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Fabio Licciardello

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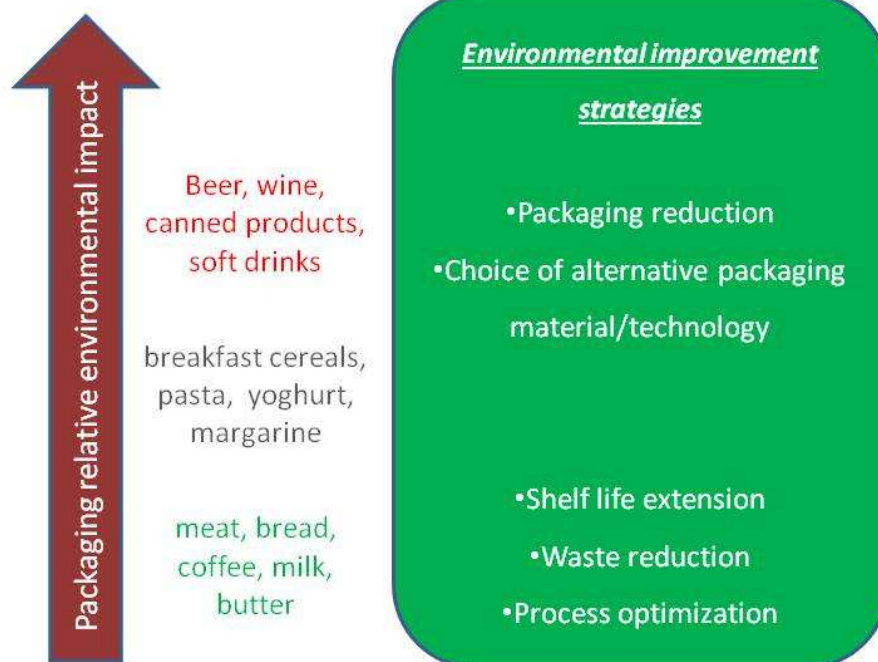
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ACCEPTED MANUSCRIPT

**Packaging, blessing in disguise. Review on its diverse contribution to food sustainability.**

Fabio Licciardello

Di3A, University of Catania, via S. Sofia 100, 95123 Catania, Italy

*Email address: fabio.licciardello@unict.it***ABSTRACT***Background*

Packaging has been blamed for being one of the highest environmental impacts in food productions. Although it cannot be denied that packages, with special regards for materials production, processing and disposal, carry some impact, other aspects should be considered for an objective assessment of packaging environmental role.

*Scope and Approach*

The paper, through a survey of specific literature, aims to estimate the actual relative impact of packaging with respect to the overall food products environmental load, to present an overview on the ongoing efforts spent for making packaging more sustainable and the packaging-product system more efficient and to highlight the novel positive consideration that food packaging should receive. Special focus has been addressed to the recent contributions which have correlated food waste reduction, achieved through packaging innovations, with an overall environmental improvement.

*Key Findings and Conclusions*

Considerations based on the packaging relative environmental impact and on the potential of suitable innovations to reduce food wastes, lead to a broader concept of sustainable packaging and should drive future strategies for sustainability improvement. Packaging reduction and a shift to alternative materials and/or technologies should be especially addressed for products characterized by a high packaging relative impact; viceversa, when packaging represents a low burden compared to other life cycle phases, the overall environmental performance will be improved with measures aimed at reducing food waste, which, in turn, could imply an affordable increase in the packaging impact.

**Keywords:** environmental impact, food waste, materials reduction, shelf life, sustainable packaging.

34

## 35 **1. Introduction. Food packaging advances towards sustainability**

36 Food packaging has done enormous progress in the last decades, driven by the increasing  
37 demand for high-quality, safe food and by the growing concern towards environmental issues.  
38 The role of food packaging in the overall sustainability of food productions is controversial: the  
39 popular belief that packaging is responsible for high environmental impacts collides with  
40 scientific evidence of packaging benefits in terms of food waste reduction potential. Overall, the  
41 positive environmental role of food packaging is well-established for the insiders, while it should  
42 be clarified to the public opinion, whose position remains somehow hostile. Packaging  
43 reputation by consumers can be inferred from a study by by Tanner & Kast (2003) who report  
44 that an environment-friendly food product is, ideally, “*domestically produced rather than*  
45 *imported from abroad; furthermore, it is organically grown, seasonal, fresh (rather than frozen),*  
46 *and unwrapped*”. Indeed, it is unquestionable that packages are responsible for some  
47 environmental impact associated with their life cycles (Huang & Ma, 2004; Ingraio et al., 2015a),  
48 and especially with the production of raw materials, processing and end-of-life phase, including  
49 recycling, incineration and landfill disposal. Recent studies on the life cycle impact of various  
50 packaging materials have increased awareness and made available useful information which can  
51 represent the basis for environmentally-responsible choices (Siracusa, Ingraio, Lo Giudice,  
52 Mbohwa, & Dalla Rosa, 2014; Speck, Selke, Auras, & Fitzsimmons, 2015). According to  
53 Peelman et al. (2013), sustainability of food packaging can be achieved at three levels; 1) at the  
54 raw materials level: the use of recycled materials and of renewable resources are two strategies  
55 for reducing CO<sub>2</sub> emission and the recourse to fossil resources; 2) at the production level,  
56 through more energy-efficient processes; 3) at the waste management level, considering reuse,  
57 recycling and biodegradation. On one hand, much effort has been dedicated to decreasing the  
58 packaging impacts, by the development of novel biobased materials and through the optimization  
59 of packaging use and the improvement of materials performances which, in turn, allows the shift  
60 to lighter and thinner packages. On the other hand, packaging innovations have been developed,  
61 with the aim of increasing the packaged product quality, extending the shelf life and ultimately  
62 reducing the possibility of food to turn into waste.

