticks	4	25
Patsias et al. (2006)	14–15	NS	16–20	Fried chicken breast fillets	4 ± 0.5	20
Jiménez et al. (1997)	5	8	12–21	Chicken breasts	4	21

MAP: modified atmosphere packaging; NS: not studied.

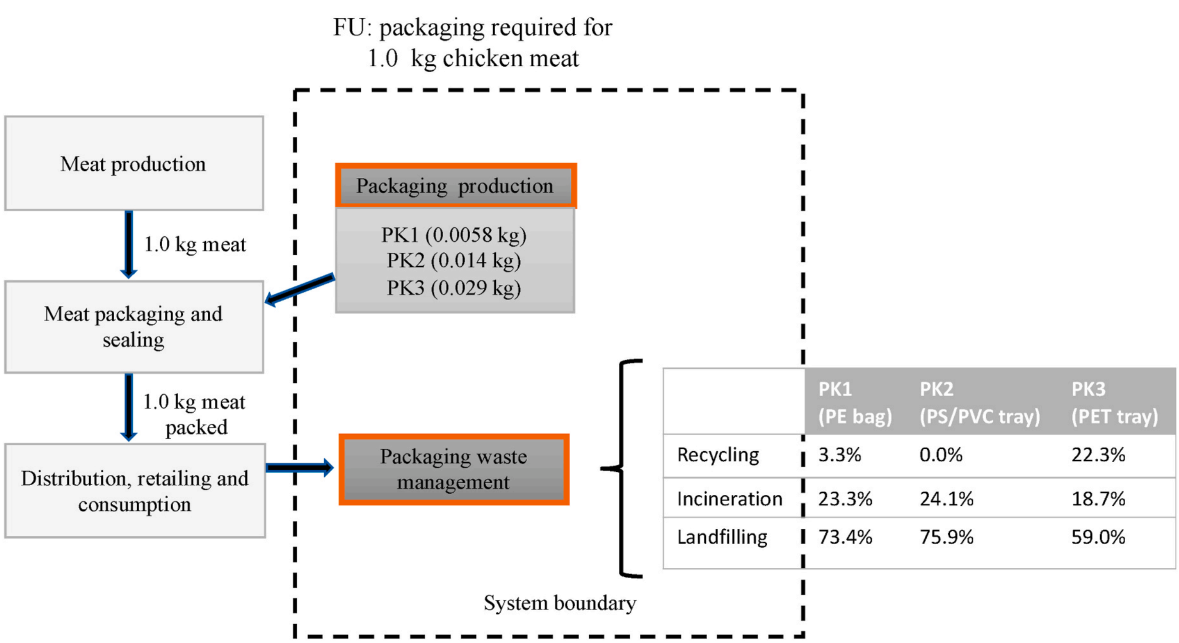


Fig. 3. Systems boundaries for the LCA comparison of meat-packaging systems having the same shelf life.

incineration, and landfilling. Additionally, the formula considers the downcycling effects on recycled material and its quality.

In this paper, the CFF approach is employed as recommended by the EC, particularly for packaging, to yield results applicable to the EU market. Nonetheless, the outcomes obtained through the CFF are compared with those derived from the cut-off approach in the supplementary material (see Figs. S1 and S2). The cut-off approach is one of the more frequently employed methods, including in studies related to food packaging (Heller et al., 2019).

2.2. Comparison-category 2: packaging systems having different shelf lives

As previously stated, the meat-packaging systems categorised for comparison encompass PK1–3 (PK1, PK2, and PK3), all featuring air in their headspaces, and PK3-MA, distinguished by a modified atmosphere. Consequently, PK1–3 were assumed to share the same shelf life and percentage of food waste, while PK3-MA exhibited distinct values for shelf life and food waste percentage. Food waste percentages here are related to the total amount of food produced at the slaughterhouse gate.

2.2.1. Models to estimate food waste from shelf life

Various models are available in the literature for estimating food waste at a given shelf life (Coffigniez et al., 2021). However, each model has its unique characteristics and limitations. Consequently, inclusion-exclusion criteria were established to select the most suitable models for the present analysis. For example, a model proposed by Spada et al. (2018) for estimating food waste based on expired products returned from the shelf was excluded because it is only applicable to products with shelf lives exceeding 30 days.

Three papers, presenting a total of five models linking food waste to the shelf life of a product, were reviewed and summarised below. The current paper derives three pertinent adapted methods from these studies to estimate food waste from retail to consumer at a specified shelf life (Table 3).

Conte et al. (2015) established a correlation between the probability of food loss (*FLP*) and the shelf life (*SL*) of packaged cheese, relying in part on empirical data pertaining to the product's shelf life across various packaging designs and packaging-atmosphere conditions. The study provided three theoretical relationships between *FLP* and *SL*. The authors assumed that an *FLP* of 0 implies an *SL* of infinity (no food waste) while an *FLP* of 1 implies an *SL* of 0 (all food is wasted). The three equations (Eq.), namely: first order, sigmoid and straight line are shown by Eq. (1–3)respectively.

$$\mathrm{FLP} = \exp(-\mathrm{k_a} \times \mathrm{SL}) \tag{1}$$

$$\mathrm{FLP} = \frac{1}{1-\exp(-1)}\left[\exp\left(\frac{1}{-\mathrm{k_b}\times \mathrm{SL}}\right) - \exp(-1)\right] \tag{2}$$

$$\mathrm{FLP} = 1 - \mathrm{k_c} \times \mathrm{SL} \tag{3}$$

The constants k_a, k_b and k_c are the kinetic constants of the above equations respectively. It is important to note that Eq. (3), as displayed here, was inaccurately written in the original article, possibly due to a typographical error. The form presented here was deduced from the data supplied by Conte et al. (2015), and it was derived by plotting the *FLP* data against *SL*. To calculate the kinetic constants, the authors assumed an *FLP* of 8% for packed foods (Lebersorger and Schneider, 2011) and an *SL* of 75 days, representing the maximum shelf life obtained in their study. Using the information above, the authors calculated the kinetic constants: $k_a = 3.37 \times 10^{-2}\ \mathrm{day}^{-1}$; $k_b = 9.67 \times 10^{-2}\ \mathrm{day}^{-1}$; $k_c = 1.23 \times 10^{-2}\ \mathrm{day}^{-1}$.

