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TITLE:

Assessing the environmental consequences of shelf life extension: conventional versus active packaging for pastry cream

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ABSTRACT:

Shelf life extension can reduce food losses throughout the entire food chain, and packaging can be an effective way to attain this goal. Along these lines, active packaging is an appealing alternative that uses natural antimicrobial compounds to inhibit the growth of microorganisms causing food spoilage. Specifically, a packaging was developed based on polyethene film with a coating fully compatible with food (all components declared as food additives and food contact materials). Furthermore, this bag is mono-material, meaning it can be considered fully recyclable after use. In this study, conventional and bioactive bags carrying viable *Lactococcus lactis* subsp. *lactis* and phytic acid with antimicrobial activity were used to pack pastry cream. The environmental implications of the packaging choice have been assessed by applying life cycle assessment to both the empty packages and the complete food-packaging system. To assess the empty packages, a bag of 200 mL capacity was the functional unit, and all life cycle stages were included, from cradle to waste treatment. In that case, the active packaging implies an increase in all the impact categories due to the application of the bacterial coating on the conventional bag film. When assessing the food-packaging systems, the functional unit was 218 g of packed pastry cream, and the system boundaries included the whole life cycle of the pastry cream-package, also considering indirect effects in terms of shelf life and food waste. Under this perspective, the environmental load of the coating production is offset by the extension of the product`s shelf life from 3 to 13 days, with the subsequent reduction in the waste generated along the food chain. In this way, a reduction in all the impact categories corresponding to the pastry cream in active packaging is observed, ranging from 45% for ionizing radiation to 75% for climate change. It can be concluded that, despite the limitations regarding waste estimation, extending the shelf life of foods is a key issue when assessing the environmental impacts of novel packages. Future research should focus on developing better models based on empirical data, which relate product shelf life and potential waste. In addition, a holistic sustainability assessment should also consider economic issues under a life cycle approach.

KEYWORDS: antimicrobial active packaging; food waste; LCA; shelf life

1. Introduction

Halving the rate of food loss and waste (FLW) is agreed as an effective way to increase the sustainability of food systems, which, at the same time, contributes to achieving both the UN Sustainable Development Goals and the goals of the Paris Agreement on climate change, (Hanson et al., 2019). According to FAO (Gustavsson et al., 2011), FLW can be defined as the mass of food lost or wasted in the part of food chains leading to edible products going to human consumption. Specifically, “food losses” take place at the production, postharvest and processing stages in the food supply chain, and those losses occurring at retail and final consumption are instead called “food waste” (Parfitt et al., 2010). Product expiration is a critical factor of waste at retailing and consumption. Taking into account that most of the FLW in Western countries takes place at retail and consumption stages, shelf life extension can play a crucial role in reducing food waste. In this context, packaging is an effective way to prevent food spoilage and increase the shelf life of foods. Therefore, extending food shelf life using innovative packaging technologies could be a reliable approach to increasing the global sustainability of a food product.

In addition, we must not forget that consumers demand less processed foods, made with natural ingredients, and free of synthetic preservatives. Along these lines, the development of active packaging (AP) using natural antimicrobial compounds that inhibit the growth of microorganisms that cause food spoilage, arises as an interesting way to extend a product´s shelf life. Numerous studies have demonstrated that incorporating antimicrobials in polymer films or coatings is more effective than adding them directly to the food product (Appendini and Hotchkiss, 2002; Falguera et al., 2011; Rocha et al., 2013). Indeed, films and coatings immobilize antimicrobial agents providing a protective environment for them, and can also modulate their release from the packaging to the food (Aloui and Khwaldia, 2016).

Bacteriocins are antimicrobial peptides resulting from the metabolism of certain bacteria. Particularly, bacteriocins from lactic acid bacteria (LAB) have been a breakthrough in the food industry because, besides increasing food safety and shelf-life, they ensure the health and safety of consumers (Reis et al., 2012). However, the use of bacteriocins has limitations due to the gradual depletion of this compound during storage time. For this reason, the incorporation of viable LAB directly into the films instead of just using their bacteriocins is a good tool to solve this problem (Espitia et al., 2016). LAB, not only produce bacteriocins *in situ* in the food, but they also have other mechanisms, such as the production of organic acids or the competition against spoiling microorganisms for nutrients, that can increase antimicrobial activity.

Despite the key role of packaging in food preservation, it also represents an environmental issue, mainly related to its production and especially concerning packaging waste treatment. Life cycle assessment (LCA) is a useful and standardized tool to address the environmental sustainability of products, such as packaging, considering all the stages in their life cycle. Nevertheless, when analyzing the environmental impacts of food packaging, many LCA studies do not take into account the packed product (Williams and Wikström, 2011) although, in that way, the influence of the product and product waste on the environmental impact of the product-packaging system is neglected (Grönman et al., 2013; Molina-Besch, 2016). Thus, recent LCAs on packaging, and specifically on AP (Manfredi et al., 2015; Vigil et al., 2020; Zhang et al., 2015), have included the food life cycle in the system boundaries; although these studies considered different packaging systems, such as coextruded films and coatings that release organic volatile substances, or nanocomposites obtained by melt blending. The development of AP implies an additional environmental impact due to the use of resources to produce and stabilize the coating.

Therefore, to evaluate the sustainability of AP, we need to assess whether the environmental burdens resulting from the packaging production offset the potential beneficial effects in terms of food waste reduction due to the product's shelf life extension. This implies elucidating the relationship between the product's shelf life and the amount of food waste generated, which will be a data to be used in the LCA. This relation is not direct and, as pointed out in WRAP (Waste & Resources Action Programme, 2013), empirical determination is hard. In fact, studies on waste reduction initiatives should take into account the reactions of each stakeholder, requiring behavioural knowledge which often implies expensive field research (Lebersorger and Schneider, 2011). In addition, differences in local infrastructure and practices for packaging and food waste treatment increase the uncertainty when quantifying the impact of such initiatives and makes it difficult to propose global (or regional) strategies. In section 2, different approaches to estimating the relationship between the product's shelf life and the amount of food are reviewed.

Previous studies have shown the viability of PVOH-based films incorporating Lactococcus lactis as a coating for AP (Settier et al., 2019, 2020), and the effect of this AP on food shelf life extension (Settier et al. 2021). This AP can be easily implemented, is valid for food contact and, after consumption, the resulting packaging waste is monomaterial and therefore fully recyclable. As a further step to decide the feasibility of the product, the sustainability of the AP needs to be analysed. Thus, the aim of this study is to compare the environmental impacts of conventional packaging (CP) and the developed AP for a specific food, namely fresh pastry cream, also considering the reduction in the product´s loss and waste. Specifically, we addressed (i) the environmental impact of the two packaging alternatives, CP and AP, and (ii) the environmental impact of the complete system food-packaging considering the food wasted according to the shelf life of each alternative.

2. Review on shelf life of foods and related food waste

There is an increasing body of studies which claim that shelf life extension would reduce avoidable FLW along the supply chain, mainly at retailing and consumption. However, there is limited data available on the relation between shelf life and food waste and the perspectives used in the literature to calculate this relation are very different. Although according to the definition given in Section 1, food waste refers to retailing and consumption, from now on the term will also include the food losses in the processing stage.

Food waste generation at the household level has been modeled by WRAP (2013) by using discret event simulation applied to milk waste. The model takes into account different factors affecting food waste production at home. Among them, the effect of an increase of shelf life and the effect of an increase of the milk durability once the packaging is open. This model has been further used by Manfredi et al. (2015) and by Valsasina et al. (2017) in prospective LCA studies to evaluate the effect of shelf life extention of milk due to alternative packaging and new processing technologies, respectively.

The influence of consumer behaviour on food waste as a consequence of shelf life extension due to the use of nano-packaging was assessed by Zhang et al. (2019) for different kinds of food. The authors conducted a stated-preference survey to indirectly quantify the production of food waste. In addition, a sensitivity analysis revealed that the uncertainty of the estimation on shelf life extension had a limited influence on the beneficial effect of the use of nano-packaging. Notwithstading, the authors emphasize that the results obtained with those approaches remain to be confirmed with laboratory tests and observational studies.