63

### 64 *1.1 A wider concept of environmentally-sustainable packaging*

65 Plastics are the most widely used materials for packaging purposes, due to several advantages  
66 such as low cost and light weight, high versatility, flexibility, transparency, heat sealability, good  
67 mechanical and barrier performances. The high consumption of packaging is accompanied by a

68 huge waste generation: according to data from EU-28 referred to 2013, 156.9 kg of packaging  
69 waste was generated per inhabitant (Eurostat), plastic representing 19% of the total consumed  
70 plastic.

71 The end of life of plastics, especially, raises environmental concern, as these materials are not  
72 biodegradable and they are difficult to recycle (Sorrentino, Gorrasi, & Vittoria, 2007). Michaud,  
73 Laura Farrant, & Jan, (2010) proved that mechanical recycling is the most environmentally  
74 favourable option for waste treatment of plastics, followed by incineration and landfill. However,  
75 recycling is not always viable for food packages. Siracusa, Rocculi, Romani, & Dalla Rosa  
76 (2008) observed that recycling of food packaging materials is often impracticable or non-  
77 convenient since they are contaminated by food residues, suggesting that biopolymers can be  
78 considered a solution to waste-disposal problems associated with synthetic plastics. As an  
79 example, traditional expanded PS trays commonly used for meat packaging cannot be recycled  
80 due to the meat exudates absorbed in the cellular structure, while an effective solution is  
81 represented by expanded polylactic acid (PLA) trays, which could be disposed (and composted)  
82 along with the organic fraction (Ingrao et al., 2015b). Apart from the environmental problems  
83 caused by plastic packaging waste treatment, conventional materials contribute to the depletion  
84 of fossil resources.

85 Biopolymers, produced from renewable materials, have undertaken the challenge to replace, at  
86 least for some applications, the traditional synthetic polymers. According to the European  
87 Bioplastics organization, bioplastics are plastics based on renewable resources (biobased) or  
88 plastics which are biodegradable and/or compostable,. Hence, not all biopolymers biodegrade:  
89 this is the case of polyethylene (“green-PE”) or polyethylene terephthalate (“bio-PET”) obtained  
90 from renewable resources, which are chemically identical to the conventional polymers. On the  
91 other hand, a wide range of biodegradable biopolymers are available, which have found  
92 application in food packaging: PLA, starch, polyhydroxyalkanoates (PHA), cellulose, zein,  
93 chitosan, soy protein isolate, whey protein isolate, gluten etc. Peelman et al. (2013) published an  
94 exhaustive review of biopolymers for food packaging, offering detailed information on their  
95 process, characteristics and applications. In every case, whether biodegradable or simply bio-  
96 based, biopolymers carry environmental advantages, either in terms of safeguard of non-  
97 renewable resources or reduction of impact in the waste disposal stage, or both.

98 Another important issue in sustainable packaging is materials reduction which, unexpectedly,  
99 still represents a viable path towards the improvement of sustainability. The concept of  
100 “overpackaging” is not new, however, the fight against overpackaging still offers good potential  
101 for sustainability improvement. The reason for that resides probably in the scarce knowledge on

102 packaging by decision makers of food companies, and in recalcitrance to changes. In particular,  
103 and this is especially the case of small and medium-sized companies, packaging is not regarded  
104 as a major issue and packaging systems are not reconsidered and updated in the light of advances  
105 in materials development. The fact that packaging not only has an environmental impact, but  
106 directly affects the budget of the company, leads one to give packaging optimization for granted:  
107 this is not always true. For sectors such as the beverage industry, where packaging represents the  
108 highest environmental impact (and a significant cost for producers), packaging reduction and, in  
109 particular, the minimization of the PET parison weight, covers strategic importance: any change  
110 in the packaging material and/or design, however, should not affect the CO<sub>2</sub> retention  
111 performance, which is the key parameter determining the shelf life of the product (Coriolani,  
112 Rizzo, Licciardello, & Muratore, 2006; Licciardello, Coriolani, & Muratore, 2011; Licciardello  
113 et al., 2016). The continuous developments in materials science allow to offer the companies  
114 packaging materials with improved performances and reduced weight, with a net positive  
115 economic and environmental balance. Packaging reduction, hence, remains a potential strategy  
116 for overall impact reduction, provided it does not affect the product shelf life standards. Two  
117 recent comparative shelf life studies on industrial bread have highlighted the potential to  
118 significantly reduce packaging weight (by about 20%) of sliced durum wheat bread characterized  
119 by a long shelf life, without affecting the shelf life standards (Licciardello, Cipri, & Muratore,  
120 2014; Licciardello et al., 2017). A change in the packaging system, from thermoformed to flow-  
121 pack, allowed a further reduction of packaging but also reduced the commercial life of the  
122 product, which could still fulfil the shelf life requirements for the short-range distribution. These  
123 case-studies highlight that the spotlight on packaging optimization should be kept turned on,  
124 despite the simplicity of the problem which, however, does not assure that the problem itself is  
125 being addressed; moreover, these examples emphasize the importance of shelf life assessment in  
126 packaging reduction and the need for a close-knit collaboration between producers and food  
127 packaging scientists in order to synergically address food packaging sustainability.