In another study, Westergaard-Kabemaan and Olsen (2016) developed an empirical model for the relationship between shelf life and food waste for yoghurt products. The model sought to establish a relationship between the percentage of yoghurt left on the shelves and the number of shelf days. The authors used a continuous linear function to approximate the relationship between the percentage of yoghurt left on the shelves and the shelf life. The continuous linear function assumed that yoghurt has a constant probability (p) of being sold on each day it is on the shelf. Therefore, the ex-ante probability of yoghurt being sold within day t (day t included), called $P(t)$, is given by Eq. (4).

$$\mathrm{P(t)} = 1 - (1-\mathrm{p})^{\mathrm{t}} \tag{4}$$

Given a distinct shelf life, the daily probability of the yoghurt being sold can be calculated. Assuming that the waste rate is given by a percentage w and that the total shelf life is n, the daily probability can be calculated as shown byEq. (5–6).

$$1 - w = 1 - (1-\mathrm{p})^{\mathrm{n}} \tag{5}$$

Rearranging Eq. (5), the daily probability of yoghurt being sold can be calculated as shown by Eq. (6).

$$\mathrm{p} = 1 - \sqrt[n]{1-(1-w)} \tag{6}$$

To simplify the calculation of food waste rate at retail at a given w, n and t—as defined by Westergaard-Kabemaan and Olsen (2016)—we substituted Eq. (6) into Eq. (4) and simplified to obtain Eq. (7). Since $P(t)$ is the ex-ante probability of yoghurt being sold within day t, then $1 - P(t)$ is the probability of it not being sold, which is equivalent to the percentage food waste (*FW*) within day t, assuming t is the shelf life of the product. Thus Eq. (7) was rearranged to obtain Eq. (8), where *FW* is the food waste (%) at a given shelf life, t, and w is the waste rate (%) associated with the total or maximum shelf life, n, of the product.

$$\mathrm{P(t)} = 1 - (w)^{\frac{\mathrm{t}}{\mathrm{n}}} \tag{7}$$

$$\mathrm{FW} = (w)^{\frac{\mathrm{t}}{\mathrm{n}}} \tag{8}$$

Zhang et al. (2019) also proposed a model to estimate the percentage of food waste reduction at the consumer level. Based on a survey of consumer behaviour, their model established an empirical relationship between shelf-life extension and food waste reduction across various food products. The survey data was input into a model and graphed. The authors provide a graphical diagram (not visually depicted in this paper) from which the relationship between shelf-life extension and food waste reduction can be estimated (see Fig. 7 in (Zhang et al., 2019)).

Indeed, beyond the initial studies that formulated the five previously described models, only two additional studies—specifically, one on pastry cream (Settier-Ramirez et al., 2022) and another on fresh-cut vegetables (Vigil et al., 2020)—utilised these established models to

Table 3
Summary of adapted methods used in this paper to estimate food waste at a given shelf life.

Method	Final formulas using the same nomenclature[a]	Needed information	Comments	Applied by:
Method 1 (Source: Conte et al. (2015))	First order: FW = exp (-ka × SL)	ka and SL	Needs validation with real data.	Vigil et al. (2020)
	Sigmoid: FW = 1/(1-exp(-1))[exp(1/(-kb × SL)) -exp(-1)]	kb and SL		
	Straight line: FW = 1-kc × SL	kc and SL		
Method 2 (Modified after: Westergaard-Kabemaan and Olsen (2016))	$\mathrm{FW} = \mathrm{fw}^{\left(\frac{\mathrm{SL}}{\mathrm{SL_m}}\right)}$	fw, SL and SLm	The original model proposed by Westergaard-Kabemaan and Olsen (2016) was only applicable to retail. In this form, it could be applied from retail to consumption.	Settier-Ramirez et al. (2022) (used the original model applicable only to retail)
Method 3 (Combination of the original model proposed by Westergaard-Kabemaan and Olsen (2016) with Zhang et al. (2019))	Retail (R): $\mathrm{FW_R} = fw_R^{\left(\frac{\mathrm{SL}}{\mathrm{SL_m}}\right)}$ Consumption (C): Fig. 7 in (Zhang et al., 2019)	Retail: fwR, SL and SLm Consumption: SL extension (which is equal to SLm minus SL) and fwC	Requires several assumptions, which may increase the uncertainty of the result.	The combination of models applied here for the first time.

[a] *FW*: percentage food waste at a given shelf life; FW_R: *FW* at retail; *SL*: shelf life; *SLm*: maximum shelf life for a particular food product; *fw*: percentage food waste associated with *SLm*; *fwR*, and *fwC*: fw at retail and consumption respectively; k_a, k_b, and k_c: kinetic constants—can be calculated by first substituting *fw* for *FW* and *SLm* for *SL* in each respective equation in Method 1.

project food waste with respect to product shelf life (see Table 3).