In a study on cheese packaging, Conte et al. (2015) considered three models to relate the probability of food waste with product's shelf life, namely a first order kinetics, a sigmoid and a straight line. The authors do not properly specify the links of the food chain to which this food waste corresponds, although it can be inferred that both retailer and consumer stages are affected. The proposed models span between 0 (shelf life reaches infinity) and 1 (shelf life is zero). In addition, based on Lebersorger and Schneider (2011), they assign an 8% by mass of avoidable food waste to the package causing the greatest shelf life extension. These data allowed the parameters of the three models to be obtained, although the results were not validated with real data. This model was later adopted by Vigil et al. (2020) in a case study on fresh cut salad.

An economic perspective was adopted by Gutierrez et al. (2017) to determine the waste at the retailer level in a case study on two packaging alternatives for cheesecake. Due to the short shelf life of the product, the authors apply an economic model that considers the minimum amount of delivered product to consingnement that must be sold to select the most advantageous packaging solution for the firm. In addition, they assume that the distribution of sales follows an exponential function and calculate food waste as the difference between the product consigned to the market place in a week and the quantity sold during that time period.

Westergaard-Kabelmann and Olsen, (2016) used cost benefit analysis to quantify the potential impacts of the application of new bacteria strains to extend yoghurt shelf life. The authors estimated the yoghurt waste and the potential waste reduction accruing from shelf life extension not only at retailing and household consumption, but also at the production stage. As to the production stage, the underlying assumption was that extending the product's shelf life would allow larger production batches. The authors considered data on the reduction of the number of batches from a dairy manufacturer together with data on the relationship between batch size and frequency and waste reduction from Berlin and Sonesson (2008). The waste at retailer was estimated based on two case studies in supermarkets, where the percentages of yoghurt left on the shelves were monitored for an increasing number of shelf days. These discrete observation sets were approximated by a continuous exponential function. On the other hand, waste reduction at the household level was estimated by adapting the milk model developed by WRAP (2013).

Spada et al. (2018) identified a relationship between the shelf life and an important food waste component, i.e. the product returned from the market. To this aim, they used a statistical approach to model real market data. An inverse function between shelf life and returned product was found for those products with a shelf life between 30 and 50 days.

Summarizing, different perspectives have been applied to estimate the waste generated by shelf life expiration. It must be noted that the reviewed models are not always validated with real data on food waste. On the one hand, food waste quantification entails difficulties, as data are often sparse and with high uncertainty due to the low representativeness of the sampled data and also to the methodological assumptions (Amicarelli and Bux, 2020; Corrado et al., 2019). On the other hand, this data are even more difficult to obtain when the product system studied is a new one, as in this case study, which increases the uncertainty. In consequence, when using these models in LCA, the uncertainty will be propagated to the impact results.

3. Materials and methods

3.1. Packaging description

In this study, *Lactococcus lactis* subsp. *lactis* was chosen as the microorganism producer of antimicrobial agents for developing the active packaging. Indeed, among lactic acid bacteria (LAB), *L. lactis* is considered as GRAS (Generally Recognized As Safe) by the FDA (Food and Drug Administration) and produces nisin, a well-studied bacteriocin classified as GRAS with antimicrobial activity against Gram-positive bacteria such as *Listeria monocytogenes*

(Benkerroum and Sandine, 1988). In addition, nisin is currently applied worldwide in milk-based products (Silva et al., 2018). However, nisin is only effective against Gram-positive bacteria (Holcapkova et al., 2018; Kuwano et al., 2005). Researchers have shown that the addition of chelating agents to nisin increases the antimicrobial effectiveness against Gram-negative bacteria (Boziaris and Adams, 1999; Delves-Broughton, 1993). Phytic acid (PA) is a food additive which is present in nuts, grains and legumes with high chelating capacity. It was used in combination with *L. lactis* to broaden the antimicrobial spectrum to Gram-negative bacteria and to extend the shelf life of food products.

Polyvinyl alcohol (PVOH), a synthetic biodegradable and biocompatible polymer was selected to deliver living *Lactococcus lactis*, as it is water soluble, and valid for both food contact and as food additive (Codex Alimentarius; Food and Agriculture Organization/World Health Organization, 2004; Annex II to Regulation (EC) No. 1333/2008). Previous studies have shown that the combination of a PVOH matrix with a small amount of casein hydrolysates (HCas) leds to further *L. lactis* viability, enhancing the antimicrobial activity (Settier-Ramírez et al., 2020, 2019).

To develop the active packaging, two coating forming solutions (CFS) with PVOH and HCas, one with *L. lactis* and the other one with phytic acid (PA) were prepared, as described elsewhere (Settier-Ramírez et al., 2021). These coatings were applied onto polyethylene film (PE) and left to dry at 60 ºC during 3 sec. The total coated surface was (20 cm x 10 cm) on both sides and a 0.8 cm margin of PE was left around the coating to make bags by heat-welding at 180 ºC for 1.5 seconds. The average thickness was 72 µm for PE and 12 ± 3 µm for both coatings. Therefore, the final polymer coating concentrations were 10^{-3} g PVOH/cm^2 and 10^{-3} g HCas/cm^2. Control bags were made with neat PE films.

The product under consideration is a handmade pastry cream (PC), prepared at lab scale as follows: semi-skimmed milk (59%), cornmeal (6%), eggs (23%), sugar (11.5%) and vanilla extract (0.5%) were stirred and heated at 100 ºC for 10 minutes. After cooling, 218 g of pastry cream were properly packaged and stored under refrigerated conditions.

3.2. Quantification of pastry cream shelf life and associated food waste with the two packaging alternatives

The shelf life of a food is defined as the time after its production under controlled storage conditions, in which it suffers a loss or unacceptable changes in its sensorial or physicochemical properties, or when a change in its microbiological profile occurs. The study of the shelf life of homemade pastry cream packaged in both active and conventional packaging was carried out during storage at 0, 1, 3, 7, 10, 13, and 20 days. This analysis consisted of monitoring safety and quality by studying the growth of both pathogen and spoilage microorganisms and sensorial quality. The shelf life of the pastry cream increased from 3 days with conventional packaging to 13 days with active packaging (Settier-Ramírez et al., 2021). As commented in Section 1 and Section 2, product shelf life is related to the amount of food waste. Thus, the pastry cream wasted at manufacturing, retailing and household storage was quantified according to the previously estimated shelf life following Westergaard-Kabelmann and Olsen (2016).

At the manufacturing stage, waste production is closely related to the number of batches, as each production batch requires cleaning. Berlin and Sonesson (2008), estimated around 5.3% to 6.7% waste in yogurt production with 2-3 production batches. In the present study, we assumed that the waste generated when processing the pastry cream is the same than that of yogurt, since both are viscous products. Hence, for the pastry cream in the conventional PE bags, 3 batches per week (every other day), with 6% waste, have been considered. In addition, Westergaard-Kabelmann and Olsen (2016) estimated that reducing batch frequency by one batch per week can reduce production waste by 33%-50%, which would require an extra of 4 to

5 shelf life days. Hence, for the active packaging, which increases the shelf life to 13 days, and assuming 33% waste reduction to be conservative, 2% waste in the production stage was considered.

As concerns the pastry cream wasted before consumption because shelf life expiration, both at retailing and household, the model proposed by Westergaard-Kabelmann and Olsen (2016) for yogurt was applied. Based on discrete data on the percentages of yogurt left on retailer shelves and the number of shelf days, these authors adopted a continuous linear function assuming that the product had a constant probability (p) of being sold each day it is on the shelf. The ex-ante probability of the product being sold within day t (day t included), called P(t), is given by:

$$\textit{Ex ante probability for yogurt being sold within day t} = P(t) = 1 - (1 - p)^t \qquad (1)$$

Assuming that the waste rate is given by a percentage w and that the total shelf life is n, the daily probability of the yoghurt being sold can be calculated as:

$$(1 - w) = 1 - (1 - p)^n \qquad (2)$$

$$p = 1 - \sqrt[n]{1 - (1 - w)} \qquad (3)$$

Westergaard-Kabelmann and Olsen, (2016) reported values for w varying from 1.4% for UK (Lee et al., 2015) and 2.5% for French supermarkets. Therefore, by using equation (3), w = 1.95%, the average of UK and FR data, and n = 13, p was calculated; then, the ex-ante probability of the pastry cream not being sold before shelf life for n = 3 (conventional package) and 13 days (active packaging) was calculated using equation (1), which corresponds to 40% and 2% of wasted product, respectively.