128 Among packaging innovations offering the possibility for reducing materials thickness, are  
129 nanotechnologies: even if they have not yet reached widespread application in food packaging  
130 due to some toxicological concern, nanotechnologies offer a great potential for the improvement  
131 of key features of packaging, especially barrier and mechanical properties (Wyser et al., 2016).  
132 The application of nanotechnologies to packaging polymers is generally performed by  
133 nanocoatings applied on the polymer surface or by dispersion of nano-objects or nanophases  
134 within a polymer matrix. These approaches are aimed at enhancing gas and water vapour barrier,  
135 mechanical and/or other functional properties of the packaging materials. Actually, nanoclay-

136 polymer and biopolymer composites (Kuorwel, Cran, Orbell, Buddhadasa, & Bigger, 2015;  
137 Lavorgna et al., 2014; Aloui et al., 2016) and graphene (Loryuenyong, Saewong, Aranchaiya, &  
138 Buasri, 2015; Barletta, Puopolo, Tagliaferri, & Vesco, 2016) offer a high potential for the  
139 development of packaging materials with improved performance and reduced thickness.

140

## 141 **2. Packaging relative environmental impact**

142 Not only the common belief has neglected packaging positive role in the safeguard of products  
143 and food loss reduction, but it has generally overestimated its environmental impact, which, in  
144 fact, is often minimal compared to overall products impact (Hanssen, 1998).

145 Various studies have assessed the life cycle environmental impact of different food products,  
146 part of which have highlighted the contribution of packaging to overall environmental load,  
147 which will be hereafter referred to as “**packaging relative environmental impact**” (PREI). A  
148 literature survey brings out variable figures: for instance, while some studies have pointed out  
149 that packaging impact represents 1-10% of overall burden (Silvenius et al., 2014), others have  
150 stated that it is among the most relevant impacts in the food chains (Manfredi and Vignali, 2015).  
151 In fact, PREI is tightly dependant on the food impact, but also on the packaging solution adopted  
152 for that product. The environmental contribution of packaging for meat and dairy products is  
153 usually low, as a result of the high environmental impact in the primary production and  
154 processing stages: this is the case of milk, whose environmental load in the agricultural phase  
155 masks other impacts from the whole life cycle (Meneses, Pasqualino, & Castells, 2012), thus  
156 representing a special case among beverages (see after). On the other hand, PREI is usually  
157 higher for those products containing high amounts of water and/or whose ingredients originate  
158 from lower-carbon footprint primary stages, such as vegetables and beverages (dairy excluded)  
159 (Ardente, Beccali, Cellura, & Marvuglia, 2006; Amienyo, Gujba, Stichnothe, & Azapagic, 2013;  
160 Manfredi & Vignali, 2015; Cimini & Moresi, 2016).

161 However, products packed in glass or tinplate usually show high PREI, irrespective of the food  
162 category. A survey of publications reporting environmental data of food products and their  
163 packaging is shown in **Table 1**. It has to be noted that sources which grouped the impacts arising  
164 from packaging materials and operations into subsystems including other phases (such as  
165 transport, distribution etc) have not been considered herewith. In this review, Global Warming  
166 Potential (GWP) data have been considered for comparative purposes, since this environmental  
167 category is the most widely used in scientific papers. The considered studies usually adopted a  
168 cradle-to-gate approach, however, for those studies performed on a cradle-to-grave basis, the

169 phases of distribution, retail and consumption were not taken into account in the calculation of  
170 PREI. Therefore, **Table 1** reports the PREI, expressed as %GWP, for various food products.

171 As anticipated above, beverages, including carbonated soft drinks, wine and beer, are  
172 characterized by high PREI. In particular, for carbonated soft drinks, relative GWP ranges from  
173 49 to 59% in the case of PET bottles, and can be as high as 75 and 79% for products bottled in  
174 glass and aluminum cans, respectively (Amienyo et al., 2013). PREI for beer ranges from 48-  
175 54% for large and small-sized glass bottles, to 58% for aluminum cans (Cimini & Moresi, 2016)  
176 but other studies have attributed to beer packaging impacts as high as 78% (Koroneos, Roumbas,  
177 Gabari, Papagiannidou, & Moussiopoulos, 2005) or generally “very high” (De Marco, Miranda,  
178 Riemma, & Iannone, 2016). Similarly, the case of wine shows medium to high PREI, ranging  
179 between 34 (Gazulla, Raugei, Fullana-i-Palmer, 2010) and 56% (Bonamente et al., 2016; Fusi,  
180 Guidetti, & Benedetto, 2014), and has been calculated to be as high as 82% of total GWP,  
181 according to Vázquez-Rowe, Rugani, & Benetto (2013).

