

Food losses, shelf life extension and environmental impact of a packaged cheesecake: A life cycle assessment

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1 **Food losses, shelf life extension and environmental impact [of a packaged](#)**
2 **[cheesecake](#): a life cycle assessment**

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24 ABSTRACT

25 Packaging is associated with a high environmental impact. This is also the case in the food
26 industry despite packaging being necessary for maintaining food quality, safety assurance
27 and preventing food waste. The aim of the present study was to identify improvements in
28 food packaging solutions able to minimize environmental externalities while maximizing the
29 economic sustainability. To this end, the life cycle assessment (LCA) methodology was
30 applied to evaluate the environmental performance of new packaging solutions. The
31 environmental impact of packaging and food losses and the balance between the two were
32 examined in relation to a cheesecake that is normally packaged in low density polyethylene
33 film and has a limited shelf life due to microbial growth. A shelf life extension was sought
34 via application of the well-established modified atmosphere packaging (MAP) technique.
35 Samples for MAP (N₂/CO₂: 70/30) were placed inside multilayer gas barrier trays, which
36 were then wrapped with a multilayer gas and water barrier film (i.e. AerPack packaging);
37 control batches were packaged in gas barrier recycled polyethylene terephthalate (XrPet)
38 trays and wrapped with a XrPet film. Samples were then stored at 20°C and inspected at
39 regular intervals for chemical-physical, microbiological and sensory parameters. Results
40 show that the new packaging solution could considerably extend the shelf life of
41 cheesecakes, thereby reducing food waste and decreasing the overall environmental impact.
42 Moreover, the new packaging allows one to minimize transport costs and to generate
43 economies of scale in manufacturing.

46 *Keywords:* Life cycle assessment, modified atmosphere packaging, environmental impacts,
47 shelf life

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53 **1. Introduction**

54 According to the European Commission (European Commission, 2010), food waste in the
55 EU accounts for around 89 million tons of waste per year and, if the current trends persist,
56 this figure is expected to increase to 126 million tons by 2020. In fact, the food/drink
57 manufacturing and retail/wholesale supply chain produces the largest share of EU food waste
58 (58%), followed in second place by household waste (44%). In addition to ethical and
59 economic concerns, food waste has negative consequences on natural resources. In fact, as
60 pointed out by Manfredi, Fantin, Vignali & Gavara (2015), food waste is socially and
61 ethically unacceptable because of the persistent high number of malnourished people and
62 also because of the number of consequences on the environment such as emissions into air,
63 water and soil in the phases of production and supply chain. Moreover, as noted by WRAP
64 (2009) in the case of the United Kingdom, reducing the considerable amount of household
65 food and drink waste would save households money, whilst reducing the environmental
66 impact.

67 Thus, each step of the entire food chain (farmers, food manufacturers, retailers, consumers)
68 has the capacity to play a significant role in preventing and reducing food waste. However, it
69 is worth noticing that most of the loss in retail occurs in relation to baked goods, meat,
70 seafood and ready-to-eat foods due to their high level of perishability (Gunders, 2012). As
71 highlighted by Gunders (2012), several drivers influence in-store retail losses, such as
72 expectations of aesthetic perfection and expired “sell by” or “best before” dates. In fact,
73 market research has shown that many customers select their preferred stores based on the
74 quality of perishable goods; thus retailers are highly motivated to display products of the
75 perfect shape, size, and colour. Furthermore, products are generally discarded just before
76 they reach their sell by or best before dates.

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78 In this context, packaging is well-known to play an active role in preventing food waste by
79 preserving food quality and, in turn, guaranteeing safety, even though it is itself associated
80 with a high environmental impact that may even be higher than that associated with the
81 production/loss of some food products. However, quantifying environmental impact is
82 difficult, also due to differences in local practices regarding waste treatment, thus the
83 available evidence is rather sparse and inconclusive. [The Directive 94/62/EC, nevertheless,](#)
84 [has imposed to EU countries, targets for the recycling rates of packaging waste, but the](#)
85 [complex situation where the industry is responsible for an activity that is carried out by local](#)
86 [authority poses potential conflicts \(Ferreira da Cruz et al., 2014a\). These problems concern](#)
87 [the recycling system structure, the account for the cost of managing packaging waste, and the](#)
88 [environmental impacts from conservation of raw materials and diversion of waste from](#)
89 [landfills \(Ferreira da Cruz et al., 2014b\). WRAP \(2011\) emphasizes the role of the food](#)
90 industry in food waste prevention that can act by influencing behaviour and facilitating
91 behaviour change through the way the industry packages and presents products to the
92 consumer.

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93 Innovations in packaging could represent a tool for increasing the global sustainability of
94 food production and reducing food loss and waste achieved through extending shelf life –
95 defined as the time span during which the quality of the food product is satisfactory.
96 [The present study aims to contribute to the literature by identifying potential packaging](#)
97 [improvements that in addition to extending the product shelf life also minimize](#)
98 [environmental externalities and thereby maximize the economic outcome and thus](#)
99 [incentivize their application. As far as we are aware, no previous study has analyzed these](#)
100 [issues from the perspective of the food industry. A cheesecake was chosen as the food model](#)
101 [as it has a short shelf life that is mainly limited by mould growth. This product is normally](#)
102 [packaged in cardboard trays wrapped with Low Density Polyethylene \(LDPE\) film and](#)
103 [shows a maximum mould-free shelf life of 1 week. To extend the shelf life, a Modified](#)

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106 Atmosphere Packaging (MAP) approach was applied and sensory, textural and other
107 chemical-physical parameters were assessed, being the primary factors affecting the shelf life
108 of a food product. The results will enable decision-makers to understand the performance,
109 economic and environmental trade-offs that need to be made between the alternative
110 packaging systems in order to make the most appropriate packaging choices in a sustainable
111 perspective.

112 The paper is organized as follows: after this introduction, a short literature review on the
113 LCA of food packaging and its importance for the limitation of food waste is presented in the
114 second section. The description of the methodological approach adopted is provided in the
115 third section. The fourth section contains the results and their discussion while concluding
116 remarks are presented in the fifth and final section.

118 **2. LCA of food packaging and its importance for the limitation of food waste**

119 The Life Cycle Assessment (LCA) approach allows one to account for the environmental
120 aspects (European Commission, 2012). This methodology is mainly applied to industrial
121 products and processes, and it is the subject of increasing interest due to for its application in
122 evaluating the environmental impacts of products, processes or activities. Indeed, it is often
123 employed for assessing the equilibrium between technological innovation and environmental
124 protection (Siracusa, Ingrao, Lo Giudice, Mbohwa, & Dalla Rosa, 2014; Manfredi &
125 Vignali, 2015). As far as food packaging and LCA are concerned, a number of studies have
126 applied this methodology over recent years (Williams & Wilkström, 2011; Siracusa et al.,
127 2014; Silvenius, Grönman, Katajajuuri, Soukka, Koivupuro, & Virtanen, 2014; Wikström,
128 Williams, Verghese, & Clune, 2014; Manfredi, Fantin, Vignali & Gavara, 2015; Zhang,
129 Hortal, Dobon, Bermudez, & Lara-Lledo, 2015). One strand of research analyses the
130 relationship between the environmental impacts of food waste and packaging alternatives.
131 For instance, Williams & Wilkström (2011) examined the environmental impact of