Finally, based on Lebersorger and Schneider (2011) a 7.5% of uneaten food in the original sales packaging for dairy products was assumed as the cream wasted after consumption (leftover).

3.3. Life cycle assessment

Life Cycle Assessment (LCA) was applied to assess the environmental impact of the developed product systems. Following the ISO (2006) guidelines, the LCA phases were developed.

3.3.1. Goal and scope definition

The main purpose of this study was to carry out a comparative assessment of the environmental profiles of two packaging systems, namely a conventional PE packaging (CPE) and a bioactive PE packaging (BPE) that includes an antimicrobial coating. From an environmental perspective, the bioactive packaging will be a viable alternative to the conventional one if the environmental impacts of the system packaging-product are lower than those of the conventional system, Eo if the life cycle impacts of the active packaging alone increase (Silvenius et al., 2013; Williams and Wikström, 2011). Thus, a twofold goal was pursued:

- To make a comparison between the environmental impacts of CPE and BPE packaging. In this way, the environmental profiles from the different packaging materials can be calculated, independently from the product class they will contain, thus making it possible to use the results for other case studies.
- To make a comparison of the complete product-packaging system taking into account the influence of the two packaging alternatives on the shelf life of the packaged pastry cream and the subsequent food waste. In this case, PC-CPE corresponds to the pastry cream with conventional PE packaging, whereas the pastry cream packaged in the bioactive PE packaging is named PC-BPE.

The systems under study according to this twofold goal are described in Figure 1. To reach the first goal, the functional unit chosen is one packaging with 200 mL capacity (Figure 1A) and the systems boundaries comprise all the life cycle stages of the packaging including the waste treatment (Figure 2). The functional unit for the second goal of the study corresponds to 218 g of packaged pastry cream (Figure 1B) consumed in EU28 (which corresponds to 200 mL of pastry cream, since product density is 1.09 kg/L). According to this, the system boundaries (Figure 2) include the whole life cycle of the pastry cream-package system. The pastry cream is included to understand the impact of each type of package on food waste and assess its influence on the environmental profile of the product. The life cycle begins with the production of both the packaging and the raw materials for the pastry cream manufacturing, packages are then filled with pastry cream and transported to the supermarket, where they are stored at the market rag, and ends with the waste treatment. It must be noted that the production and application of the coating corresponds only to the active packaging, whereas all the other stages are common to the two product systems analyzed, although the reference flows change depending on the shelf life of the product, as calculated in section 2.2.

Figure 1.

Figure 2.

3.3.2. Reference flows

When considering the pastry cream-package system to reach the second goal of the study, it must be taken into account that the food waste generated implies that, at the beginning of the food production chain, more food must be produced to fulfil the product demand at consumption. Thus, the reference flows have been calculated by using the percentages of wasted pastry cream from section 3.2. From the same reference unit, that is, 218 g of pastry cream to be consumed, the amount of pastry cream to be processed, delivered to the supermarket, and purchased have been estimated (Table 1). Summarizing, per each 218 g of PC-CPE consumed, around 187 g are wasted, whereas in the case of PC-BPE the calculated amount of pastry cream waste in the same stages is 25.2 g.

3.3.3. Life cycle inventory

The amount of each component for a 200 mL bag of CPE and BPE is shown in Table 2, this data is used both when assessing the empty packages and the cream-packaging system. Primary data were used for the production of the active coating. Processes corresponding to the raw materials for the production of the two packaging alternatives were taken from GaBi database (Sphera Solutions GmbH, Leinfelden-Echterdingen, Germany). Since inventory data on phytic acid was not available in GaBi database or in Ecoinvent 3.5, citric acid was used as an approximation in this study. As to the production of casein hydrolysate, the most energy intensive processes were considered, namely skim milk microfiltration and heat treatment, by using data from Depping, (2020), and the subsequent spray drying process from GaBi database. Inventory data for the production of the frozen LAB were adapted from the study of Pénicaud et al. (2018), considering freezing for 3 months as the average preservation time for the LAB. For the coating preparation and application by using rotogravure technique, the data provided by Manfredi et al. (2015) for a case study on active packaging were adapted taking into account the surface area of the bag.

Inventory data for the production of raw materials for the pastry cream, namely milk, sugar and maize starch flour, have been taken from GaBi database, except eggs, which were taken from Abín et al. (2018), although, instead of including meat from exhausted hens as an avoided product, an economic allocation was carried out. Food loss and waste at the agricultural, postharvest and processing stages of the raw materials for the pastry cream were considered.

To this aim, the food loss percentages corresponding to those stages were taken from Garcia-Herrero et al. (2018), which in turn are based on FAO data for Europe (Gustavsson et al., 2011) and Spanish data (MAGRAMA, 2013). The electricity consumption for preparing the cream was extrapolated based on industrial catalogue data for an equipment with 120 L capacity and 12 kW power. The cleaning of the equipment was not considered in the study due to lack of data, however it must be taken into account that the potential impact of cleaning would be lower when using the active packaging, given that the number of batches per week is reduced, as commented in section 3.2.

An average distance of 25 km was considered for the transportation of the pastry cream between the production center and the supermarket, with a refrigerated truck (Ecoinvent 3.5). Once the pastry cream is delivered to the retailer, 1.5 days of cold storage at the supermarket were considered, with an average energy consumption of 40 kWh/m^3/year (Duiven and Binard, 2002). Following Manfredi et al. (2015) assumptions, a class A refrigerator of 298 L with an average annual consumption of 292 kWh was considered for household storage.

It was assumed that the pastry cream wasted before consumption, that is, because the shelf life date expired, was landfilled without separating the packaging. In this case, the GaBi process “Municipal solid waste on landfill” was used. In case the pastry cream was consumed, the packaging was disposed of according to the average European end-of-life (EoL) data. The rates of each EoL treatment for plastic packaging in the EU28 in 2017 were taken from Eurostat (2020a, 2020b). According to this source, 74.6% of the plastic waste is recovered (Eurostat, 2020a) and 41.9% is recycled (Eurostat, 2020b). The incineration rate has been set by subtracting the recycling rate from the recovery rate, as recycling is a kind of recovery, which means that 33% of the plastic waste is incinerated. The remaining 25.1% was supposed to go to landfill. Processes corresponding to PE incineration and PE landfill of GaBi database were used and, to give a better insight of the environmental consequences of these treatments, the avoided loads due to electricity and thermal energy generation in the incineration process were considered. For the same reason, PE recycling was modelled by including the burdens of the recycling process and the credits from the material obtained.

As to background processes, electricity mix and thermal energy for EU28 were also taken from GaBi database.

3.3.4. Impact assessment

The impact assessment method ReCiPe 2016 v1.1 (Huijbregts et al., 2017) was used in this study. This method considers midpoint and endpoint indicators. The midpoint indicators include eighteen impact categories (abbreviated name and units in brackets): Climate change (CC, expressed as kg CO2 eq.), fine particulate matter formation (FPMF, kg PM2.5 eq), fossil depletion (FD, kg oil eq), freshwater consumption (m3), freshwater ecotoxicity (Fw-Etx, kg 1,4 DB eq.), freshwater eutrophication (Fw-Eu, kg P eq.), human toxicity carcinogenic and no carcinogenic (Htx-CC and Htx-NC, kg 1,4 DB eq.), ionizing radiation (IR, kBq Co-60 eq. to air), land use (LU, annual crop eq.·y), marine ecotoxicity (M-Etx, kg 1,4 DB eq.), marine eutrophication (M-Eu, kg N eq.), metal depletion (MD, kg CU eq.), photochemical ozone formation in ecosystems and human health (POP-Etx, POF-HH, kg NOx eq.), stratospheric ozone depletion (SOD, kg CFC-11 eq.), terrestrial acidification (TA, kg SO2 eq.) and terrestrial ecotoxicity (T-Etx, kg 1,4-DB eq.).

To better understand the relative significance of impact category results, normalization was applied. In this way, abstract impact scores for every impact category are translated into relative contributions of the product to a reference situation (Sleeswijk et al., 2008). Specifically, the normalized factors of midpoint impact for ReCiPe at world level expressed as person equivalents available in GaBi software were applied.