182 Canned products, despite the high environmental impact of the food itself (in the case of fish or  
183 meat), are always characterized by very high PREI: these products often associate a high life  
184 cycle impact of the product with a high burden due to packaging. On the other hand, meat, dairy  
185 products (cheese, butter) and coffee, which are all characterized by high impacts especially due  
186 to the farming or processing phase, usually show low or very low PREI. An interesting study  
187 (Del Borghi, Gallo, Strazza, & Del Borghi, 2014) performed on tomato industrial products has  
188 recently compared various packaging solutions, showing high PREI values (36.3-46.8%) for  
189 products packed in glass bottles and even higher values (46.1-55.0%) for those packed in tin-  
190 plated steel cans; on the other hand, carton-based containers allow a dramatic reduction of the  
191 package impact, which amounts to just 9.7-12.1% for such products. Indeed, the authors propose  
192 the reduction of package weight and the switch to different packaging materials as viable  
193 improvement options. Similar conclusions were drawn by Iribarren, Hospido, Moreira, & Feijoo  
194 (2010) who studied the carbon footprint of mussels, and found that the contribution of tinplate  
195 can packaging was as high as 88%.

196 These data suggest that food products can be categorized into *high, average and low-PREI*  
197 *products* (**Figure 1**): such simplification is proposed with the sole aim of focusing the reader’s  
198 attention on the low relative importance of packaging as environmental burden, in some cases,  
199 and on the need for strategies for packaging optimization, reduction and/or innovation in other  
200 cases. For instance, products packed in glass jars or in tinplate cans are characterized by very  
201 high PREI, irrespective of the food nature. In these cases, the reduction of the packaging weight,  
202 obtained either by reducing the glass/steel thickness or by changing the package geometry, and

203 the shift to alternative materials, such as plastic for retort packaging, could be effective strategies  
204 for the improvement of environmental performances. Similarly, the challenge for the soft drink  
205 industry, which suffers high PREI, is to maximize the CO<sub>2</sub> barrier performances of the bottle  
206 while minimizing the PET preform weight (Coriolani et al., 2006; Licciardello et al., 2016). On  
207 the other hand, the sustainability improvement for products characterized by low PREI, has to  
208 take into consideration measures able to minimize the possibility that food turn into a waste.

209  
210 **3. Accounting for food loss in packaging sustainability assessment: some wastes are worse**  
211 **than others!**

212 Food requires large amounts of energy and resources and causes some environmental impact,  
213 whether it is consumed or not. Wasted food, hence, causes unnecessary environmental impact, in  
214 addition to carrying ethical concern (FAO, 2013).

215 A modern and in-depth vision of food packaging minimizes its evil role, which is often trivially  
216 (and unfairly) correlated with the use and disposal of plastics and materials from non-renewable  
217 resources. For many years, the attention of the public opinion and of the legislators has focused  
218 on the negative environmental impact of packaging, disregarding its important role in the  
219 safeguard of products, hence its potential for food wastes reduction (Svanes et al., 2010;  
220 Wikström & Williams, 2010; Williams, Wikström, Otterbring, Löfgren, & Gustafsson, 2012).  
221 Unfortunately, this approach has not exhausted its misleading course, and consumers often  
222 believe that packaging reduction is the most direct and effective way towards environmental  
223 impacts reduction in the food sector. The new concept promotes packaging potential to lower the  
224 environmental impact of productions by prolonging shelf life and reducing food wastes along the  
225 distribution chain and at the household level. Indeed, wastes reduction across the entire food  
226 chain must be addressed in the perspective of global sustainable development.

227 Avoidable food losses over the whole food value chain in Europe have been estimated to range  
228 around 280 kg per capita per year (Gustavsson, Cederberg, Sonesson, & van Otterdijk, 2011),  
229 45% of which are generated at the household level (Beretta, Stoessel, Baier, & Hellweg, 2013).  
230 It has been reported that most of the losses occurring at the processing level are unavoidable,  
231 while those occurring in households are mainly avoidable (Beretta et al., 2013). Also, losses  
232 occurring at the process level are usually less relevant from an environmental point of view,  
233 since they are often fed to livestock; in contrast, losses occurring at home and in restaurants do  
234 not find an alternative use and are usually entirely lost (Beretta et al., 2013). Interestingly,  
235 Williams et al. (2012) found that 20-25% of household food wastes are packaging-related,  
236 highlighting the need for improving packaging systems and investing on packaging research and

237 innovation transfer. A survey (Monier et al., 2010) carried out on EU27 reported that the annual  
238 losses across the food value chain, except agricultural production stage, range from about 50 kg  
239 to more than 500 kg per capita, as a function of the country, with an average of 180 kg per  
240 capita: also this study confirmed that the major contribution is represented by household wastes  
241 (42%). Similarly, Kranert et al. (2012) estimated annual food losses in Germany as 100-180 kg  
242 per capita, excluding the phases of agricultural production. Data collected since 1974 demonstrate  
243 that food waste has increased by 50% and has assumed such proportions that it has to be  
244 regarded as a global problem (Caronna, 2011).