Table 3 presents three adapted methods derived from the various models described earlier. To enhance clarity, the primary variables (*FW*, *fw*, *SL* and SL_m) and abbreviations used in these three methods have been standardised; where, *FW* is the percentage food waste (%) at a given shelf life (*SL*, days) of a product, and *fw* is the food waste (%) at the maximum shelf life (SL_m, days) of the product. Thus, in Method 1, $FW = FLP$ (Eq. 1–3 while in Method 2, $fw = w$; $SL = t$; $SL_m = n$; $FW = 1 - P(t)$, as in Eq. (7). The three methods outlined in Table 3 cover the entire spectrum from retail (encompassing food waste during distribution) to the consumer.

2.2.2. Estimation of food waste for chicken-meat-packaging systems

The assumed percentages of avoidable food waste related to production for chicken meat at retail (including distribution) and consumption were 4% and 11%, respectively (FAO, 2011). Considering that PK3-MA has the longest shelf life (15 days), it was assumed that this extended shelf life corresponds to a 15% avoidable food waste (i.e., the total percentage of food waste for retail and consumption related to the total meat produced at the slaughterhouse gate). As a result, the estimation of food waste linked to each meat-packaging system utilised a maximum shelf life (SL_m) of 15 days and a minimum food waste (*fw*) of 15%. Subsequently, the percentage food waste associated with meat-packaging systems employing air (PK1–3, i.e., PK1, PK2, and PK3) was calculated using the three methods outlined in Table 3. The relevant details for each method are presented below, and the results are summarised in Table 4.

Method 1: The kinetic constants (k_a, k_b and k_c) were calculated using a minimum percentage of food waste of 15% (i.e., total for retail and consumption) at a maximum shelf life of 15 days.

Method 2: As Eq. (8) incorporates terms independent of the meat-packaging life cycle stage, it was presumed that the model is relevant to both the retail (including distribution) and consumption life cycle stages. Consequently, the percentage of food waste linked to a 6-day shelf life (i.e., meat packaged with air), considering a maximum shelf life of 15 days and a minimum food waste of 15%, can be estimated using the model.

Method 3: This method is derived from the combination of two models: one initially developed exclusively for retail (Eq. (4–6) (Westergaard-Kabelmann and Olsen, 2016), and the other tailored for consumption (Zhang et al., 2019). Consequently, the estimated food waste at retail for packaging with air ($SL = 6$ days; $fw_R = 4\%$) was calculated as 27.6%. Simultaneously, the consumption-related food waste, determined using the model proposed by Zhang et al. (2019), was approximately 11.8% (i.e., a shelf-life extension of 9 days using PK3-MA resulted in about 7% *FW* reduction, so the *FW* associated with using PK1–3 instead of PK3-MA would be $fw_C/0.93$, where $fw_C = 11\%$). Thus, the overall percentage of food waste from retail to consumption was estimated at 39.4%.

Unexpectedly, Method 1 (model 'a') and Method 2 yielded nearly identical food waste estimates, approximately around 47%. This figure falls within proximity to the overall average value of 44.7% derived from all five models. In Method 3, employing the model by Zhang et al. (2019) appears to underestimate the percentage of food waste at the consumer level when compared to the 18.9% food waste reported by Williams et al. (2020) for chicken meat (see Fig. 1). If we consider 18.9% as the food waste for meat packaged with air at the consumer, combining it with the retail food waste of 27.6% results in a total of 46.5%, as opposed to the 39.4% indicated in Table 4, which is approximately 47%. Hence, this paper adopts 47% as the percentage of food waste for chicken meat products packaged with air. Nonetheless, a sensitivity analysis is conducted and discussed in Section 3.2.2, considering other percentage food waste values—24.3% (the lowest value in Table 4) and 18% (an arbitrary value).

Table 4
Percentage food waste (FW) estimates at retail and consumption for chicken meat products packaged with air.

Method	Model type	Kinetic constant (k, $\mathbf{day^{-1}}$)	Food waste (FW) (%)
1	a. first order	1.26×10^{-1}	46.9
	b. sigmoid	2.56×10^{-1}	24.3
	c. straight line	5.67×10^{-2}	65.9
2	NA	NA	46.8
3	NA	NA	39.4

NA: not applicable.

2.2.3. LCA methodology (for packaging systems having different shelf lives): system boundaries, inventory and impact category

The functional unit (FU) chosen to align with the objective of the study outlined in this section was 1 kg of consumed chicken meat. This specific FU is significant as it accounts for food waste from retail to consumption, linked with the various meat-packaging systems. The analysed system boundaries are shown in Fig. 4. It should be noted that FAO food waste percentages (ie., 15% chicken meat waste) always refer to the edible fraction of the food (thus, in the present case, the chicken meat without bones), while the amounts of chicken meat presented in Fig. 4 correspond to chicken meat with bones. Nevertheless, due to the distributive property of multiplication respect to addition, if we calculate the amount of edible chicken meat, apply the FAO waste percentage, and then convert again to the amount corresponding to chicken meat with bones, the amounts in Fig. 4 remain the same.

The methodology and software employed to model the food-packaging systems in this section remains consistent with what was mentioned in Comparison-Category 1 (Section 2.1.1.). However, for the comparison presented here, only the Climate Change impact category from the EF 3.0 method was considered. This decision stems from an earlier publication (Tetteh et al., 2022) from our research team, where the environmental impact of chicken meat production was exclusively detailed in this specific impact category.