4. Results and discussion

4.1. Environmental impacts of the PE packaging with and without bioactive coating

Firstly, the environmental impacts of the two PE packaging alternatives (without considering the food) are compared (Table 3). As expected, CPE shows lower environmental impacts, since more elements are needed for the packaging production; in addition, eight of the impact categories have negative values due to the avoided loads caused by the EoL treatment stage, which offset the environmental impacts of the packaging production. Those avoided loads, as explained in section 2.3.3, are implicit in incineration and recycling treatments, whereas landfill does not produce any useful energy o product and therefore has no negative values.
As can be observed in Figure 3A, for the CPE bag, the production of low density PE is the main contributor to all the impact categories, whereas the EoL stage shows negative values except for MD and Fw-Eu, which contribute to 82% and 43% of the total impact category respectively, mainly caused by landfill.

Figure 3.

The contribution analysis for the active packaging (Figure 3B) shows that the coating production is responsible for most of the impact categories. It must be noted that the production of the LAB has a low contribution to this stage, whereas the production of casein hydrolysate and citric acid are the main causes of the high values of the coating in most of the impact categories. As commented in section 2.3.3, phytic acid was replaced by citric acid due to lack of inventory data for this compound, hence results may change if phytic acid production is accounted. PE production also means a great share of CC (64% of the total impact), FPMF (46%), FD (136%), FwC (43%), POF (81% and 82% for ecosystems and human health, respectively) and TA (57%). EoL stage has negative values for all the impact categories except for FwEu (less than 1%) and MD (18%), which are caused by landfilling the packaging waste.

Figure 4.

The normalization of the midpoint impact categories (Figure 4) highlights the categories which appear to be the most critical ones for the two analysed packaging systems. For BPE, human toxicity carcinogenic is the most critical impact, although this impact seems negligible for CPE. FD is also critical for both CPE and BPE, followed by CC and TA.

4.2. Environmental impacts of the packed pastry cream

In this section, the environmental impacts of the food-packaging systems (PC-PCE and PC-BPE) are analysed. As commented in section 3.3.1, this allows to understand the impact of the two packages in the context of the food packaged within them, also considering the effect of the shelf life on the packaged food and its subsequent waste. As can be observed in Table 4, in this case, the active packaging shows lower environmental impacts, with differences ranging from 36% for SOD, TA and T-Ecotx, to 76% for CC. This is due to the lower amount of food waste generated when using the active packaging as a consequence of the elongation of the product shelf life. In other words, the food waste avoided by the use of bioactive packaging is more significant than the environmental burden generated by the bioactive coating.
In the contribution analysis, the life cycle stages have been grouped in four items, as follows:

- Pastry cream, which includes the production of the consumed pastry cream, which in both cases is 218 g per FU.
- Wasted pastry cream, which includes the production of the pastry cream surplus that is wasted through manufacturing, retailing and consumption stages. The amount of wasted pastry cream depends on the kind of packaging, as shown in Table 1.
- Packaging, which includes the packaging production. The amount of packaging will depend on the amount of pastry cream purchased by the retailer taking into account the waste.
- Distribution & use, which includes the transport, storage at retailer and household, and consumption of the packed pastry cream.
- End of life (EoL), which includes all the inputs and outputs related to the treatment of both packaging and pastry cream waste. the amount of waste to be treated differs depending on the kind of packaging (see Table 1).

Figure 5 reports the relative contribution of each of those five items to the product-packaging system for PC-CPE (A) and PC-BPE (B). Pastry cream manufacturing together with the wasted pastry cream are, as expected, the main cause of impacts in both systems. These two items represent jointly 84-100% of the total environmental burdens in PC-CPE, and 91-99% in CP-BPE. That is, once food and food waste are included in the system boundaries, the impact of the production of the packaging becomes a small part of the impact of the total system, as reported in previous studies (e.g. Conte et al., 2015; Dilkes-Hoffman et al., 2018; Dobon et al., 2011; Manfredi et al., 2015).

For PC-CPE, the production of 218 g (200 mL) of pastry cream is the main cause of the impacts (48 to 57%, depending on the category), followed by the production of the wasted cream (36 to 43% of the total impact, depending on the impact category). The high share of the wasted pastry cream is explained by the high percentages of waste, as per each 218 g consumed 202 g are wasted. The remaining life cycle stages have a very low contribution to all the impact categories. It must be noted that LDPE production is the main responsible of FD impact category (12% of the total impact of the system), and 2% of CC, POF-ecosys and POF-HH. The distribution & use stage means 3%-6% of toxicity related impacts (Fw-Etx Htx-NC, M-Etx and T-Etx). As to EoL, it is responsible of 14% of CC (mainly because of PE incineration) and 11% of MD.

The results for PC-BPE show that the production of the pastry cream is the main cause of impacts (78 to 89% of the total impact, depending on the impact category). The wasted cr means 9-11% of the total impact (depending on the category) because, in this case, it amounts 27.3 g (see Table 1). The packaging is, on average, the third source of impacts in almost all categories, meaning 7-0.5% of the total impacts, except for FD (16% total impact). Only for toxicity related impacts (Fw-Etx, Htx-C, Htx-NC and T-Etx), the product distribution & use stage shows again higher values than the packaging production. The normalization phase (Figure 6) highlights Htx-C as the most critical impact category for the two food-packaging systems analyzed, followed by Fw-Eu and M-Eu. On the other hand, the normalized values of Htx-NC, IR and MD have a rather low significance.

B

Figure 5.

Figure 6.

4.3. Discussion

The results of the environmental impacts of the two PE packaging alternatives show that CPE presents lower environmental impacts, as more elements are needed for the packaging production. These results totally change when the systems boundaries comprise the food packaged within them, also considering the effect of the shelf life on the packaged food and its subsequent waste. In that case, packaging production means a small share of the impact of the total system, as reported in other studies (Conte et al., Silvenius et al., 2013), and PC-BPE shows a lower impact because the wasted product decreases as a consequence of the product shelf life extension. These results reinforce the hypothesis that increasing product shelf life through alternative packaging is crucial to reduce food waste, even if the impact of the packaging itself increases (see subsection 3.3.1). Previous studies on other AP alternatives achieve similar results, although the active packaging materials were different, as well as the approach used to estimate the food waste generated (Manfredi et al., 2015; Vigil et al., 2020; Zhang et al., 2015). The method used to estimate the amount of wasted food due to shelf life expiration is thus decisive when comparing the two product-packaging systems. As commented in section 1, the relationship between product's shelf life and the amount of wasted food is not direct and empirical determination is hard, specialy when studying a new food product or packaging. Thus, an alternative model from the literature has been used to identify this relationship, namely the exponential relationship proposed by Conte et al. (2015). In this case, 55.8% of the pastry cream is wasted when the shelf life is 3 days (scenario PC-CPE_alt) and 8% waste is generated when it is 13 days (scenario PC-BPE_alt), whereas according to the model proposed in section 2.2 the pastry cream wasted varies from 40% to 2% for PC-CPE and PC-BPE, respectively.

The results of the alternative scenarios (Figure 7) show 36-45% increase on the impact values for the PC-CPE_*alt* vs. the conventional reference system, and 4-5% increase for the PC-BPE_*alt* vs. the bioactive reference system. Therefore, using this alternative model, differences between the conventional and bioactive food packaging system are even greater. Although these results could be used to reinforce the results of the study, some criticisms can be made to the proposal of Conte et al. (2015). On the one hand, an 8% waste is associated to the product with the highest shelf life, without any empirical evidence of the real amount of waste. On the other hand, that value corresponds to the leftovers accounted for by Lebersorger and Schneider, (2011) for food consumption in general, without distinguishing food types such as dairy, meat products, etc.

Figure 7.

To better understand the potential environmental benefits of the proposed AP, the environmental break-even rate has been calculated by using the equation proposed by Yokokawa et al. (2018). According to those authors, the break-even rate represents the required reduction of food waste rate provided by the alternative packaging that can sufficiently decrease the overall environmental impacts. In this case study, the break-even rate varies depending on the impact category from 0.4% for MD to 6.7% for IR. This means that the increased impacts from shifting to bioactive packaging for pastry cream can be offset by a decrease in the amount of waste due to shelf life expiration.