245 The time has come for food losses to be analyzed in terms of environmental burden: this  
246 objective can be successfully addressed by the Life Cycle Assessment (LCA) methodology  
247 (Beretta et al., 2013). Such determinations would also allow the estimation of the environmental  
248 benefits of reducing food waste and *decide whether investing resources for reducing the waste of*  
249 *a specific product is environmentally reasonable*. Indeed, it has been theorized (Shiina, 1998;  
250 cited by Roy et al., 2009) that the reduction of food losses determines the decrease of  
251 environmental impact until a certain point, below which a further reduction of losses would  
252 imply a sharp increase of impact, due to the excessive measures necessary for that (**Figure 2**).  
253 More recently, it has been established that the reduction of food losses generally determines an  
254 improvement of the overall sustainability of the products value chain. Various studies have  
255 suggested that packaging that reduce food waste can improve environmental sustainability even  
256 if the new solution itself carries a higher impact (Wilkström & Williams, 2010; Williams &  
257 Wilkström, 2011; Silvenius et al., 2014, Verghese, Lewis, Lockrey, & Williams, 2015). An  
258 increase in packaging impact would be environmentally reasonable only when this is  
259 counterbalanced by an impact reduction due to shelf life extension and/or improved product  
260 protection along the chain.

261 Given the above, it is crucial to understand in which cases it is “environmentally reasonable” to  
262 further increase the packaging impact for achieving a shelf life extension or, vice versa, when it  
263 is more appropriate to address packaging reduction strategies for an overall sustainability  
264 improvement.

265  
266 *3.1. Packaging innovation for shelf life extension and food waste reduction.*  
267 Packaging represents the ultimate defense of food products: its role of protection has evolved  
268 into an active function with the development of functional packaging materials, which has been  
269 regulated by European legislation. In particular, Regulation 450/2009 (EU, 2009) defines active  
270 materials as “*materials and articles that are intended to extend the shelf-life or to maintain or*  
271 *improve the condition of packaged food; they are designed to deliberately incorporate*

272 components that would release or absorb substances into or from the packaged food or the  
273 environment surrounding the food". Active packaging can be classified into emitters and  
274 scavengers: the first class, in turn, comprises antimicrobial and antioxidant packaging, while  
275 scavengers (or absorbers) usually include oxygen, carbon dioxide and ethylene absorbers (Lee,  
276 Yam, & Piergiovanni, 2008). Far from presuming to analyze the scientific panorama on  
277 functional packaging, which has been thoroughly reviewed by many comprehensive articles (De  
278 Azeredo, 2013; Gómez-Estaca, López-de-Dicastillo, Hernández-Muñoz, Catalá, & Gavara,  
279 2014; Lee, 2016; Fang, Zhao, Warner, & Johnson, 2017), this paragraph aims at highlighting the  
280 potential of active packaging at extending food shelf life and reducing food wastes.

281 The concept of functional packaging represents the last frontier of food packaging: literature is  
282 crawling with publications on the development of innovative functional materials based on  
283 conventional or novel matrices including antioxidant and/or antimicrobial compounds, with  
284 special regards for substances of natural origin, or other systems aimed at scavenging gases from  
285 the package headspace. **Figure 3** shows the trend in the last 10 years of total publications on  
286 active food packaging, on active antimicrobial and antioxidant food packaging and  
287 scavengers/absorbers.

288 Packaging is also the ultimate defence of food producers against insect insect pests: almost every  
289 packaging material can be perforated by insects, with penetration time depending on the insect  
290 species and life stage, on the type of product contained and on the material nature and thickness  
291 (Riudavets, Salas, & Pons, 2007; Licciardello, Cocuzza, Russo, & Muratore, 2010; Stejskal et al.,  
292 2017). Insect-resistant packaging, hence, could represent an important strategy for reducing wastage  
293 of packaged products, such as cereals, pasta, dried legumes and fruits, which are especially threatened  
294 by pests. Few works have addressed this cutting-edge area: Licciardello et al. (Licciardello,  
295 Muratore, Suma, Russo, & Nerín, 2013) proved the effectiveness of polyolefinic films coated with  
296 different concentrations of citronella, oregano and rosemary essential oils against *T. castaneum*, with  
297 observed repellency levels up to 87% for citronella; other authors (Kim, Song, Han, Park, & Min,  
298 2014, Kim, Park, Na, & Han, 2016; Jo et al., 2015) developed insect-resistant packaging films by  
299 incorporation of cinnamon essential oil as a repellent against *Plodia interpunctella* into plastic  
300 matrices, using controlled release systems to slow down the active components release. Repellent or  
301 insect-proof packaging relying on the release of active components has been included in the wider  
302 category of active packaging (Navarro, Dov, Sam, & Finkelman, 2007), however, this classification  
303 does not seem appropriate, in the light of European Regulations concerning "active and intelligent  
304 packaging" (EU, 2009). In fact, repellent packaging is not designed to release substances into the  
305 packaged food, but to the outer environment, and the possible interaction of such components with  
306 the packaged food is not intentional and, actually, undesirable.