The percentage composition of the modified atmosphere gas was assumed to be N_2 (15%), CO_2 (25%), and O_2 (60%), based on a study on chicken meat by Herbert (2014). However, previous research shows that the composition of the gas does not significantly impact the LCA results (Conte et al., 2015). Data for wasted meat production were obtained from (Tetteh et al., 2022). The current Spanish government statistics on food waste EoL management provided for the year 2020 (MITECO, 2023) are: Composting (68.6%); Incineration (8.0%); Landfilling (23.4%). Data for the composting process was taken from Colón et al. (2012), as it is the most recent study providing specific data for 'in-vessel' composting in Spain. Databases from the LCA software have in-vessel composting for Austria, which may not accurately reflect the situation in Spain. Both the incineration and landfilling datasets used for food waste, taken from Sphera databases, included energy recovery.

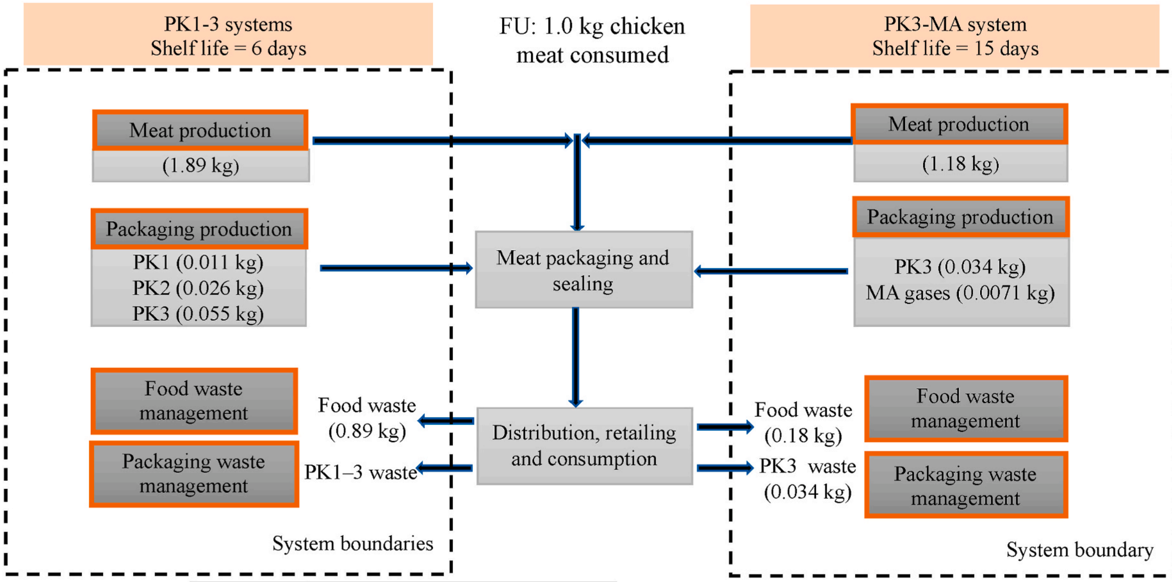
3. Results and discussion

The results are organised based on the two aforementioned comparison-categories as follows: in Section 3.1, packaging systems with identical shelf lives are discussed, while Section 3.2 focuses on packaging systems with varying shelf lives.

3.1. Comparison-category 1: packaging systems having the same shelf life

3.1.1. Environmental comparison of the three packaging systems

The results for all impact categories of the three packaging systems (PK1–3) are depicted in Fig. 5(a). PK1 (PE bag) stands out as the optimal choice for whole chicken carcasses, while PK3 (PET tray) performs the least favourably among the three packaging types compared. This



Packaging waste	PK1 (PE bag)	PK2 (PS/PVC tray)	PK3 (PET tray)
Recycling	3.3%	0.0%	22.3%
Incineration	23.3%	24.1%	18.7%
Landfilling	73.4%	75.9%	59.0%

Food waste	
Composting	68.6%
Incineration	8.0%
Landfilling	23.4%

Fig. 4. Systems boundaries for the LCA comparison of meat-packaging systems having different shelf lives.

results can be largely attributed to the packaging-to-food (PTF) ratio and, when PTF ratios are identical, the type of packaging raw material. The PTF ratio represents the ratio of kg packaging to kg food. Interestingly, PK2, a non-recyclable multilayer tray, outperforms PK3—a comparatively highly recyclable monolayer tray—in all impact categories except two (see Fig. 5(a)). This discrepancy arises due to the significant role played by the PTF ratio (Table 1). PK3 exhibits the highest PTF ratio (0.0292) compared to PK2 (0.0138) and PK1 (0.00585). This implies that despite both PK2 and PK3 having the same weight of packaging (see Table 1), to package 1 kg of meat, PK3's raw material requirement is at least twice that of PK2 and even greater than that of PK1, significantly impacting its environmental footprint. Although not visually represented in this paper, our findings indicate that if PK3 were to have a lower PTF ratio (i.e., 0.0138, the same as PK2), PK3's Climate Change impact would be reduced by approximately 53% (from 0.087 to 0.041 kg CO_2 eq.), outperforming PK2 in eight out of sixteen impact categories. This underscores the substantial influence that the PTF ratio can exert on the comparison results.

The influence of End-of-life (EoL) treatment compared to raw materials and packaging manufacturing can be seen in Fig. 5(b), for PK3 system, showing the small contribution of EoL in most of the impact categories. This remains valid for all three studied packaging systems.