The break-even rate depends on the EoL treatment, and it can be thus calculated for other EoL treatments. If the break-even rate is calculated taking into account incineration very similar values are obtained (from 0.5% for MD to 6.6% for IR). Other treatments could be assessed taking into account that the break-even rate will be higher when EoL technologies are less harmful for the environment (Yokokawa et al., 2018). In any case, the landfill process used in the calculations is not specific for the product, and the same for the incineration; hence, different break-even rates could be obtained if specific EoL processes were used. The limitations as to EoL processes and other quality issues related to the obtained results are commented in section 4.4.

4.4. Limitations, theoretical implications, and future research direction

This case study has some limitations. Firstly, some data quality issues should be improved to reach more reliable results. It must be borne in mind that although packaging disposal has been modelled according to data for EU28, all the product wasted because of expiration is supposed to be landfilled. However, the landfill process used has not been adapted to the input of a specific food or packaging, that is, it does not reflect the specific emissions caused by the disposal of the studied product. In any case, this issue would affect both systems proportionally to the generated waste. Furthermore, the wastewater resulting from cleaning in the pastry cream manufacturing stage has not been included due to lack of data. Accounting that treatment would mean a greater difference between the impacts of the two systems because, as commented in section 2.2, a reduction in both the number of batches and the subsequent cleaning is expected if the shelf life of the product increases due to the bioactive packaging.

In view of the results, those issues are though less decisive than the models used to calculate waste production, which is the main limitation faced in this type of studies. Therefore, more accurate models relating waste production and shelf life are needed for different types of products (e.g. dairy, vegetables, etc), mainly at retail, consumption and at different geographical contexts. To this aim, different approaches are required. Interviews with producers and measurements at processing or pilot plants seem effective methods to estimate food waste at processing. As concerns retailing, models based on statistical data at supermarkets, as the one used in this case study, are useful to describe the probability of a product being sold before reaching its shelf life. Modelling the relation between waste generation and shelf life at the household level is complex, as it involves consumer behavior. Discrete event simulation allows modelling waste streams at home, giving new insights in the area (WRAP, 2013). In addition, leftovers after consumption should be quantified according to the packaging design by conducting emptying experiments (e.g. Silvenius et al., 2013). The development of this kind of models would also imply choosing suitable methods to quantify food waste (e.g. mass balances, food diaries) and estimating the associated uncertainty (Corrado et al., 2019; Amicarelli and Bux, 2021).

Research studies have remarked the potential of active packaging systems to extend the shelf life and thus reduce food spoilage of different types of food products (Sofi et al., 2018; Soltani Firouz et al., 2021). A proper packaging design based on active coating could overcome several issues related to food waste. The results of the present study can provide data to food manufacturers, supporting decisions for adopting packaging innovations. To this aim, the role of bridging institutions and collaborations between research centres is pivotal (Cammarelle et al., 2021).

5. Conclusions

The extension of food shelf life has proved to be a key issue when assessing the environmental impacts of novel packages. Along these lines, active packaging arises as a packaging technology which allows the reduction of FLW along the product chain. In this study, the environmental implications of packaging selection have been assessed considering both the direct and indirect effects, in terms of shelf life and food waste. Specifically, a conventional PE packaging and a bioactive one, consisting on a PE bag coated with PVOH and casein hydrolysates containing *L. lactis* and phytic acid with shelf-life enhancing capacity, have been compared.

Results show that although the addition of active coating means an increase of the environmental impact of the packaging, it can be offset by the potential benefits related to the reduction of food waste. These reductions concern not only refrigerated storage at retailing, but also at manufacturing, as the number of batches per week can be decreased, and at consumption, because once the packaging is open the antimicrobial effect is still active. However, results interpretation should be made with caution. The assumptions adopted cause uncertainty in the results, mainly because waste percentages and waste causes correspond to different countries and to a different product, yogurt, although it is also a viscous food. Thus, the calculation of the break-even rate of food waste can help to determine a threshold of food waste reduction provided by the alternative packaging that can decrease the overall environmental impacts. In any case, despite the limitations to estimate the wasted product, there is no doubt that shelf life extension through packaging innovation can significantly reduce the environmental impacts of the whole food-packaging system.

To reduce the uncertainty of the results, future research is needed to develop more accurate models that relate product shelf life and the potential waste, which would require an interdisciplinary approach. In addition, the economic sustainability should also be considered, taking into account potential changes in the manufacturing and retailing stages and internalizing the benefits to the environment of waste reduction.

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Table 1. Pastry cream flow in the life cycle stages

Cream flow in the life cycle stages	**Average waste PC-CPE**	**Pastry cream in PC-CPE (g)**	**Average waste PC-BPE**	**Pastry cream in PC-BPE (g)**
cream waste after consumption	7.5%	16.4	7.5%	16.4
Consumed pastry cream		218.0		218.0
*cream waste due to expiration**	40%	147.2	2%	4.3
Pastry cream stored* to consume 218 g at home		365.2		222.3
cream waste at manufacturing	6%	23.3	2%	4.5
Pastry cream manufactured to consume 218 g cream at home including wasted cream		388.5		226.9

*at retailing/home

Table 2. Components of conventional and bioactive PE-packaging of 200 mL capacity

	PC-BPE	PC-CPE	Units
Polyethylene (PE)	3,82E-03	3,82E-03	kg
Polyvinyl alcohol (PVOH)	4,00E-04	-	kg
Casein hydrolizate	4,00E-04	-	kg
Lactococcus lactis subsp. *lactis*	3,96E-06	-	kg
Fitic acid (50% in water)	4,99E-04	-	kg

Table 3. Environmental impacts of 200 mL PE bags without (CPE) and with bioactive coating (BPE)

	CPE	BPE
Climate change, default, excl biogenic carbon (kg CO2 eq.)	$9{,}57\cdot10^{-3}$	$1{,}55\cdot10^{-2}$
Fine Particulate Matter Formation (kg PM2.5 eq.)	$9{,}42\cdot10^{-6}$	$2{,}31\cdot10^{-5}$
Fossil depletion (kg oil eq.)	$4{,}24\cdot10^{-3}$	$5{,}31\cdot10^{-3}$
Freshwater consumption (m3)	$1{,}43\cdot10^{-4}$	$3{,}45\cdot10^{-4}$
Freshwater ecotoxicity (kg 1,4 DB eq.)	$-3{,}46\cdot10^{-7}$	$1{,}80\cdot10^{-5}$
Freshwater Eutrophication (kg P eq.)	$8{,}53\cdot10^{-9}$	$1{,}04\cdot10^{-6}$
Human toxicity, cancer (kg 1,4-DB eq.)	$-1{,}13\cdot10^{-6}$	$5{,}98\cdot10^{-5}$
Human toxicity, non-cancer (kg 1,4-DB eq.)	$-3{,}03\cdot10^{-4}$	$1{,}03\cdot10^{-3}$
Ionizing Radiation (kBq Co-60 eq. to air)	$-5{,}93\cdot10^{-5}$	$2{,}14\cdot10^{-4}$
Lan use (Annual crop eq.·y)	$-1{,}02\cdot10^{-4}$	$2{,}19\cdot10^{-3}$
Marine ecotoxicity (kg 1,4-DB eq.)	$-1{,}99\cdot10^{-6}$	$2{,}15\cdot10^{-5}$
Marine Eutrophication (kg N eq.)	$-4{,}70\cdot10^{-8}$	$3{,}41\cdot10^{-6}$
Metal depletion (kg Cu eq.)	$6{,}03\cdot10^{-6}$	$2{,}77\cdot10^{-5}$
Photochemical Ozone Formation, Ecosystems (kg NOx eq.)	$1{,}57\cdot10^{-5}$	$2{,}44\cdot10^{-5}$
Photochemical Ozone Formation, Human Health (kg NOx eq.)	$1{,}56\cdot10^{-5}$	$2{,}37\cdot10^{-5}$
Stratospheric Ozone Depletion (kg CFC-11 eq.)	$-1{,}01\cdot10^{-9}$	$1{,}62\cdot10^{-8}$
Terrestrial Acidification (kg SO2 eq.)	$3{,}25\cdot10^{-5}$	$6{,}42\cdot10^{-5}$
Terrestrial ecotoxicity (kg 1,4-DB eq.)	$-5{,}80\cdot10^{-4}$	$3{,}53\cdot10^{-3}$