307 Together with functional packaging, packaging innovations in general have the potential to  
308 increase food shelf life and reduce the possibility of food to turn into a waste. To date, only a few  
309 papers among those addressing packaging innovations have considered food losses/wastes, and  
310 in particular, three recent papers have taken food waste into account for the environmental  
311 assessment of food product systems. Manfredi et al. (Manfredi, Fantin, Vignali, & Gavara, 2015)  
312 studied the potential of antimicrobial packaging applied to fresh milk preservation, in the light of  
313 food waste reduction. The authors performed an environmental assessment on the system using  
314 the Life Cycle Assessment (LCA) methodology, taking into account the food waste reduction  
315 potential of the applied technology: results demonstrated that, despite a slight increase in the  
316 package life cycle impact, overall environmental benefits could be achieved thanks to the  
317 reduction of milk waste, thus strengthening the importance of including food waste among the  
318 variables considered in a LCA study of food packaging systems. Zhang et al. (Zhang, Hortal,  
319 Dobon, Bermudez, & Lara-Lledo, 2015) assessed the environmental sustainability of new active  
320 packaging systems for fresh beef, based on four impact categories: global warming, non-  
321 renewable fossil energy consumption, acidification potential and eutrophication potential; these  
322 authors used a novel approach which took into account the food loss reduction potential of the  
323 proposed strategy. Analyzing the various scenarios, the authors identified specific levels of food  
324 loss saving which could offset the additional impacts generated by the use of active packaging,  
325 thus justifying the adoption of the innovative systems; specifically, 0.1% (for the latter two  
326 categories) and 0.6% (for the former two categories) represented the breakeven points. In this  
327 context, the recent study of (Gutierrez, Meleddu, & Piga, 2017) focused on the environmental  
328 and economic effects of an extension in the shelf life of a traditional bakery product. These  
329 authors pointed out that prolonging the shelf life from 7 to 28 days, thanks to a suitable  
330 packaging system based on modified atmosphere and alternative packaging materials, leads to an  
331 improvement of environmental sustainability, based on several impact categories, as a result of  
332 the food loss reduction and of improved distribution efficiency. An economic sustainability  
333 assessment performed by the authors also proved that a shelf life extension would allow to  
334 minimize transport costs, generating economies of scale and downsizing the minimal scale of  
335 production, which is especially beneficial for small companies.

336

#### 337 **4. Future trends and conclusion**

338 Packaging is generally considered by consumers as somewhat superfluous and, at worst, a  
339 serious waste of resources and an environmental menace: this is caused by the misconsideration  
340 or unawareness of its many important functions (Robertson, 2013). While continuing to address

341 innovation, packaging scientists should rehabilitate the packaging image to public opinion, by  
342 highlighting its positive effects and enormous potential. Sustainable packaging, hence, should be  
343 both efficient, aiming at minimizing materials, energy and resources depletion, and effective, i.e.  
344 it should maximize its positive role of protection towards food. Overall, the “packaging”  
345 environmental issue should not be generalized, and it would be more appropriate to focus on the  
346 “packaging-product system” instead on packaging alone. Developments in active packaging  
347 significantly contribute to widening the available tools for shelf life extension. However,  
348 strategies for quality maintenance after package opening (secondary shelf life) have not received  
349 the same attention and could be further developed, with promising potential for food wastes  
350 reduction at the household level. The estimation of food waste reduction associated with  
351 packaging scenarios and its contribution to sustainability represents the actual challenge of the  
352 whole issue, due to the complexity characterizing the food supply chains. The optimization of  
353 packaging systems, aimed at reducing packages thickness and weight, also shows wide margins  
354 for improvement especially for small and medium-sized food companies. This would require  
355 more collaboration between companies decision-makers and food packaging researchers, in  
356 order to ensure that the change of packaging system does not affect the product shelf life  
357 standards. Most studies on packaging sustainability have correlated the eco-profiles to materials  
358 production, transport and disposal; however, food waste reduction potential associated with  
359 packaging technologies should always be included in the environmental assessment of food  
360 packaging systems: this novel approach is increasingly being applied and will significantly  
361 contribute in the discussion on food products sustainability. If food losses are included in the  
362 environmental assessments, then an increase, rather than a reduction, of the packaging impact  
363 could often result in a decrease of the overall impact of productions.

364 A wise approach to the reduction of food wastes through packaging technologies should consider  
365 the impact associated with different product categories: since some foods (e.g., meat and dairy  
366 products) carry much higher impact than others (e.g., vegetables and cereals), it follows that,  
367 from an environmental perspective, *some wastes are worse than others*. Moreover,  
368 consideration of packaging relative impacts is crucial for implementing suitable strategies aimed  
369 at improving food products sustainability. In general (**Figure 1**), *packaging materials reduction*  
370 *and the choice of alternative materials and/or packaging techniques should be attempted in the*  
371 *cases of high-PREI products, provided shelf life standards are maintained; on the other hand,*  
372 *when packaging represents a low relative burden, environmental improvement should rely on*  
373 *process optimisation, shelf life extension and wastes reduction which, in turn, could require an*  
374 *(affordable) increase of the packaging impact.*