Fig. 5(b) illustrates the contribution of various life cycle stages to all impact categories, focusing solely on PK3. Meanwhile, Fig. 6 displays the contribution specifically to the Climate Change impact category for the three compared packaging systems. Fig. 5(b) shows that the raw material acquisition and pre-processing stage significantly influences all impact categories except two (Ionising radiation and Water use), which are mostly influenced by packaging manufacturing. On the other hand, end-of-life (EoL) waste treatment contribution depends on the type of packaging. For instance, as depicted in Fig. 6, both PK1 (a recyclable PE bag with a 3.3% recycling rate in Spain (Lopez-Aguilar et al., 2022)) and PK2 (a non-recyclable multilayer tray) exhibit an EoL Climate Change impact equal to that of packaging manufacturing. In contrast, for PK3 (a comparatively highly recyclable monolayer tray, with a 22.3% recycling rate in Spain), the Climate Change impact from packaging manufacturing is nearly five times that of its EoL impact. Electricity consumption emerges as the primary contributor to the environmental impact of the packaging manufacturing life cycle stage.

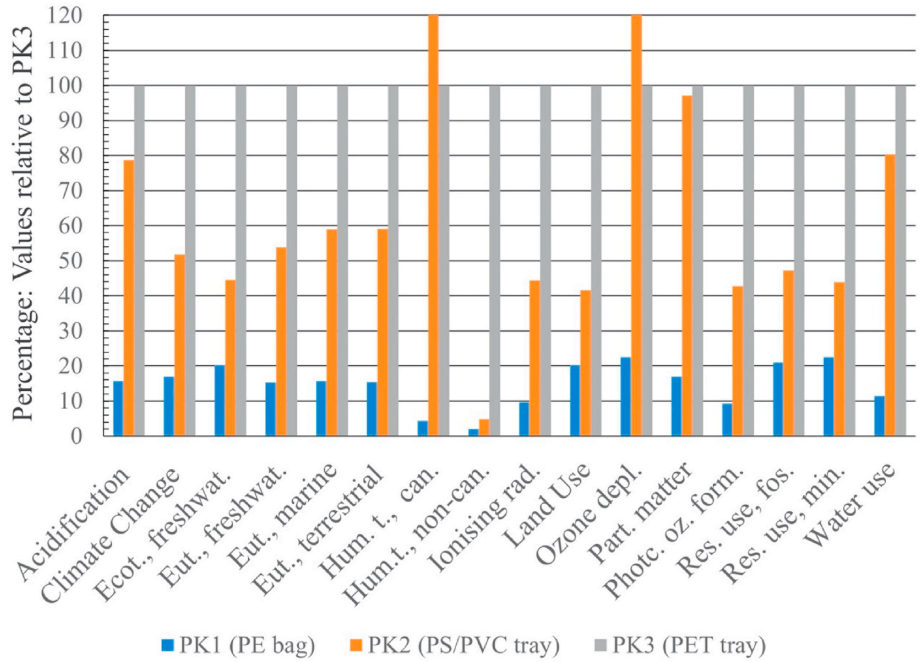
It is important to mention here that, although a packaging is designed to be recyclable (i.e., PK1, a PE bag), the conditions for it to be really recycled depend on the location where this EoL treatment needs to be produced. The lower recycling rate of PK1 in Spain (3.3%) had an adverse effect on its recycling credits compared to PK3 (22.3%). In the case of PK2, despite being non-recyclable, the credits obtained from its energy recovery through incineration process appear to counterbalance its lack of credit from recycling. This observation does not imply that 'no recycling' is preferable; rather, as illustrated by PK3, higher recycling rates are more desirable. To emphasise the significance of end-of-life (EoL) scenarios, it is recommended to incorporate supplementary impact indicators such as circularity or littering indicators. However, these are not commonly integrated into Life Cycle Assessment (LCA) studies due to a lack of consensus.

In summary, the findings presented here indicate that, when considering constant shelf life and food waste rates, the most significant factors influencing the environmental impact of meat packaging are the packaging-to-food (PTF) ratio and the type of packaging material. These primary conclusions remain valid despite the limitations of the present academic study. Notably, the data on packaging originates from 2012, and PK3 (PET tray) is not a genuine packaging. In reality, it features a modified atmosphere (PK3-MA), thereby increasing the shelf life of the chicken meat and consequently decreasing the meat waste. Therefore, its impact will likely be much lower compared to the others discussed here, as will be further elaborated in the following section.

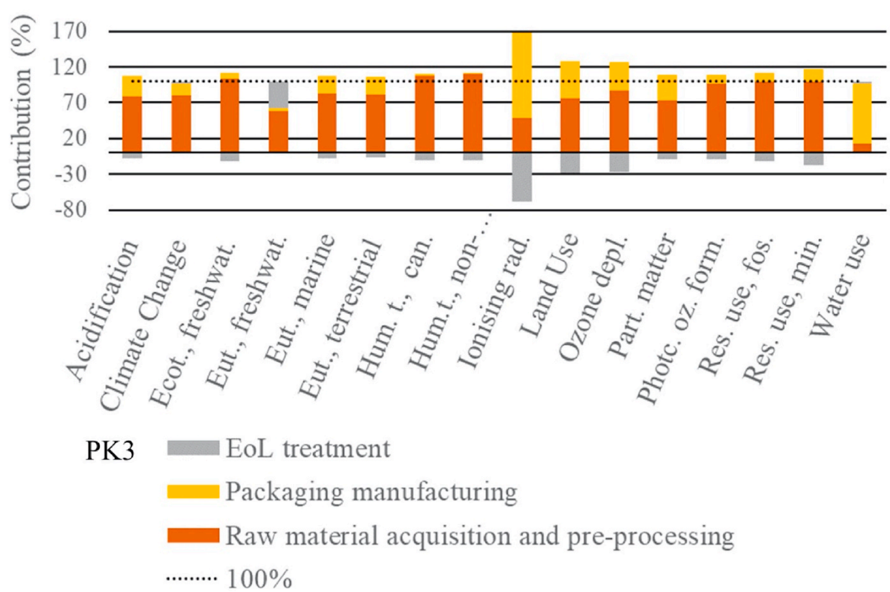
3.2. Comparison-category 2: packaging systems having different shelf lives