Table 4. Environmental impacts of the pastry cream in conventional PE packaging (PC-CPE) and bioactive PE packaging (PC-BPE)

	PC-CPE	PC-BPE
Climate change, default, excl biogenic carbon (kg CO2 eq.)	$7,39\cdot10^{-1}$	4,20·10-1
Fine Particulate Matter Formation (kg PM2.5 eq.)	$2,79\cdot10^{-3}$	$1,80\cdot10^{-3}$
Fossil depletion (kg oil eq.)	$1,02\cdot10^{-1}$	$6,54\cdot10^{-2}$
Freshwater consumption (m3)	$3,21\cdot10^{-2}$	$2,07\cdot10^{-2}$
Freshwater ecotoxicity (kg 1,4 DB eq.)	$3,91\cdot10^{-3}$	$2,52\cdot10^{-3}$
Freshwater Eutrophication (kg P eq.)	$1,69\cdot10^{-4}$	$1,09\cdot10^{-4}$
Human toxicity, cancer (kg 1,4-DB eq.)	$5,65\cdot10^{-3}$	$3,68\cdot10^{-3}$
Human toxicity, non-cancer (kg 1,4-DB eq.)	$5,31\cdot10^{-2}$	$3,52\cdot10^{-2}$
Ionizing Radiation (kBq Co-60 eq. to air)	$6,82\cdot10^{-3}$	$4,69\cdot10^{-3}$
Lan use (Annual crop eq.·y)	$8,40\cdot10^{-1}$	$5,39\cdot10^{-1}$
Marine ecotoxicity (kg 1,4-DB eq.)	$3,39\cdot10^{-3}$	$2,20\cdot10^{-3}$
Marine Eutrophication (kg N eq.)	$9,68\cdot10^{-4}$	$6,22\cdot10^{-4}$
Metal depletion (kg Cu eq.)	$8,64\cdot10^{-3}$	$5,00\cdot10^{-3}$
Photochemical Ozone Formation, Ecosystems (kg NOx eq.)	$1,55\cdot10^{-3}$	$9,94\cdot10^{-4}$
Photochemical Ozone Formation, Human Health (kg NOx eq.)	$1,47\cdot10^{-3}$	$9,39\cdot10^{-4}$
Stratospheric Ozone Depletion (kg CFC-11 eq.)	$4,93\cdot10^{-6}$	$3,17\cdot10^{-6}$
Terrestrial Acidification (kg SO2 eq.)	$6,44\cdot10^{-3}$	$4,14\cdot10^{-3}$
Terrestrial ecotoxicity (kg 1,4-DB eq.)	$7,46\cdot10^{-1}$	$4,80\cdot10^{-1}$

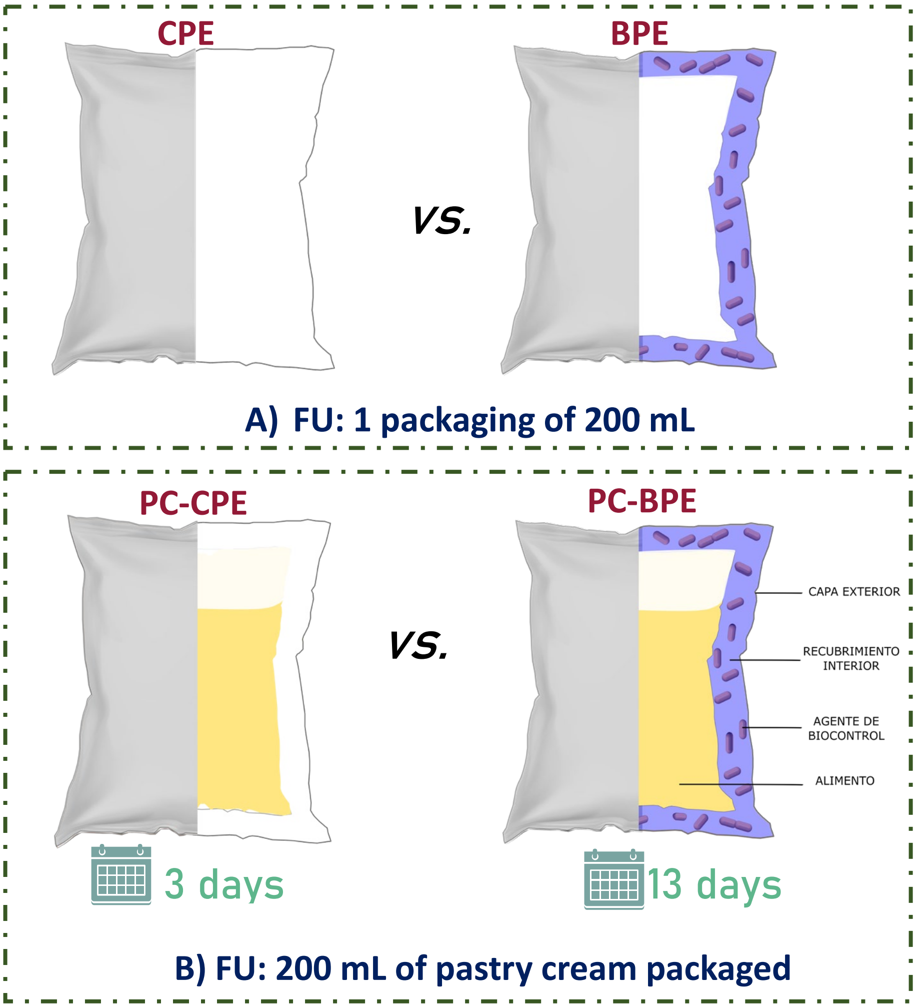

Figure 1. Systems under study and functional unit (FU) used in each case. A) Conventional PE packing (CPE) vs. bioactive PE packaging (BPE). B) Pastry cream in conventional PE packaging (PC-CPE) vs. pastry cream in bioactive PE packaging (PC-BPE).