375  
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379

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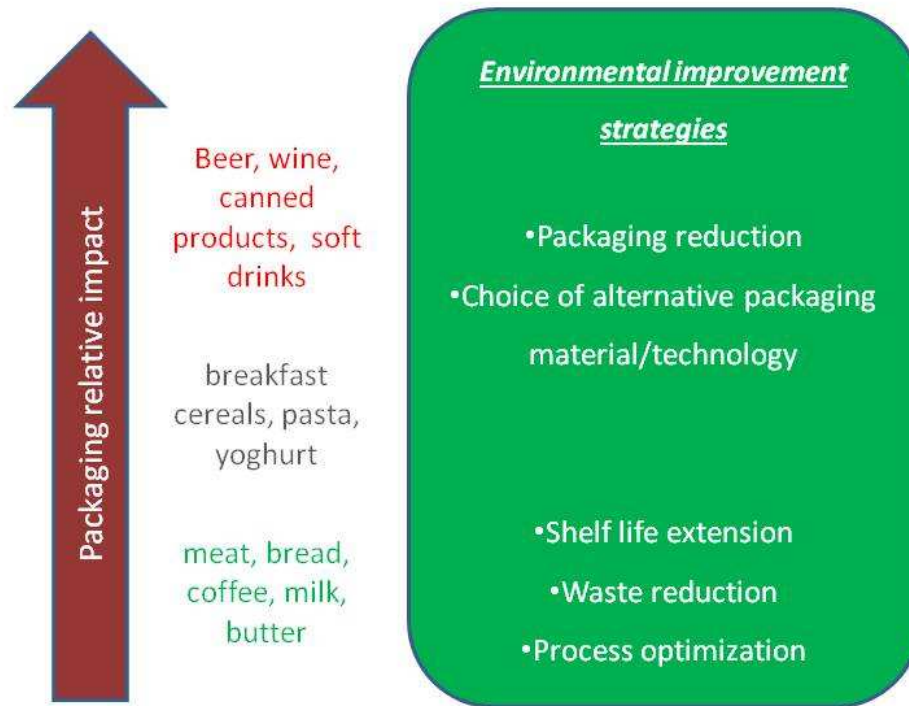
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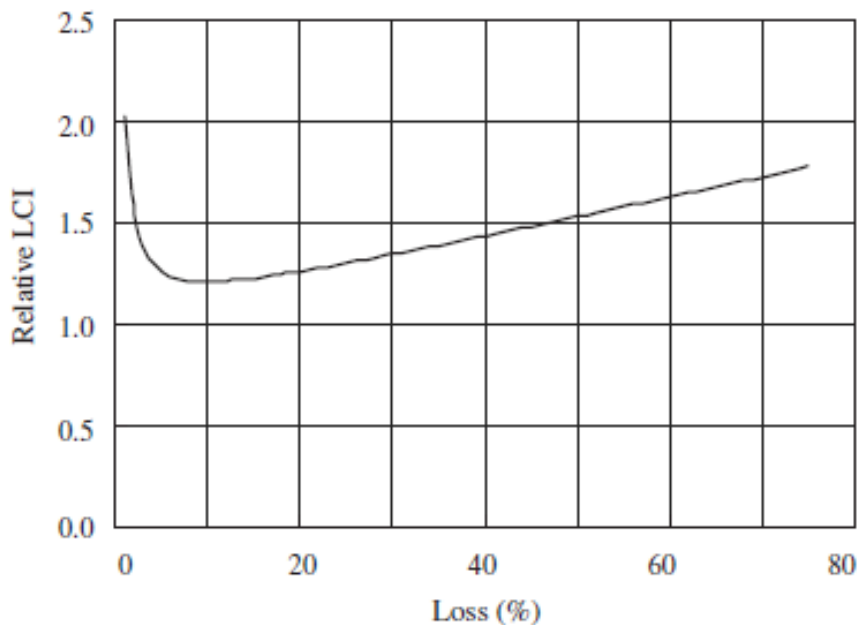
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612 **Table 1.** Packaging relative environmental impact (PREI), as calculated from the reported literature contributions,  
 613 for various food products.