Eliminato: Sustainability, by definition, is based upon a framework that encompasses environmental, social and economic dimensions, and it can be analysed

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8 136 packaging and food losses and the balance between the two for 5 different food items
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10 137 (cheese, bread, milk, ketchup and beef). Their results show that packaging that reduces food
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12 138 waste can provide an important tool for reducing the total environmental impact; even if the
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14 139 impact associated with the packaging itself is greater than the impact associated with the
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16 140 food loss. As highlighted by the authors, this is particularly relevant in the case of cheese and
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18 141 bread. To investigate these findings further, Wilkström, et al., (2014) analyzed the
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20 142 consequences of omitting food waste from the LCA of packaging systems. The paper shows
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22 143 the packaging attributes that influence food waste; the goal being to demonstrate how
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24 144 packaging attributes may affect consumer behaviour and food waste, and thus influence the
25
26 145 outcome of a LCA study on packaging. Additionally, the authors highlight that a reduction in
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28 146 food waste may often incentivize a packaging format with a higher climate impact. Silvenius
29
30 147 et al. (2014) examined the environmental impacts of food waste and how packaging choices
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32 148 can even constitute a factor that causes food waste. The paper presents the results of three
33
34 149 LCA case studies of packaged food products (ham, dark bread and yogurt drink) with
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36 150 different assumptions about the packaging sizes and alternative materials. According to their
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38 151 results, packaging solutions that minimize waste generation in households as well as in the
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40 152 distribution and retail processes will minimize the environmental impacts of the entire
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42 153 product-packaging chain.
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44 154 Furthermore, Manfredi, Fantin, Vignali & Gavara (2015) apply LCA to compare the
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46 155 environmental performance of a traditional packaging system with the performance of
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48 156 packaging coated with an active layer for fresh milk packaged in Tetra Top® beverage
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50 157 containers. The final aim is to study the influence of the packaging on the amount of milk
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52 158 waste. The findings show that there is a reduction in milk waste by employing the second
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54 159 solution and a consequent reduction of environmental impacts due to milk saving. Similarly,
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56 160 with the aim to assess the overall environmental performance of the food and packaging
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58 161 system considering the effect of food loss reduction by using active packaging Zhang,
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163 Hortal, Dobon, Bermudez & Lara-Lledo (2015) perform a LCA to evaluate an essential oil
164 component-enabled packaging for fresh beef. Their findings show that the active packaging
165 solutions could reduce beef losses at the retail of the EU market.

166 In a recent study, Conte and colleagues (2015) employed LCA to evaluate a new packaging
167 design concept and their aim was to provide an eco-indicator able to measure the
168 environmental effect of packaging alternatives. Their study focused on an Italian cheese
169 product and considered shelf life and food loss probability. The findings highlighted that in
170 order to minimize environmental implications, it is fundamental that the capacity of
171 packaging to reduce food loss is considered, in addition to the impact of the packaging
172 production and disposal phases.

173 This thought is in line also with the study of Manfredi and colleagues (2015) that
174 demonstrates the importance of including food waste in the analysis of packaging systems by
175 employing LCA. As they pointed out, it is a central issue the evaluation of the relationship
176 between packaging design and food waste for the environmental sustainability of packaging
177 solutions. In fact, a preliminary LCA analysis on the food and its shelf life connected with
178 the packaging allows one to assess several aspect of a product environmental impacts and
179 has the potential to help evaluations to minimise the food waste.

180 It is also important to note that from the retailer's point of view, the package should protect
181 the product and deliver it undamaged to the final consumer. Therefore, its role must also be
182 considered from an environmental perspective when comparing different packaging
183 solutions, especially for highly perishable products with a short shelf life. Albrecht,
184 Brandstetter, Beck, Fullana-i-Palmer, Grönman, Baitz, Deimling, et al., (2013) show the
185 preferable environmental performance for three transport packaging systems, but especially
186 indicate the necessary relevance to merging economic and social aspects into a LCA.
187 Merging economic aspects will be one of the study goals. LCA is particularly relevant in this
188 kind of analysis since it involves a simplified procedure that allows one to identify particular

Spostato in giù [2]: It is also important to note that from the retailer's point of view, the package should protect the product and deliver it undamaged to the final consumer. Therefore, its role must also be considered from an environmental perspective when comparing different packaging solutions, especially for highly perishable products with a short shelf life (Albrecht, Brandstetter, Beck, Fullana-i-Palmer, Grönman, Baitz, Deimling, et al., 2013).

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198 characteristics but also key issues associated with a product in order to improve its
199 sustainability. In fact, as reported in Ferreira et al. (2016) LCA can serves several purposes
200 that, however, have in common the assessment of the environmental dimension.

202 3. Methods

204 3.1 Goal and scope, the product and the system.

205 The objective of this study was to compare the environmental impacts and the economic
206 aspects associated with different food preservation methods as a way to potentially improve a
207 business's overall performance. Specifically, the research project is aimed at validating new
208 packaging solutions in the food market in order to extend product shelf life. To this purpose,
209 screening LCAs were performed on existing products in order to evaluate the environmental
210 performance of alternative packaging solutions. Screening LCAs entail a simplified
211 procedure that allows one to identify particular characteristic or key issue associated with the
212 analysis that will normally be the subject of further, more intensive study (Christiansen et al.
213 1997). The simplification may involve exclusion of certain life cycle stages, system inputs or
214 outputs, or impact categories, or the use of generic data modules rather than data specific to
215 the system under study. Moreover, reducing the complexity of the LCA implies reducing the
216 cost, time and effort required to run it.

217 The product under consideration is a typical cheesecake produced in Sardinia (Italy),
218 composed of a wheat-based pastry crust and a cheese filling. The cheesecake is prepared as
219 follows: wheat flour (70%) is mixed with animal fat (15%) for 20 minutes; water (15%) is
220 then added and mixed until the shortcrust pastry develops. The shortcrust pastry is laminated
221 and cut to obtain pastry circles of 12 cm in diameter. The filling is made up by mixing
222 freshly grated ewe's cheese (75%), sugar (11%), semolina (4%), egg yolks (4%), dry raisins
223 (4%) and grated orange rind as flavouring (2%).

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Eliminato: The present study aims to contribute to the literature by identifying potential packaging improvements that in addition to extending the product shelf life also minimize environmental externalities and thereby maximize the economic outcome and thus incentivize their application. As far as we are aware, no previous study has analyzed these issues from the perspective of the food industry. A cheesecake was chosen as the food model as it has a short shelf life that is mainly limited by mould growth. This product is normally packaged in cardboard trays wrapped with LDPE film and shows a maximum mould-free shelf life of 1 week. To extend the shelf life, a MAP approach was applied and sensory, textural and other chemical-physical parameters were assessed, being the primary factors affecting the shelf life of a food product. The results will enable decision-makers to understand the performance, economic and environmental trade-offs that need to be made between the alternative packaging systems in order to make the most appropriate packaging choices in a sustainable perspective. ¶