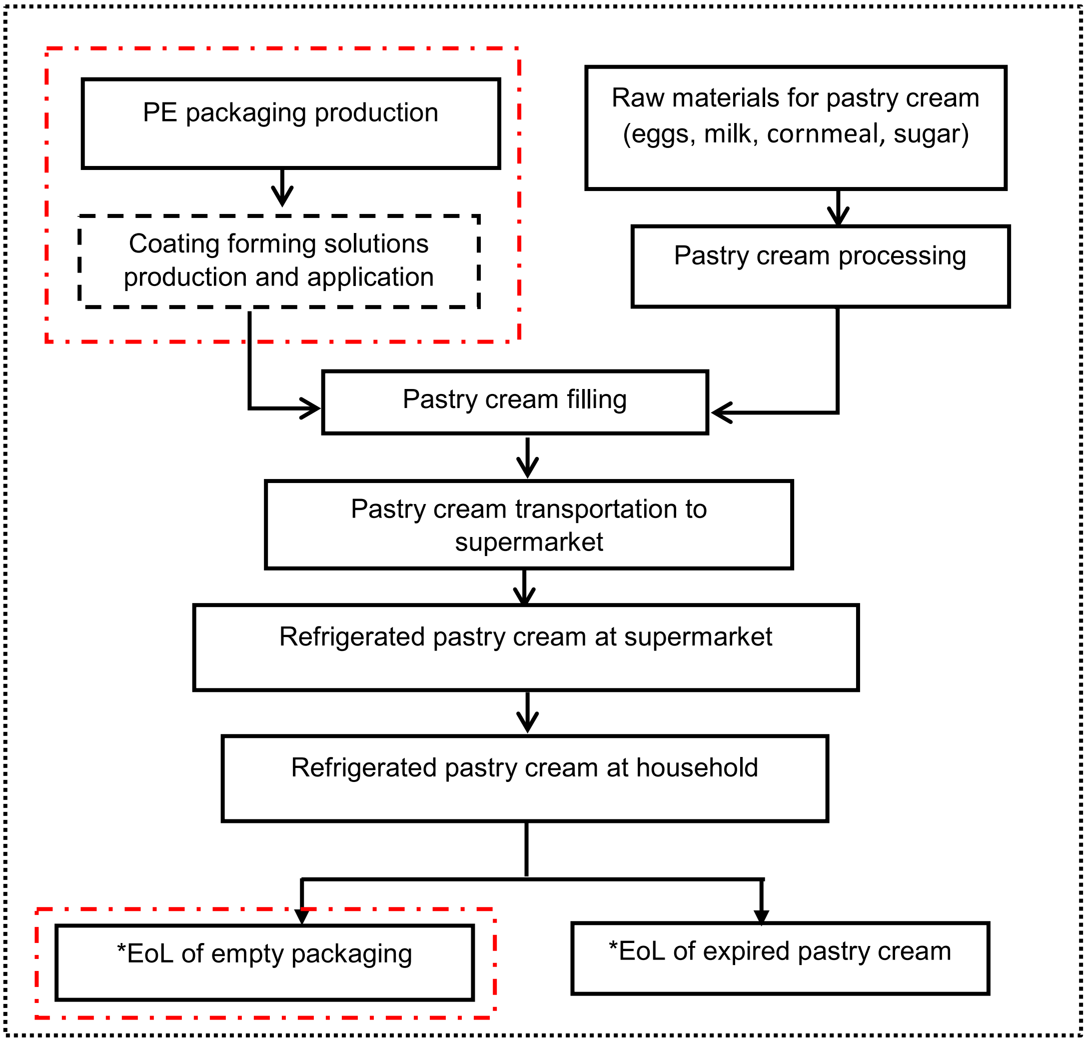

Figure 2. System boundaries of the food-packaging system and of the empty packaging (red dashed line). The stage in black dashed line occurs only in the active packaging. *EoL refers to the end of life treatment.

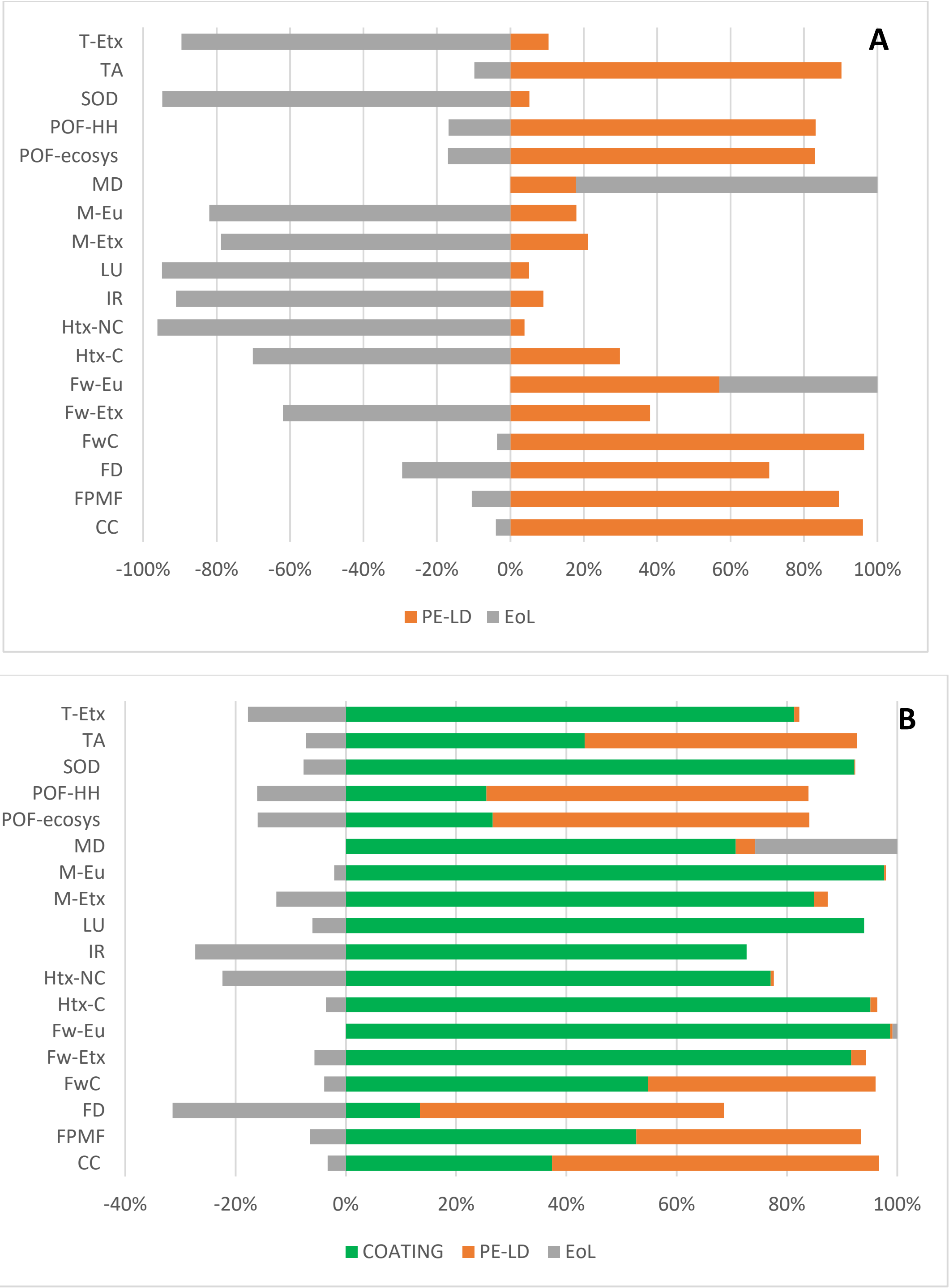

Figure 3. Contribution analysis of 200 mL PE bags without (A) and with bioactive coating (B)

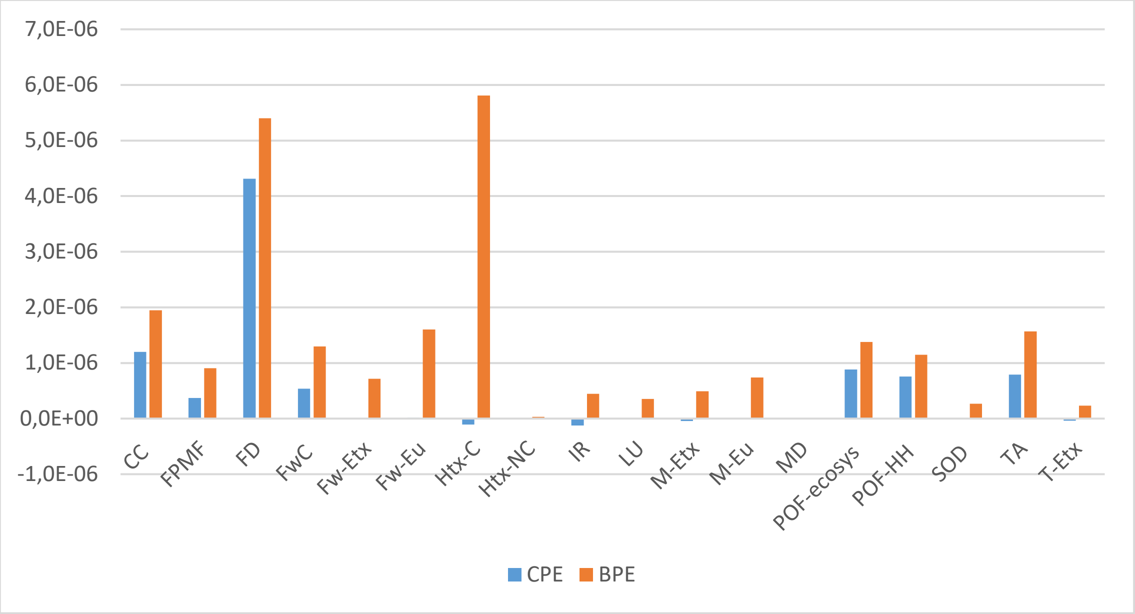

Figure 4. Comparison of normalized impact results of conventional PE packaging (CPE) and bioactive PE packaging (BPE).