Packaged product		PREI (GWP%)	Reference
Beef		6.5	Williams & Wilkström, 2011
		1.2	Zhang et al., 2015
Beer	aluminum can 33cl glass bottle 33cl glass bottle 66cl	78.0	Koroneos et al., 2005
		very high	De Marco et al., 2016
		58.0	Cimini & Moresi, 2016
		54.00	Cimini & Moresi, 2016
		48.00	Cimini & Moresi, 2016
Bread		9.9	Williams & Wilkström, 2011
Breakfast cereals		15.2	Jeswani et al., 2015
Butter		<3.5	Büsser & Jungbluth, 2009
		very low	Nilsson et al., 2010
Canned sardines		71.1	Almeida et al., 2015
Canned tuna		60.0	Hospido et al., 2006
		58.0	Avadí et al., 2015
		30.0	Mungkung et al., 2012
Carbonated soft drinks	aluminum can 0.33 L	79.0	Amienyo et al., 2013
	glass 0.75 L	75.0	Amienyo et al., 2013
	PET 0.5 L	59.0	Amienyo et al., 2013
	PET 2 L	49.0	Amienyo et al., 2013
Cheese		1.7	Williams & Wilkström, 2011
Cheese (Cheddar)		1.1	Kim et al., 2013
Cheese (Mozzarella)		1.8	Kim et al., 2013
Coffee		<3	Büsser & Jungbluth, 2009
Coffee (instant)		10-15	Büsser & Jungbluth, 2009
Ketchup		51.8	Williams & Wilkström, 2011
Margarine		10-20	Nilsson et al., 2010
Milk		13.9	Williams & Wilkström, 2011
		9.2	Hospido et al., 2003
		3.3	Høgaas Eide, 2002
		7.0	Manfredi et al., 2015
Mussels, canned		88.7	Iribarren et al., 2010
Orange juice		4.8-5.3	Dwivedi et al., 2012
Pasta	carton box	about 28	Dolci et al., 2016
	pillow-bag	about 18	Dolci et al., 2016
Pasta		about 13	Bevilacqua et al., 2007
Tomato puree	carton-based pack glass bottle	41.0	Manfredi & Vignali, 2014
		36.3-46.8	Del Borghi et al., 2014
		9.7-12.1	Del Borghi et al., 2014
Tomato, chopped	glass bottle tinplate steel can	46.5	Del Borghi et al., 2014
		55.0	Del Borghi et al., 2014
Tomato, peeled	tinplate steel can	46.1-51.5	Del Borghi et al., 2014
Wine		43-82	Vázquez-Rowe et al., 2013
		34.2	Gazulla et al., 2010
		55.9	Fusi et al., 2014
		56.1	Bonamente et al., 2016
		73.0	Pattara et al., 2012
Yoghurt		about 18	González-García et al., 2013



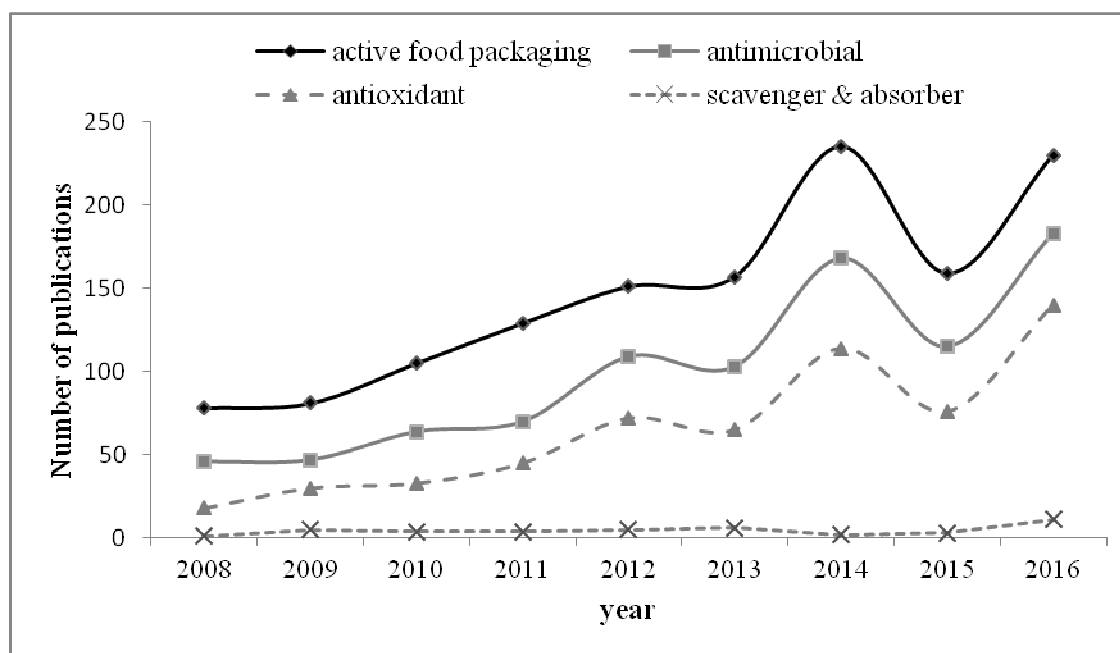
615  
 616 **Figure 1.** Proposed environmental improvement strategies for different packaged foods  
 617 categories based on packaging relative impact.  
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 620  
 621 **Figure 2.** Relation between level of food losses and environmental impact generated. Reprinted  
 622 from Roy et al. (2009), with permission from Elsevier.

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626

627 **Figure 3.** Number of publications in the last 10 years pertaining “Active food packaging”,  
628 among which: “antioxidant”, “antimicrobial” and “scavenger & absorber” using Scopus. Queries  
629 were referred to the Title, Abstract and/or Keywords.

630

**Packaging, blessing in disguise. Review on its diverse contribution to food sustainability.**

Fabio Licciardello

**Highlights**

- Food waste is an environmental issue, and some wastes are worse than others
- Both impacts of food waste and packaging should drive decisions for sustainability
- Packaging environmental assessment should account for waste reduction potential
- Knowing packaging relative impact helps select strategies for more sustainable food