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247 MAP (N₂/CO₂ – 70/30) samples were packaged in multilayer ethylene vinyl
248 alcohol/polystyrene/polyethylene (EVOH/PS/PE) gas barrier trays (AerPack B5-30,
249 Coopbox Italia, Reggio Emilia, Italy) and wrapped with a multilayer (EVOH/OPET/PE) gas
250 and water barrier film (54 μm, EOM 360B, Sealed Air, USA). Ambient atmosphere samples
251 (acting as control samples) were packaged in gas barrier recycled polyethylene terephthalate
252 (XrPet) trays and wrapped with an XrPet film (Coopbox Italia, Reggio Emilia, Italy).
253 Samples were subsequently stored at 20°C. The functional unit (F.U.) considered for the
254 analysis corresponds to a tray containing two cheesecakes, with a total weight of
255 approximately 300 gr. In the case of XrPet the F.U. has a shelf life (SL) of 7 days, whether in
256 the case of the AerPack the SL is of 28 days.
257 The boundaries of the system are provided in Figure 1 and are defined in such a way to be as
258 realistic as possible. The LCA was performed from a cradle to gate perspective, meaning that
259 all phases from raw material extraction to the retail gate (i.e. supermarket) are included. As
260 such, the involved phases were: 1) production of the raw materials employed in food and
261 packaging production; 2) food and packaging manufacture that leads to the, 3) packaging of a
262 tray containing two cheesecakes; 4) logistics system; 5) transport to retail and 6) disposal of
263 food and packaging.
264 This study considers the role of packaging in preserving food quality and safety as well as
265 the influence of packaging on food spoilage and loss and therefore on cheesecake shelf life
266 and finally, the waste disposal. As far as the disposal phase is concerned, the food waste is
267 treated as bio waste and then collected by the municipal waste service that provide for the
268 incineration, a treatment method that involves combustion of waste material. This method
269 treats waste to reduce its volume and hazard and destroys potentially harmful substances. In
270 the case of bio-waste, there is almost no residue from incineration (JRC, 2011). The plastic
271 waste is sent to a mechanical recycling following the work by Perugini et al. (2005). The
272 authors collected data about material and energy flows related to the production of recycled

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- Eliminato: of food waste, the role of packaging in preserving food quality and safety, and the influence of packaging on food spoilage and loss and therefore on cheesecake shelf life
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PET and polyethylene from plastic waste. We just consider data related to the production of 1 kg of mechanically recycled polyethylene.

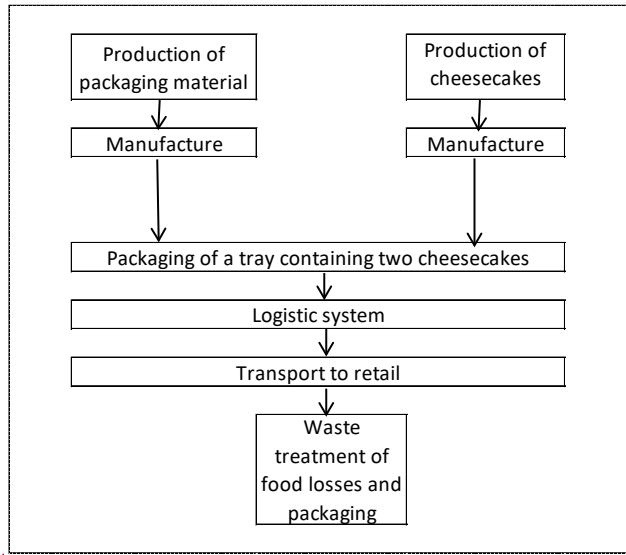


Figure 1. System boundaries.

3.2 Inventory analysis

The inventory data related to the most important aspects of the study are primary data, that are defined as information measured and gathered in-person and on-site. In fact, these data were collected through a detailed questionnaire completed through face-to-face interviews, or by telephone, with 6% of the representative bakery-manufacturing companies located in the north-west of Sardinia in 2015. According to ATECO 2007¹, these companies are classified as “producers of baked food”, code 10.7. According to the 2011 industry and services census data (ISTAT, 2011), a total of 244 companies belonging to this classification

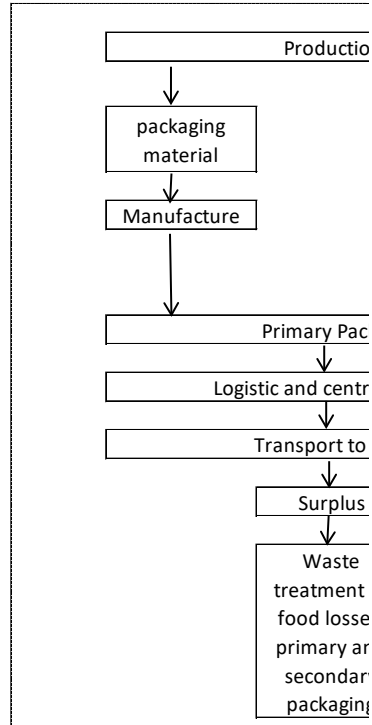
¹ ATECO is the classification adopted by the Italian National Statistics Institute (ISTAT) for the classification of economic activities.

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313 are present in the area. Ninety-nine point seven percent of them are classified as either small
314 (1–2 employees) or medium (3–49 employees) sized businesses.

315 All processes carried out within the companies relate to "gate to gate" processes. The
316 questionnaire asked for information on the origin of the inputs, the relative quantities and
317 costs for 1 kg of final product, the major energy flows for each stage of production as well as
318 for information about the derivation of the packaging and its disposal options. All products
319 were distributed within Italy only.

320 Secondary data, that are data that has been derived from averages, statistical projections, and
321 spot-checked primary sources, are used for the "upstream" or "downstream" processes of

322 cheesecake production. We employed the ecoinvent v.3.1 database (Ecoinvent, Zurich,
323 Switzerland) for the packaging material and packaging manufacturing (i.e. thermoforming
324 and extrusion), and we referred to the Agri Footprint v.1.0 database for the agricultural
325 phases of food production (Agri Footprint, Gouda, The Netherlands), both embedded in the

326 software SimaPro, version 8.05.13. These databases contain almost all processes needed for
327 the consumption of resources, materials and energy, as well as the use of transport means.
328 The fabrication of production equipment (i.e. capital goods) was excluded from the analysis
329 due to the assumed low attribution of these phases to a single packaged cheesecake and it is
330 also in line with ISO 14044 requirements for LCAs (Frischknecht et al. 2007).

331 A brief summary of the principal processes and input data for the production and processing
332 stage are shown in Table 1 and Table 2. Primary data related to electricity consumption were
333 collected from the business premises directly, while data used to describe the processes

334 related to electricity production (i.e. voltage level) were obtained from the Italian national
335 energy system. Electricity is the primary power input employed in the cheesecake production
336 phase and in the packaging phase. It is used for the mixing phase of ingredients, both of the
337 pastry and of the filling, for the lamination of the shortcrust pastry and for the cooking phase
338 and for the MAP packaging solution. Inventory data regarding electricity are extrapolated

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Spostato in giù [3]: These databases contain almost all processes needed for the consumption of resources, materials and energy, as well as the use of transport means. The fabrication of production equipment (i.e. capital goods) was excluded from the analysis due to the assumed low attribution of these phases to a single packaged cheesecake

Spostato (inserimento) [3]

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353 [from the dataset ecoinvent v. 3.1 that describes the electricity available on the medium](#)
354 [voltage level in Italy. This is done by](#) showing the transmission of 1 kwh electricity at
355 medium voltage. Specifically, it includes: the electricity inputs produced and from imports
356 and transformed to medium voltage, the transmission network, the direct emissions to air
357 (SF6 from the insulation gas in the high voltage level switchgear are allocated to the
358 electricity demand on medium voltage) and the electricity losses during transmission. The
359 average technology used to transmit and distribute electricity includes underground and
360 overhead lines, as well as air-, vacuum- and SF6-insulated high-to-medium voltage switching
361 stations.