3.2.1. Comparison of packaging systems having different shelf lives

To examine the impact of shelf life on the environmental consequences of meat-packaging systems, a comparison is made between PK1–3 and PK3-MA (PK3 with modified atmosphere gas in its



(a)



(b)

Fig. 5. Environmental impact comparison of packaging systems having the same shelf life: (a) relative contribution of PK1–3 to each impact (b) relative contribution of PK3's life cycle stages to each impact—total impact above 100% is due to credits from EoL treatment.

headspace). As previously mentioned, PK1–3 were packaged with air, featuring an average shelf life of 6 days, while PK3-MA had an extended shelf life of 15 days. Consequently, the two packaging systems exhibit distinct percentages of food waste (i.e., total from retail to consumption related to the total meat produced at the slaughterhouse gate)—47% each for PK1–3 and 15% for PK3-MA (see Section 2.2.3).

The Climate Change results for the packaging systems are illustrated in Fig. 7. The findings unequivocally demonstrate that the meat-packaging system with a longer shelf life (PK3-MA) is environmentally more favourable when compared to systems with shorter shelf lives (PK1–3). Additionally, Fig. 7 reveals that the production of wasted food is the primary contributor to the Climate Change impact for all four meat-packaging systems. Meanwhile, although PK3-MA's raw material acquisition and pre-processing stage represent its second-largest contributor (0.08 kg CO_2 eq.) to Climate Change, for PK1–3, it is the end-of-life (EoL) treatment of food waste (0.19 kg CO_2 eq.). This underscores how variations in the shelf life of meat-packaging systems significantly influence their environmental impacts.

The results comparing PK3 with PK3-MA (Fig. 7) unequivocally reveal that extending the shelf life of a chicken meat product from 6 to 15 days could lead to approximately a 78% reduction in Climate Change impact. It is important to note that this evidence does not consider the potential slightly higher energy consumption associated with products packaged in a modified atmosphere (i.e., energy consumed in modifying

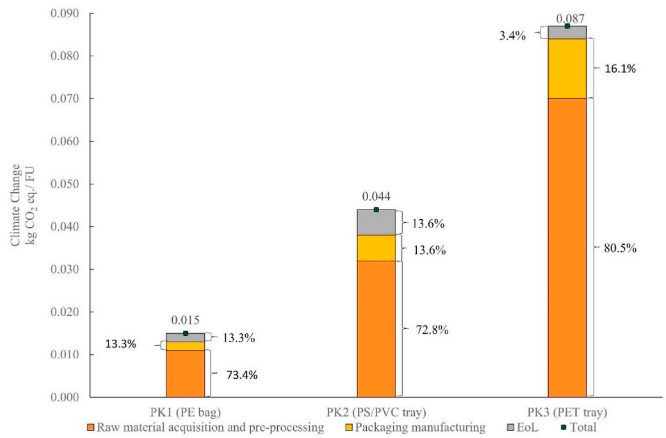


Fig. 6. Climate Change impact, according to life cycle stages, of the three packaging systems having the same shelf life. Percentages represent relative contribution of each life cycle stage to the total impact.

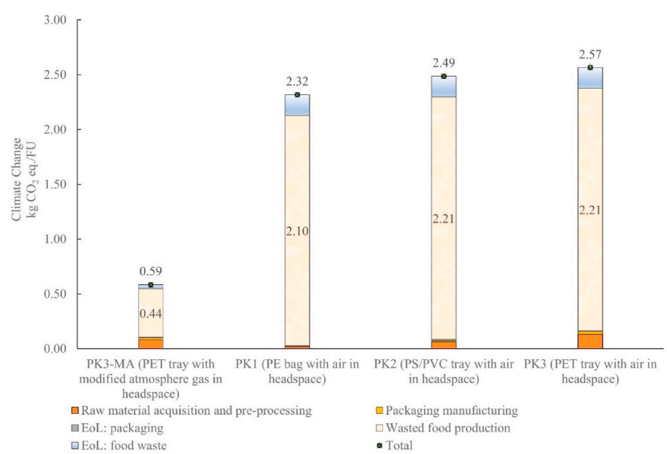


Fig. 7. Climate Change results for PK1–3 (shelf life: 6 days; food waste: 47%) and PK3-MA (shelf life: 15 days: food waste: 15%) considering differences in their shelf lives and food waste.

the packaging headspace atmosphere). Nevertheless, prior research indicates that this energy difference becomes only relevant when food waste is not considered (Conte et al., 2015).

Studies investigating the environmental impact of extending the shelf life of food packaging, especially for meat products, are scarce in the literature. For pastry cream, Settier-Ramirez et al. (2022) demonstrated that increasing its shelf life from 3 to 13 days using active packaging resulted in a 75% reduction in Climate Change impact. Furthermore, Conte et al. (2015) found, in their study on cheese packaging, that utilising a modified atmosphere increased shelf life and led to a lower environmental impact compared to packaging the same product with air.