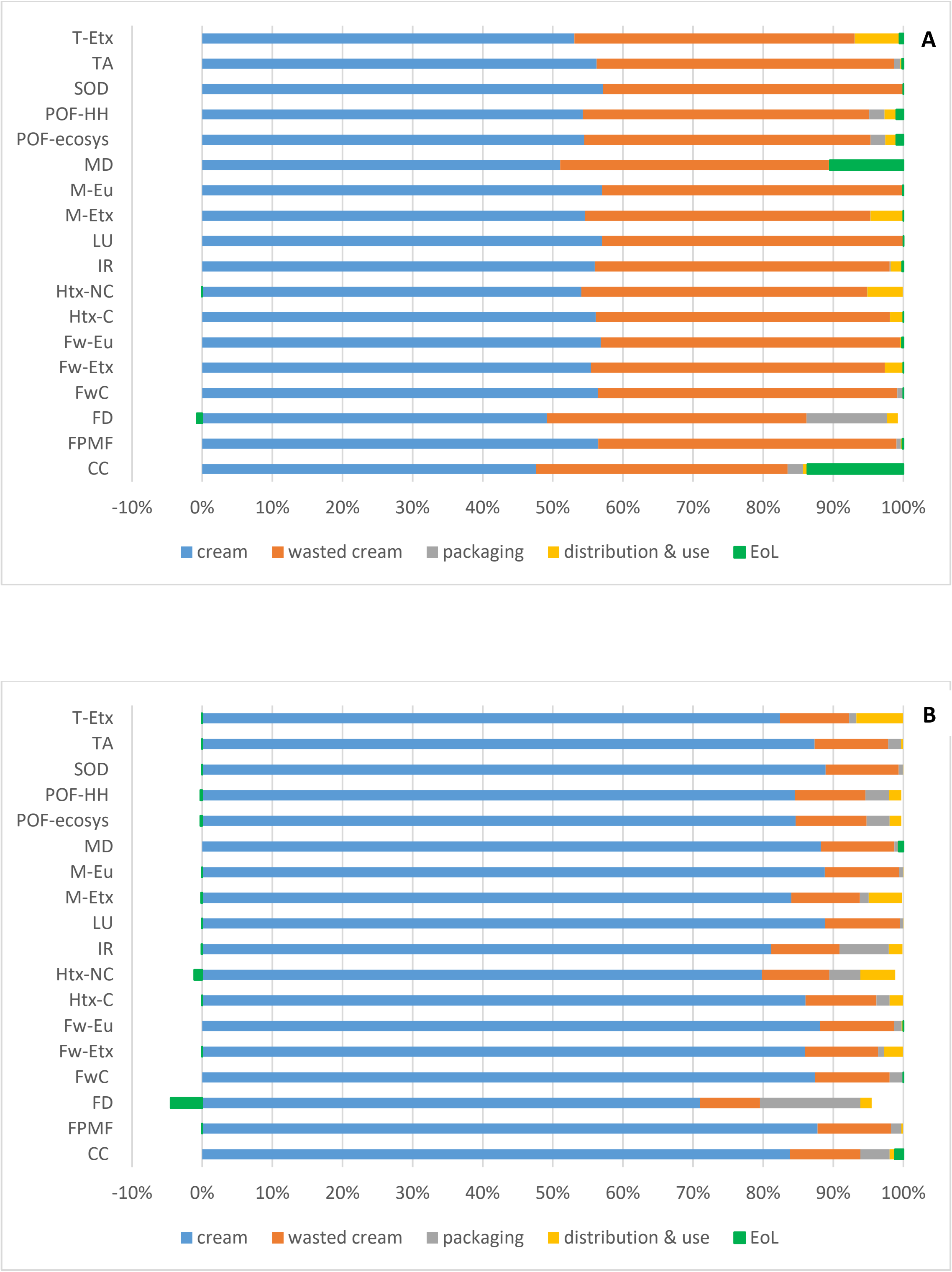

Figure 5. Contribution analysis of the pastry cream packed in conventional (A) and bioactive PE packaging (B).

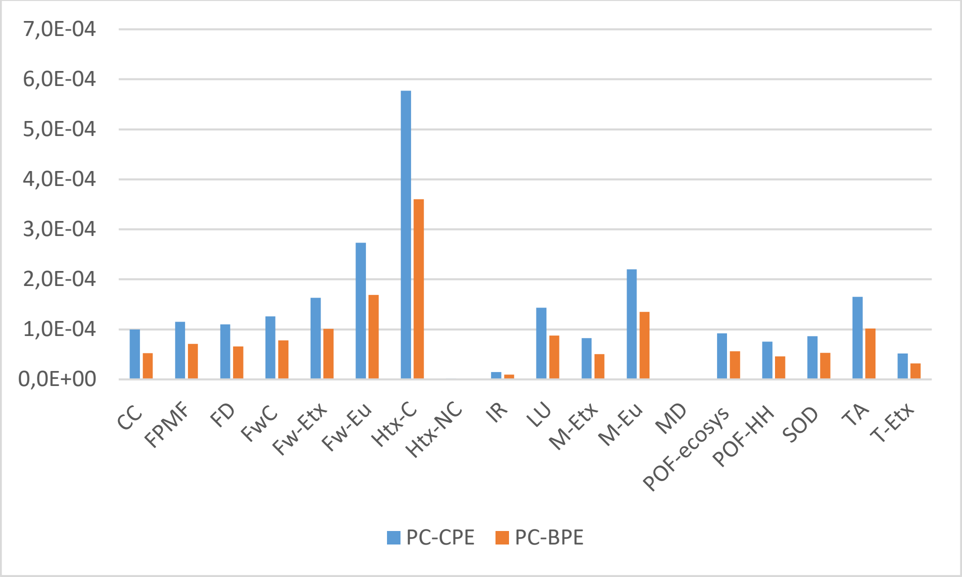

Figure 6. Comparison of normalized impact results of pastry cream in conventional PE packaging (PC-CPE) and in bioactive PE packaging (PC-BPE).

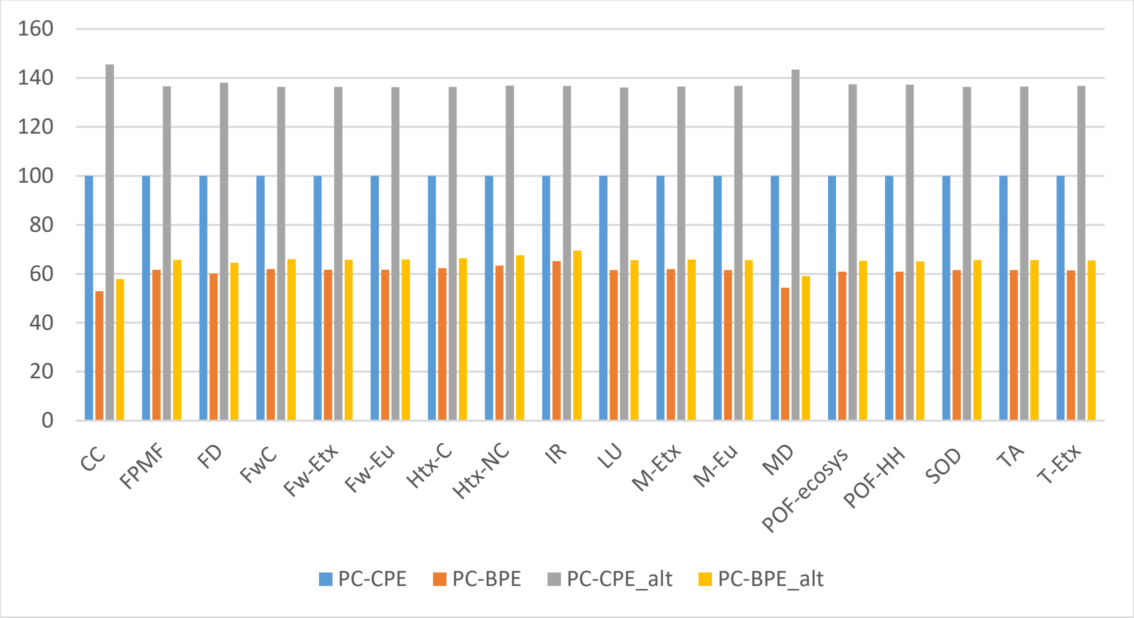

Figure 7. Percentage variation of the different impact categories for each scenario with respect to the pastry cream in conventional PE packaging.