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362 To gather detail about the packaging materials we employ the producer company technical
363 data sheets and the corresponding thermoforming and extrusion processes were identified in
364 the [ecoinvent v. 3.1](#) database. The functional unit (FU), that is a tray of cheesecake, the
365 finished product, was assumed to be delivered to the final retailer by road transport (light
366 commercial vehicle, [ecoinvent v. 3.1](#)). Based upon the data provided by the bakery-
367 manufacturing companies a distance of approximately 60 km was appraised to product
368 delivering. The data were estimated by consulting relevant resources ([i.e. specialised articles](#))
369 and own assumptions.

Eliminato: Ecoinvent v. 2.2

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370 The modelling of the end of life scenario was based upon the primary data and combined
371 with the available data in [ecoinvent v. 3.1](#). The functional unit is treated for the food part (i.e.
372 the cheesecakes) as waste disposal of bio-waste in a municipal solid waste incinerator and
373 the packaging materials are assumed to be collected by the municipal waste collection
374 service.

Eliminato: Ecoinvent v. 2.2

376 Table 1. Inventory data for the cheesecake production

Eliminato: Summary of main

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| Input | Unit | Amount per 1 kg of final product | Amount per F.U. (300 gr) | Source |
|-------|------|--|-----------------------------|--------|
|-------|------|--|-----------------------------|--------|

| | | | | |
|--|-----|-------|-------|-------------------------|
| Wheat flour | g | 300 | 84 | Agrifootprint v.1.0 |
| Animal fat | g | 100 | 28 | Agrifootprint v.1.0 |
| Grated ewe's cheese | g | 500 | 140 | <u>Ecoinvent v. 3.1</u> |
| Sugar | g | 100 | 28 | Agrifootprint v.1.0 |
| Semolina | g | 30 | 8.4 | Agrifootprint v.1.0 |
| Egg yolks | p | 2 | 0.56 | Agrifootprint v.1.0 |
| <i>Electricity-Phase of production</i> | | | | |
| Mixing | kWh | 0.138 | 0.018 | <u>Ecoinvent v. 3.1</u> |
| Lamination | kWh | 0.063 | 0.039 | <u>Ecoinvent v. 3.1</u> |
| Cooking | kWh | 0.625 | 0.175 | <u>Ecoinvent v. 3.1</u> |

Eliminato: Ecoinvent v. 2.2

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Table 2. Weight of packaging materials and electricity employed per F.U.

Eliminato: for the two samples studied

| Material | Unit | AerPack | XrPet | Source |
|--------------------------|------|---------|-------|-------------------------|
| Tray | | | | |
| EVOH/PS/PE | g | 11.25 | | <u>Ecoinvent v. 3.1</u> |
| XrPet | g | | 16 | <u>Ecoinvent v. 3.1</u> |
| Film | | | | |
| EVOH/OPET/PE | g | 2.25 | | <u>Ecoinvent v. 3.1</u> |
| XrPet | g | | 1.45 | <u>Ecoinvent v. 3.1</u> |
| Gas mixture-MAP (N2/CO2) | g | 0.035 | - | <u>Ecoinvent v. 3.1</u> |
| Electricity- MAP | kWh | 0.017 | - | <u>Ecoinvent v. 3.1</u> |

Eliminato: Ecoinvent v. 2.2

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3.3. Key assumptions

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The purpose of this study is to evaluate the effects of an extension in a food product's shelf life from both the environmental and an economic points of view. In order to explore these aspects together, we needed to consider all the producer's activities in the market place: the producer delivers its goods according to a consignment agreement, bears all goods' transport costs and the waste management burden of unsold goods. The bakery manufacturing companies adopt a "just in time" delivery system. This condition restricts or eliminates storage time span as a result of the short shelf life of cheesecakes. Conversely, other

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410 agricultural products, such as tomato-based manufactured, can benefit from a more efficient
411 logistics due their seasonality and much longer storage times (Bottani et al. 2014). Moreover,
412 we needed to understand the minimum gross operating profit (GOP) that allows the company
413 to stay in the market and therefore the minimum amount of consigned product that must be
414 sold. The unsold share allows one to proxy the food loss and therefore the waste scenario.

415 In order to evaluate these aspects, the average variable cost (AVC) to produce one unit (1
416 kilogram) of product must be calculated, equal to the sum of the costs for each production
417 input:

$$418 \quad AVC = \sum_{i=1}^I avc \quad (1)$$

419 As highlighted above, bakery/cookie manufacturing companies belong to the category of
420 small- or medium-sized businesses and are characterized by increasing returns to scale,
421 constants and equal average and marginal costs for all output, as suggested by standard
422 industrial organization theory (Nguyen and Reznec, 1991).

423 Specifically, the total variable cost of production (VC) for a bakery/cookie manufacturing
424 company is given by $VC = AVC * Q_c$, where Q_c is the quantity of product produced and
425 delivered according to the consignment agreement. The total revenue (TR) is given by $TR =$
426 $P * Q_s$, where Q_s is the quantity sold and P is the price paid to the manufacturing company.
427 The GOP is therefore given by $GOP = TR - VC$.

428 Here, we calculated the minimum amount (Q_s^{min}) of the product delivered on consignment
429 that must be sold as:

$$430 \quad Q_s^{min} = \frac{VC - (VC * \frac{P - AVC}{P})}{AVC} \quad (2)$$

431 Thus Q_s^{min} is the ratio of the variable cost of the quantity sold and the average variable cost of
432 the quantity Q_c actually delivered. When Q_s is the same as Q_s^{min} then the GOP is equal to 0,
433 i.e. no net profit is made, that is the minimum gross operating profit.

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8 434 Following this framework, using the *AVC* of 1 kg of cheesecake for the two different
9
10 435 packaging alternatives (including energy costs) and the price P , we calculated Q_s^{min} and VC .
11
12 436 Table 3 presents the food loss considered in the waste management model for the two
13
14 437 packaging alternatives: XrPet, with a shelf life (SL) of 7 days, and the AerPack with a SL of
15
16 438 28 days. If the input and output relative prices do not change, both packaging solutions have
17
18 439 the same Q_s^{min} amount and we can consider the maximum waste impact due to economic
19
20 440 grounds $(Q_c - Q_s^{min})$. In fact, it would not be rational for the businesses to operate when
21
22 441 $(Q_c - Q_s^{min})$, or when the $GOP < 0$.
23
24 442

25 443 Table 3. Economic figures for the two packaging solutions

| Plastic film | SL* | AVC (€) | P | Qc | Q^{min} | VC | GOP | FL |
|--------------|-----|---------|--------|-----|-----------|---------|-----|----|
| | | | (€) | | | (€) | (€) | |
| XrPet | 7 | 4.626 | 13.878 | 100 | 33.333 | 462.597 | 0.0 | 67 |
| AerPack | 28 | 4.643 | 13.928 | 100 | 33.333 | 464.266 | 0.0 | 67 |

34 444 *SL, shelf life in days; AVC, average variable cost in euros; P, price in euros; Qc, quantity produced and given
35
36 445 on consignment in percentage terms, Q^{min} quantity produced and given on consignment in percentage terms;
37
38 446 VC, variable costs of production in euros; GOP, minimum gross operating profit in euros; FL, food losses in
39
40 447 percentage terms.
41
42 448

43
44 449 All other things being equal (i.e. the shelf life), when the quantity sold corresponds to Q_s^{min}
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46 450 the food losses (FL) correspond to 67% of the product.
47
48 451 Accounting for the shelf life, considering an equal amount of product delivered, AerPack
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50 452 sales are greater. This is due to the fact that the product maintains its aesthetic quality and is
51
52 453 available for purchase for longer; it therefore comes into contact with a higher number of
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54 454 potential buyers. Moreover, the consumer is more likely to consider buying the product
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56 455 because he sees that the product is not yet close to its best before date. This reduces the

Eliminato: Summary of e

Eliminato: cheesecake

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458 amount of unsold product by the time of its expiration date, reducing transport and waste
459 disposal costs.