3.2.2. Sensitivity analysis

The sensitivity of the results (Fig. 7) to the percentage of food waste (FW) for PK1–3 was examined by contrasting the base case (PK3-MA: $FW = 15\%$; PK1–3: $FW = 47\%$) with two alternative scenarios:

i. Scenario 1: Utilising the lowest food waste (FW) estimates in Table 4. In this scenario, PK3-MA is considered with $FW = 15\%$, while PK1–3 is considered with $FW = 24\%$.
ii. Scenario 2: This scenario maintains PK3-MA with $FW = 15\%$ but considers PK1–3 with $FW = 18\%$. At the inflection point ($FW = 18\%$), the environmental impact of the packaging system with a longer shelf life equals that of the one with a shorter shelf life. Below this point, the preferable packaging system would be the one with a shorter shelf life.

The results exhibit sensitivity to the FW of PK1–3 (see Fig. 8). However, the most noteworthy observation from this analysis is the evidence that as the FW decreases from 47% (base case) to 18% (scenario 2): i) there is no discernible environmental benefit in choosing PK3-MA (packaged with a modified atmosphere; $SL = 15$ days; $FW = 15\%$) over PK1, and ii) PK3-MA's impact is only marginally higher than PK2 and PK3 (all packaged with air; $SL = 6$ days; $FW = 18\%$). This suggests that a crucial factor in determining the most environmentally favourable food packaging option is the percentage difference in food waste between the compared packaging systems. At a difference of 3% between the FW of PK3-MA and PK1–3, there is no substantial environmental advantage in choosing one packaging over the other. It is essential to note that $FW = 18\%$ is lower than the minimum estimate (24.3%) obtained from the three methods tested (see Table 4). This underscores the need for a scientific consensus on a validated model to predict the relationship between shelf life and food waste. In the current case, Method 1 (first order) and Method 2 (probability-based) seem to produce similar food waste estimates (which are also close to the average FW value of all five models).

3.2.3. Discussion on the models used to estimate food waste at a given shelf life

The selected models for analysis were those previously described in Section 2.2.1., and their strengths and weaknesses are summarised in Table 5. The models from Conte et al. (2015) exhibit broad applicability and ease of use, covering all steps of the supply chain and all types of products (see Table 3). However, they rely on mathematical equations that lack validation with sufficient experimental data. Conversely, the model proposed by Zhang et al. (2019) is based on a survey of 803 consumers in the United States (U.S.). While the sample size is relatively adequate, enhancing the reliability of the model, it predominantly reflects consumption habits in the U.S., which may differ slightly from those in Europe. Finally, the retail model presented by Westergaard-Kabelmann and Olsen (2016) can be applied to any food product. However, its weakness lies in its development using a small sample size, derived from data collected from only 2 retailers.

In this paper, Method 1 (Table 3) directly corresponds to the models described by Conte et al. (2015). Method 2 was derived from Westergaard-Kabelmann and Olsen (2016), adapting the mathematical equation initially developed solely for retail to include the consumer stage. Method 3 is a combination of two models (Westergaard-Kabelmann and Olsen, 2016; Zhang et al., 2019). Consequently, Method 3 was expected to be the most accurate method for representing the reality of food waste due to its origin from methods developed using real information from both retail and consumers. The inclusion of consumer attitudes, recognised as major contributing and unpredictable elements in food waste estimation (Williams et al., 2020), enhances the reliability of the results. Nevertheless, Method 3 has its own weaknesses, such as the small sample size utilised for the retail model and the fact that consumer attitudes were derived solely from data collected in the U. S. for the consumer model. Hence, none of the tested models is validated with sufficiently extensive empirical data.

The strength and novelty of this paper stem from the precise application of three distinct methods, incorporating five models focused on shelf-life-food-waste estimation for the same case study. Method 1's first-order model and Method 2 produced nearly identical results for food waste (47%), while Method 3 yielded a slightly lower value (39%). In contrast, Method 1's sigmoid and straight-line models either underestimated or overestimated food waste (24% and 66%, respectively).

A key future recommendation is the need to establish a widely accepted model for calculating food waste based on shelf life. The process should involve a comprehensive review of all existing models in the

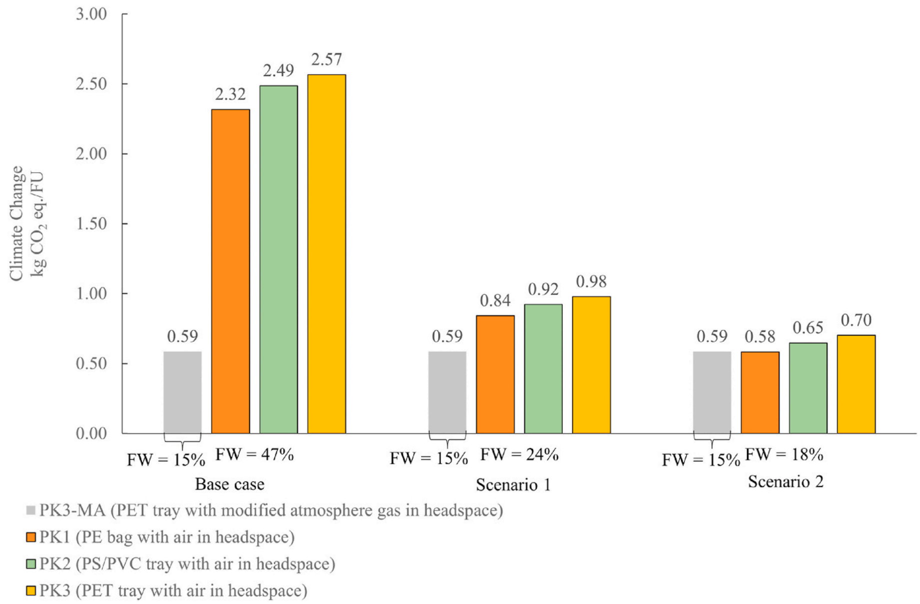


Fig. 8. Results of the evaluation of the effect of different percentages of food waste (FW) on Climate Change impact of different food-packaging systems (PK3-MA and PK1–3).