460 The distribution of sales also depends on consumer buying habits and the length of the shelf
461 life. In this regard, the entrepreneur should deliver a quantity that minimizes the $Q_c - Q_s$
462 difference. However, shelf life and commercial life may be different, especially for food
463 goods. A food may indeed have ended its business or commercial life, but not its shelf life.
464 This situation arises when the buyer decides he cannot consume the packaged product before
465 its best before date. It is not a coincidence that retailers often reduce prices to encourage the
466 sale of foods close to the expiry date.

467 Given a stock of goods, a longer shelf life is associated with higher sales compared with a
468 shorter shelf life. XrPet and AerPack packaging solutions have different shelf life durations.

469 Assuming that the distribution of sales is described by the following exponential function ,

470 $Q_t = (w - t)^x$ which measures the quantity sold on each day of the week, for the XrPet
471 packaging solution the cumulative quantity of product sold can be given as follows:

472
$$\bar{Q}_t = (w - t)^x + \sum_{t-1}^1 Q_t \quad (3)$$

473 such that

474
$$Q_s^{min} \leq \bar{Q}_t$$

475 and $SL = 7; t\text{-day} = 2, \dots, 6; w = 7$.

476 For the AerPack packaging solution, the cumulative quantity of product sold is given by:

477
$$\bar{Q}_t = (w - t)^x + \sum_{t-1}^1 Q_t + \left[\left(Q_c^w * \frac{1}{w} \right) * (SL - w) \right] \quad (4)$$

478 such that

479
$$Q_s^{min} \leq \bar{Q}_t$$

480 and $SL = 28, t\text{-day} = 2, \dots, 6; w = 7$.

481 The amount Q_t is a function of time t that elapses between the moment when the last weekly
482 product is available for sale and the end of its shelf life. Considering the time spanning ($SL -$

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w), the producer delivers its goods (Q_c^w) on consignment each week and all goods delivered are sold. In the last week, the x exponent defines the temporal distribution of products sold. For example, for $x = 2$ and AerPack packaging, $\bar{Q}_t = 391$ defines the quantity sold and FL = 9 the quantity of food losses. Use of the AerPack packaging is therefore associated with a greater weekly amount sold, thus reducing the relative food losses. Therefore, taking into account a time span of 28 days, the FL is equal to 36% of the product in the case of the XrPet packaging solution and to 9% in the case of AerPack packaging. From the viewpoint of economic sustainability, the AerPack would seem to be the most advantageous solution for the firm, despite the AVC of production being slightly higher. In fact, this solution allows for transport costs to be minimized and for economies of scale in manufacturing due to its ability to keep the product fresh for longer. The cost differences between the XrPet and AerPack packaging solutions are thus rendered negligible.

3.4 Life cycle impact assessment

LCA is a powerful method for measuring the impact of human activities on the environment. SimaPro (version 8.05.13) was used with the ReCiPe endpoint method, developed by Goedkoop et al. (2009), which characterizes life cycle inventory data according to both 'problem oriented' and 'damage oriented' approaches. The primary objective of the ReCiPe method, is to transform the long list of Life Cycle Inventory results into a limited number of indicator scores. ReCiPe defines indicators at the midpoint or endpoint level. At the midpoint level seventeen indicators are calculated, whereas three damage categories are computed for the endpoint; damage to human health; damage to ecosystems; or damage to resource availability. Endpoint indicators are easier to interpret than the large number of midpoint indicators, partially because there are fewer of them and partially because their interpretation

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511 is more tangible. Therefore, several impact categories could be considered in an
 512 environmental impact assessment, however, resource use, human health and ecological
 513 consequences (assessed according to endpoint levels) are the three main impact categories
 514 taken into account in this study due to their greater ease of interpretation.

515

516 **4. Results and discussion**

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518 **4.1 Baseline impact assessment**

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520 The results attained for the XrPet and AerPack packaging solutions are reported in Table 4
 521 for quantities sold corresponding to Q_s^{mn} and a corresponding food loss of 67% of product.
 522 The results were calculated per unit of food sold, the functional unit, corresponding to a tray
 523 containing two cheesecakes, with a total weight of approximately 300 gr. In this part of the
 524 analysis, no reference to time (i.e. shelf life) is made.

525

526 Table 4. Impact categories of the product and its loss.

Eliminato: assessment

| Impact category | Unit | XrPet | AerPack | Impact variation ^d |
|---------------------------------|-------------------------|----------|----------|-------------------------------|
| Climate change human health | DALY ^a | 1.22E-05 | 1.21E-05 | -1% |
| Ozone depletion | DALY | 1.10E-09 | 1.09E-09 | -1% |
| Human toxicity | DALY | 1.78E-05 | 1.72E-05 | -3% |
| Photochemical oxidant formation | DALY | 3.87E-10 | 3.82E-10 | -1% |
| Particulate matter formation | DALY | 1.97E-06 | 1.95E-06 | -1% |
| Ionising radiation | DALY | 7.63E-09 | 7.50E-09 | -2% |
| Climate change ecosystems | species.yr ^b | 6.48E-08 | 6.42E-08 | -1% |
| Terrestrial acidification | species.yr | 5.59E-10 | 5.55E-10 | -1% |

| | | | | |
|------------------------------|-----------------|----------|----------|-----|
| Freshwater eutrophication | species.yr | 3.08E-11 | 3.00E-11 | -2% |
| Terrestrial ecotoxicity | species.yr | 2.04E-09 | 2.03E-09 | -1% |
| Freshwater ecotoxicity | species.yr | 2.96E-11 | 2.88E-11 | -3% |
| Marine ecotoxicity | species.yr | 4.01E-09 | 3.88E-09 | -3% |
| Agricultural land occupation | species.yr | 3.47E-08 | 3.45E-08 | -1% |
| Urban land occupation | species.yr | 6.39E-10 | 6.27E-10 | -2% |
| Natural land transformation | species.yr | 2.89E-08 | 2.85E-08 | -2% |
| Metal depletion | \$ ^c | 8.99E-03 | 8.67E-03 | -4% |
| Fossil depletion | \$ | 1.57E-01 | 1.55E-01 | -1% |