Table 5
Summary of information on models used in this study for estimating food waste at a given shelf life.

Reference	Conte et al. (2015)			Westergaard-Kabemaan and Olsen (2016)	Zhang et al. (2019)
Model name	First order	Sigmoid	Straight line	NA	NA
Study design	Limited experimental data; hypotheses: 1) FLP = 1 if SL = 0 and 2) FLP = 0 if SL = ∞			Empirical observation of two retailers based on: 1) percentages of yoghurt left on the shelves and 2) the number of shelf days.	Consumer survey
Sample size	NS			2	803
Application (product)	Cheese			Yoghurt	Meat products
Application (value chain)	Post-harvest to consumer	Post-harvest to consumer	Post-harvest to consumer	Retail	Consumer
Strengths	1) Models tend to be applicable to the entire value chain (i.e., from post-harvest to consumer). 2) Easy to use.			1) Though sample size was small, the use of empirical observation helps to enhance validity. 2) Authors provided justification for mathematical equations, which makes model easy to replicate and use.	1) Adequate sample size helps to enhance validity. 2) Authors provided justification for mathematical equations, which makes model easy to replicate and use.
Weaknesses	–	Tends to underestimate food waste	Tends to overestimate food waste	Applicable to only one stage (retail) of the food value chain.	1) Applicable to only one stage (consumer) of the food value chain. 2) Since model was developed using consumer perceptions of food waste in the U.S., its applicability to other regions may be a challenge as the waste patterns may differ.
	1) Models were developed using limited experimental data, which may increase uncertainty. 2) Authors did not provide information on how model equations were proposed, which reduces their reliability and validity.				

NS: not stated; NA: not applicable; -: unavailable; FLP: food loss probability; SL: shelf life.

literature, tested with authentic statistical data from both retail and consumers. This model validation may necessitate distinct data for different food types, such as meat, fish, and vegetables.

4. Conclusions

It is crucial to design food packaging systems that prevent avoidable food waste, particularly at retail and consumer levels where food may not be sold or consumed after reaching its shelf life. In this paper, the life cycle assessment methodology was employed to environmentally compare meat-packaging systems in two distinct comparison-categories. The first involved packaging systems with the same shelf life and, consequently, the same percentage of food waste related to food produced. These packaging systems were easier to compare, as there was no need to include the food waste (it will be compensated in the comparison), and the environmental results followed usual eco-design criteria and showed that the best packaging is the simplest one, the one with the lowest packaging-to-food ratio. In contrast, the second comparison-category, which compared packaging systems with different shelf lives leading to varying percentages of food waste, was led by the product's impact and not the packaging's one.

Currently, there is no scientific consensus on using a specific model to estimate food waste at a given shelf life of a packaged product. Therefore, different shelf-life-food-waste models from the literature were reviewed, summarised, and adapted into three methods to estimate food waste (FW) from retail to consumption related to food produced at the slaughterhouse gate. The results showed that the packaging with a longer shelf life (15 days instead of 6, with a modified atmosphere in its headspace) was environmentally preferable compared to the others (irrespective of material type and packaging-to-food ratio), as it reduced the food waste from 47% to 15% of the total meat produced at the slaughterhouse gate. Because of the uncertainty of such models, a sensitivity analysis of the results at different percentages of food waste (FW) was performed and revealed that even with a FW difference about

3% between packaging types the more complex PET tray (packaged with a modified atmosphere) has similar climate change impact than the two other packaging alternatives (PS/PVC tray and PE bag—both packaged with air in their headspaces). All the FW estimate models tested here gave more than 3% FW difference when the shelf life of the packaging changes from 6 to 15 days. Differences obtained ranged from 9% to 46% of FW.

The main novelty of the present paper lies in the fact that, for the first time, three methods (from five published models) were used to estimate and compare FW associated with the shelf life of a particular food-packaging system. In Method 1, three different models (first order, sigmoid and straight line) were used. The model in Method 2 was originally developed for estimating food waste at retail but was adapted to include waste estimation at the consumer. In Method 3, two models that were developed separately for retail and consumption were combined. Method 1's first-order model and Method 2 yielded approximately the same result for food waste (47%), while Method 3 resulted in a slightly lower value (39%). Despite the expectation that Method 3 would be closer to reality, given its consideration of consumer attitudes (major contributors that are challenging to model), it still exhibits weaknesses. These include a small sample size for the retail model and reliance solely on consumer habits data from the U.S. for the consumer model.

Hence, due to the significance of food waste calculation in the environmental comparison of food packaging systems, it is recommended that existing models in the literature should be reviewed and validated by testing them with comprehensive statistical data from retail and consumers.

CRediT authorship contribution statement

Harrison Tetteh: Writing – original draft, Software, Methodology, Investigation. **Mercè Balcells:** Writing – review & editing, Validation, Funding acquisition. **Ilija Sazdovski:** Writing – review & editing, Validation, Methodology. **Pere Fullana-i-Palmer:** Writing – review & editing, Validation, Methodology. **María Margallo:** Validation, Methodology. **Rubén Aldaco:** Validation, Methodology, Funding acquisition. **Rita Puig:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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The authors of the UNESCO Chair ESCI-UPF want to state that the authors are responsible for the choice and presentation of information contained in this paper as well as for the opinions expressed therein, which are not necessarily those of UNESCO and do not commit this Organisation.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2024.100197.

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