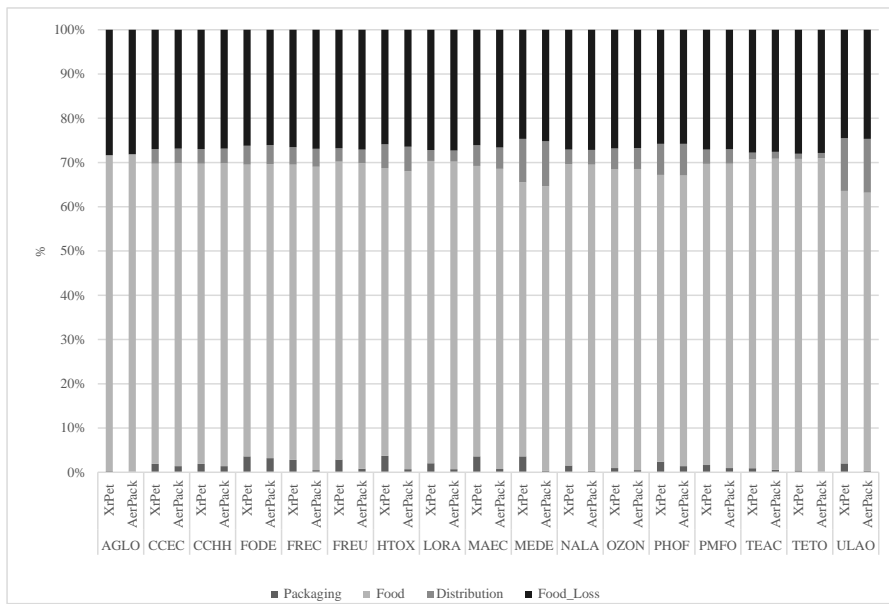
^aDALY (Disability-Adjusted Life Year): a measure of the overall severity of a disease, expressed as the number of years lost due to illness, disability or premature death. ^bSpecies.yr: a measure of the extinction rate that is the loss of species during a year. ^c\$: a measure of surplus costs of future resource production over an infinitive timeframe, considering a 3% discount rate. The unit is 2000US\$. ^dImpact variation: (AerPack score-XrPet measure score)/(AerPack score)

Overall, the XrPet solution shows a slightly higher environmental impact for each of the impact categories considered. The difference between the two solutions is rather marginal, however the impact category that varies the most relates to a high environmental impact of packaging, namely metal depletion, followed by human toxicity, freshwater ecotoxicity and marine ecotoxicity. Human toxicity concerns the effects of toxic substances on the human environment, whereas health risks of exposure in the working environment are not included. Freshwater and marine ecotoxicity refer to the impact on fresh water ecosystems as a result of emissions of toxic substances into the air, water and soil and to the impact of toxic substances on marine ecosystems, respectively. A review by Pimentel et al. (1993) linked pesticide use with negative effects on a wide range of environmental and ecosystem functions (see also Pimentel & Burgess, 2014). Pesticides have also been linked to negative

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547 impacts on human health. Mostafalou & Abdollahi (2013) reviewed the literature on the
548 correlation between pesticides and human chronic diseases and concluded that a huge body
549 of evidence exists on the connection between pesticide exposure and different disease
550 conditions. Therefore, these impact categories are mainly related with the agricultural phase
551 of raw material production.

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553 Figure 2. Impact assessment of cheesecake packaging alternatives; contribution analysis in
554 percentage terms
555 AGLO: agricultural land occupation; CCEC: climate change ecosystems; CCHH: climate change human health;
556 FODE: fossil depletion; FREC: freshwater ecotoxicity; FREU: freshwater eutrophication; HTOX: human
557 toxicity; LORA: ionising radiation; MAEC: marine ecotoxicity; MEDE: metal depletion; NALA: natural land
558 transformation; OZON: ozone depletion; PHOF: photochemical oxidant formation; PMFO: particulate matter
559 formation; TEAC: terrestrial acidification; TETO: terrestrial ecotoxicity; ULAO: urban land occupation.

Eliminato: characterization results

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561 Figure 2 reports the contribution of the different aspects of the life cycle stages, such that the
562 processes making the biggest environmental impact can be identified: *packaging* refers to

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566 packaging production and use (AerPack and XrPet); *food*, in this case, refers to cheesecake
567 production, starting from the raw materials; *distribution* includes transportation from
568 producer to retailers; and the *food loss* accounts for the fraction of food that cannot be sold
569 due to spoilage because of the reaching of the expiry date.

570 The contribution of the packaging varies between 0% (agricultural land occupation,
571 terrestrial ecotoxicity) and 4% (human toxicity, marine ecotoxicity). On average, the higher
572 impacts are found in relation to the XrPet packaging solution. On the other hand, food
573 contributions vary between 62% (urban land occupation, metal depletion) and 72%
574 (agricultural land occupation) and are mainly referable to the agricultural phase of the life
575 cycle. Distribution and food loss show the same impacts in percentage terms for both
576 packaging solutions, meaning that, in this first step of the analysis, the two phases have a
577 similar environmental impact. Overall, the contribution of food loss is greater and varies
578 between 25% (urban land occupation, metal depletion) and 28% (terrestrial acidification).

579 The ReCiPe method allows us to determine indicator scores at two levels: the previously
580 discussed seventeen midpoint indicators and three, easier to understand, damage categories
581 indicators, being: damage to human health; damage to ecosystems; and damage to resource
582 availability (Goedkoop et al., 2008). The scope to present results at the endpoint level is that
583 they are generally considered more understandable to the decision makers and may facilitate
584 more structured and informed weighting. Moreover, they allow science-based aggregation
585 across categories in terms of common parameters. The endpoint indicator scores obtained for
586 the two packaging solutions under consideration with the relative measurement unit are
587 presented in Table 5. At first glance, the XrPet solution would appear to have higher overall
588 scores than the AerPack solution in relation to the packaging and the food loss phases.

590 Table 5. Results for the damage categories indicators, ReCiPe.

Eliminato: endpoint

Formattato: Inglese (Regno Unito)

Eliminato: Damage categories

| Damage category | Alternative | Unit | Packaging | Food | Distribution | Food Loss |
|-----------------|-------------|-------------------------|-----------|----------|--------------|-----------|
| Human Health | XrPet | DALY ^a | 9.21E-07 | 2.12E-05 | 1.42E-06 | 8.43E-06 |
| | AerPack | | 3.08E-07 | 2.12E-05 | 1.42E-06 | 8.32E-06 |
| Ecosystems | XrPet | species.yr ^b | 1.94E-09 | 9.33E-08 | 3.41E-09 | 3.71E-08 |
| | AerPack | | 1.06E-09 | 9.33E-08 | 3.41E-09 | 3.66E-08 |
| Resources | XrPet | \$ ^c | 5.96E-03 | 1.09E-01 | 7.53E-03 | 4.33E-02 |
| | AerPack | | 4.98E-03 | 1.09E-01 | 7.53E-03 | 4.27E-02 |

^aDALY (Disability-Adjusted Life Year): a measure of the overall severity of a disease, expressed as the number of years lost due to illness, disability or premature death. ^bSpecie.yr: a measure of the extinction rate that is the loss of species during a year. ^c\$: a measure of surplus costs of future resource production over an infinitive timeframe, considering a 3% discount rate. The unit is 2000US\$.

However, in order to provide a clearer indication of the magnitude of each impact and to compare the overall impact of the two products better using a multi-impact assessment method, Figure 3 reports the same results normalized to the European average reference values. The single scores are obtained by dividing the impact indicators by the score of the reference situation, that is one person's share of all emission and resource use in the world during one year. In relation to both packaging solutions, the human health category is the most affected, followed by resources. However, the overall impact of XrPet is higher. It is also evident that the impact of food preparation and the distribution phase is the same for the two packaging solutions. The biggest difference relates to packaging and to food loss. The ReCiPe normalized results confirm that the AerPack has a lower environmental impact than the XrPet (Figure 3).

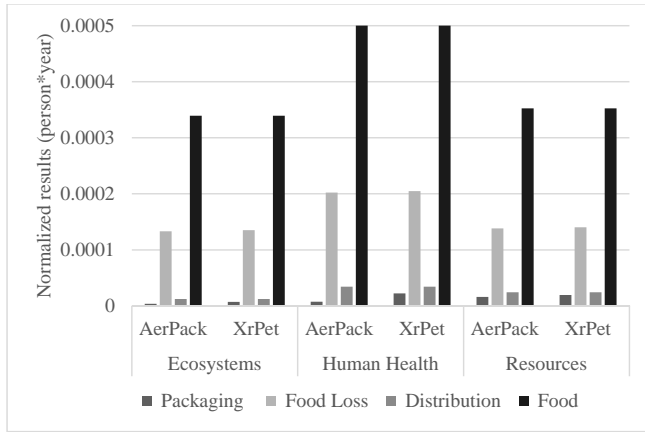


Figure 3. Normalized results.

4.2 Accounting for the shelf life

In order to account for the shelf life and the technology of the packaging better, the life cycle assessment was also computed according to the different amounts of food loss associated with the two packaging solutions over a 28 day time span, as discussed in section 2.3. The characterization results (Table 6) show that the impact variation associated with the two solutions is significantly higher compared with the previous case when no reference to time was made (Table 4). This result is mainly due to the savings in food loss and in the distribution process associated with the AerPack packaging solution. The category showing the highest variation is urban land occupation followed by metal depletion. In fact, as urban land is a finite resource, its occupation makes it unavailable for alternative uses or for use by future generations.

Table 6. Impact categories of the product and its loss.

| Impact category | Unit | XrPet | AerPack | Impact variation ^a |
|-----------------|------|-------|---------|-------------------------------|
|-----------------|------|-------|---------|-------------------------------|

Eliminato: , showing results for multiple impact categories for XrPet and AerPack

Eliminato: Figure 4 presents the weighted results of the analysis. They were obtained by multiplying the normalized results of each of the impact categories by a weighting factor that expresses the relative importance of the impact category. They have the same unit and can be added up to create one single score for the environmental impact of the products (Total).

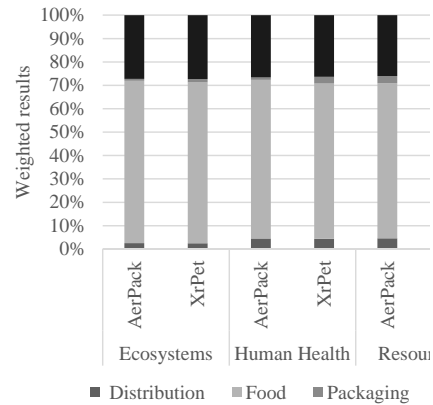


Figure 4. Weighting results, showing results for multiple impact categories for XrPet and AerPack.

Formattato: Colore carattere: Testo 1

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Eliminato: assessment

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|---------------------------------|-------------------------|----------|----------|------|
| Climate change human health | DALY ^b | 1.22E-05 | 9.48E-06 | -29% |
| Ozone depletion | DALY | 1.16E-09 | 8.61E-10 | -34% |
| Human toxicity | DALY | 1.91E-05 | 1.36E-05 | -40% |
| Photochemical oxidant formation | DALY | 4.35E-10 | 3.04E-10 | -43% |
| Particulate matter formation | DALY | 1.98E-06 | 1.53E-06 | -29% |
| Ionising radiation | DALY | 7.49E-09 | 5.87E-09 | -27% |
| Climate change ecosystems | species.yr ^c | 6.53E-08 | 5.05E-08 | -29% |
| Terrestrial acidification | species.yr | 5.32E-10 | 4.33E-10 | -23% |
| Freshwater eutrophication | species.yr | 3.07E-11 | 2.36E-11 | -30% |
| Terrestrial ecotoxicity | species.yr | 1.92E-09 | 1.58E-09 | -22% |
| Freshwater ecotoxicity | species.yr | 3.04E-11 | 2.27E-11 | -34% |
| Marine ecotoxicity | species.yr | 4.22E-09 | 3.06E-09 | -38% |
| Agricultural land occupation | species.yr | 3.14E-08 | 2.68E-08 | -17% |
| Urban land occupation | species.yr | 8.15E-10 | 5.04E-10 | -62% |
| Natural land transformation | species.yr | 2.91E-08 | 2.23E-08 | -30% |
| Metal depletion | \$ ^d | 1.09E-02 | 6.93E-03 | -57% |
| Fossil depletion | \$ | 1.63E-01 | 1.23E-01 | -32% |

638
639 ^aImpact variation: (AerPack score-XrPet measure score)/(AerPack score). ^bDALY (Disability-Adjusted
640 Life Year): a measure of the overall severity of a disease, expressed as the number of years lost due to
641 illness, disability or premature death. ^cSpecie.yr: a measure of the extinction rate that is the loss of
642 species during a year. ^d\$: a measure of surplus costs of future resource production over an infinitive
643 timeframe, considering a 3% discount rate. The unit is 2000US\$.

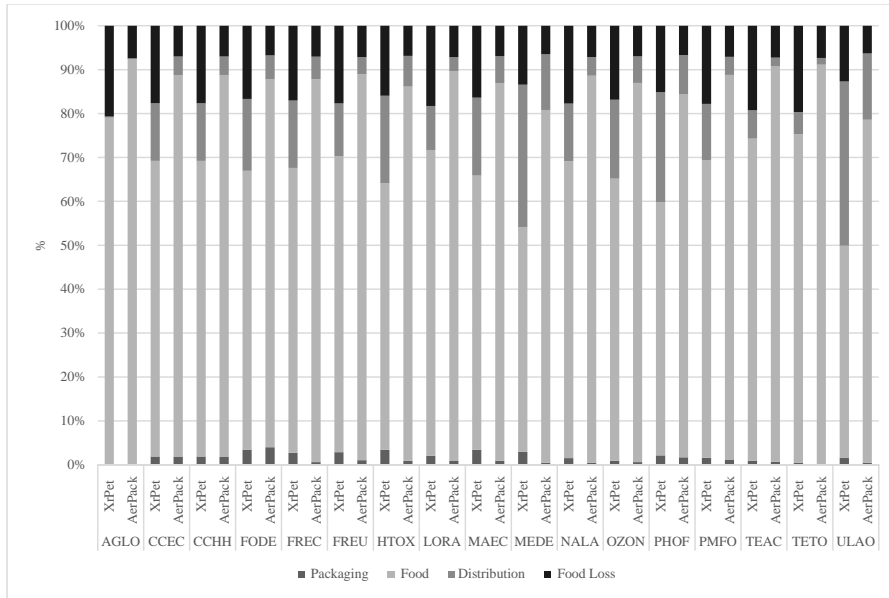


Figure 5. Characterization results in percentage.

AGLO: agricultural land occupation; CCEC: climate change ecosystems; CCHH: climate change human health; FODE: fossil depletion; FREC: freshwater ecotoxicity; FREU: freshwater eutrophication; HTOX: human toxicity; LORA: ionising radiation; MAEC: marine ecotoxicity; MEDE: metal depletion; NALA: natural land transformation; OZON: ozone depletion; PHOF: photochemical oxidant formation; PMFO: particulate matter formation; TEAC: terrestrial acidification; TETO: terrestrial ecotoxicity; ULAO: urban land occupation.

The contribution of XrPet packaging, in percentage terms, to the score of each endpoint indicator does not vary very much; figure 5 shows that the impact of packaging varies between 0% (terrestrial ecotoxicity, agricultural land occupation) and 3% (metal depletion, fossil depletion). Overall, the contribution of food ingredients and processing is the highest in both solutions. The distribution phase results provide a very clear picture: the producer makes more trips to deliver the XrPet product in the 28 day time span than for the AerPack product. Thus the environmental impact of distribution is greater in the XrPet. The impact of food loss is significant less in both solutions when shelf life is taken into consideration

Eliminato: Impact assessment of cheesecake packaging alternatives taking into account the different shelf life durations:

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664 compared with the XrPet case in which shelf life is not considered (Figure 2). However, the
 665 AerPack packaging solution, with its longer shelf life, performs the best overall, leading to a
 666 set of smaller environmental indicator scores.

667 In order to simplify the interpretation of this product comparison, the indicator scores for the
 668 damage categories, taking into consideration shelf life, are also presented (Table 7). A higher
 669 general environmental impact is observed for the XrPet solution in the packaging and food
 670 loss phases.

672 Table 7. Damage categories accounting for the different shelf life durations, ReCiPe

| Damage category | Alternative | Unit | Packaging | Food | Distribution | Food_Loss | |
|-----------------|-------------|-------------------------|-----------|----------|--------------|-----------|-----------------|
| Human Health | XrPet | DALY ^a | 9.21E-07 | 2.12E-05 | 5.67E-06 | 5.56E-06 | <u>3.34E-05</u> |
| | AerPack | | 3.08E-07 | 2.12E-05 | 1.42E-06 | 1.71E-06 | <u>2.46E-05</u> |
| Ecosystems | XrPet | species.yr ^b | 1.94E-09 | 9.33E-08 | 1.36E-08 | 2.45E-08 | <u>1.33E-07</u> |
| | AerPack | | 1.06E-09 | 9.33E-08 | 3.41E-09 | 7.53E-09 | <u>1.05E-07</u> |
| Resources | XrPet | \$ ^c | 5.96E-03 | 1.09E-01 | 3.01E-02 | 2.85E-02 | <u>1.74E-01</u> |
| | AerPack | | 4.98E-03 | 1.09E-01 | 7.53E-03 | 8.78E-03 | <u>1.30E-01</u> |

673 ^aDALY (Disability-Adjusted Life Year): a measure of the overall severity of a disease, expressed as the number
 674 of years lost due to illness, disability or premature death. ^bSpecie.yr: a measure of the extinction rate that is the
 675 loss of species during a year. ^c\$: a measure of surplus costs of future resource production over an infinite
 676 timeframe, considering a 3% discount rate. The unit is 2000US\$.

677
 678 Figure 6 reports the normalized results with respect to the European average. For both
 679 packaging solutions, the human health category is the most affected followed by resources,
 680 although the overall impact of XrPet is again confirmed to be higher. Once again, the
 681 greatest differences are observed in relation to packaging and food loss. Also in this case, the
 682 ReCiPe normalized results confirm that the AerPack solution has a lower environmental
 683 impact than the XrPet.

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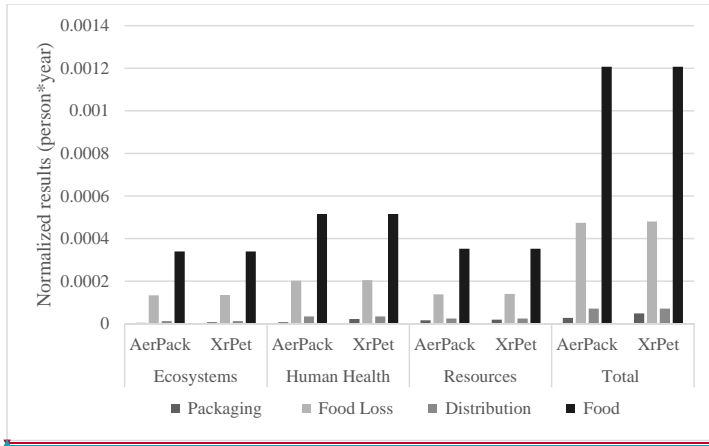


Figure 6. Normalized results

6. Conclusions

This paper applies LCA to help understand how an extension in shelf life associated with a different food packaging technology can improve the economic and environmental sustainability of a typical cheesecake. As far as economic sustainability is concerned, a change in the packaging technology allows the cheesecake producer to minimize transport costs and generate economies of scale in manufacturing due to the ability to keep the product fresh longer. [The decrease in average costs indeed is due to the decrease in average variable costs and to shelf life change. This result also reduces the minimal efficient scale of production and is particularly relevant for companies belonging to the small or medium sized businesses. The downsizing minimal scale of production indeed allow wider profit margin, as well as the resilience in the market.](#)

According to the LCA results, the extended shelf life associated with the AerPack packaging solution also has positive consequences on environmental sustainability. Unlike Conte et al., (2015), which provide an eco-indicator able to quantify the environmental indirect effects related to the different choices in the food packaging, we utilized, in order to define the

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The weighted results (Figure 7) confirm that the AerPack solution is more sustainable from an environmental point of view. The improvements achieved through use of the AerPack solution would favour a more sustainable production and sale of cheesecakes. ¶

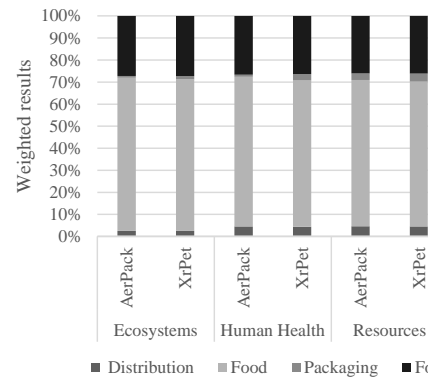


Figure 7. Weighted results for the multiple impact categories taking into account the different shelf life durations of the XrPet and AerPack packaging solutions. ¶

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725 impact of shelf life on food losses, an economic model that considers the minimum amount
726 of product delivered on consignment that must be sold. The shelf life and the food losses
727 of products associated with XrPet and AerPack packaging were then assessed according to
728 consumers buying habits. One possible selling distribution is considered to hypothetically
729 verify the advantages caused by the extended shelf life. In this sense, the analyses applied in
730 the present work were able to help us understand the ecological and economic impact of
731 different packaging solutions and thus provide a guide for food producers on decision-
732 making processes over packaging choices, such that the right balance between food losses
733 and environmental impact can be identified.

734
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738 Sustainability".

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