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

Fabio Licciardello

PII: S0924-2244(17)30164-4

DOI: 10.1016/j.tifs.2017.05.003

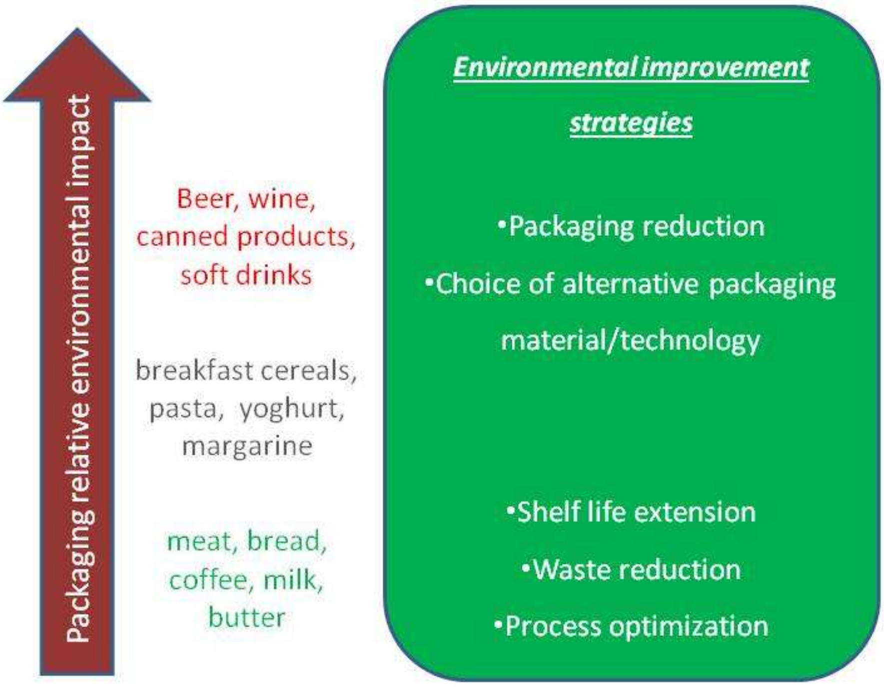
Reference: TIFS 2005

To appear in: *Trends in Food Science & Technology*

Received Date: 22 March 2017

Revised Date: 4 May 2017

Accepted Date: 5 May 2017


Packaging relative environmental impact
Beer, wine, canned products, soft drinks
breakfast cereals, pasta, yoghurt, margarine
meat, bread, coffee, milk, butter
Environmental improvement strategies
•Packaging reduction
•Choice of alternative packaging material/technology
•Shelf life extension
•Waste reduction
•Process optimization

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.

1. Introduction. Food packaging advances towards sustainability

Food packaging has done enormous progress in the last decades, driven by the increasing demand for high-quality, safe food and by the growing concern towards environmental issues. The role of food packaging in the overall sustainability of food productions is controversial: the popular belief that packaging is responsible for high environmental impacts collides with scientific evidence of packaging benefits in terms of food waste reduction potential. Overall, the positive environmental role of food packaging is well-established for the insiders, while it should be clarified to the public opinion, whose position remains somehow hostile. Packaging reputation by consumers can be inferred from a study by by Tanner & Kast (2003) who report that an environment-friendly food product is, ideally, "*domestically produced rather than imported from abroad; furthermore, it is organically grown, seasonal, fresh (rather than frozen), and unwrapped*". Indeed, it is unquestionable that packages are responsible for some environmental impact associated with their life cycles (Huang & Ma, 2004; Ingrao et al., 2015a), and especially with the production of raw materials, processing and end-of-life phase, including recycling, incineration and landfill disposal. Recent studies on the life cycle impact of various packaging materials have increased awareness and made available useful information which can represent the basis for environmentally-responsible choices (Siracusa, Ingrao, Lo Giudice, Mbohwa, & Dalla Rosa, 2014; Speck, Selke, Auras, & Fitzsimmons, 2015). According to Peelman et al. (2013), sustainability of food packaging can be achieved at three levels; 1) at the raw materials level: the use of recycled materials and of renewable resources are two strategies for reducing CO_2 emission and the recourse to fossil resources; 2) at the production level, through more energy-efficient processes; 3) at the waste management level, considering reuse, recycling and biodegradation. On one hand, much effort has been dedicated to decreasing the packaging impacts, by the development of novel biobased materials and through the optimization of packaging use and the improvement of materials performances which, in turn, allows the shift to lighter and thinner packages. On the other hand, packaging innovations have been developed, with the aim of increasing the packaged product quality, extending the shelf life and ultimately reducing the possibility of food to turn into waste.

1.1 A wider concept of environmentally-sustainable packaging

Plastics are the most widely used materials for packaging purposes, due to several advantages such as low cost and light weight, high versatility, flexibility, transparency, heat sealability, good mechanical and barrier performances. The high consumption of packaging is accompanied by a huge waste generation: according to data from EU-28 referred to 2013, 156.9 kg of packaging waste was generated per inhabitant (Eurostat), plastic representing 19% of the total consumed plastic.

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

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

Another important issue in sustainable packaging is materials reduction which, unexpectedly, still represents a viable path towards the improvement of sustainability. The concept of “overpackaging” is not new, however, the fight against overpackaging still offers good potential for sustainability improvement. The reason for that resides probably in the scarce knowledge on packaging by decision makers of food companies, and in recalcitrance to changes. In particular, and this is especially the case of small and medium-sized companies, packaging is not regarded as a major issue and packaging systems are not reconsidered and updated in the light of advances in materials development. The fact that packaging not only has an environmental impact, but directly affects the budget of the company, leads one to give packaging optimization for granted: this is not always true. For sectors such as the beverage industry, where packaging represents the highest environmental impact (and a significant cost for producers), packaging reduction and, in particular, the minimization of the PET parison weight, covers strategic importance: any change in the packaging material and/or design, however, should not affect the CO_2 retention performance, which is the key parameter determining the shelf life of the product (Coriolani, Rizzo, Licciardello, & Muratore, 2006; Licciardello, Coriolani, & Muratore, 2011; Licciardello et al., 2016). The continuous developments in materials science allow to offer the companies packaging materials with improved performances and reduced weight, with a net positive economic and environmental balance. Packaging reduction, hence, remains a potential strategy for overall impact reduction, provided it does not affect the product shelf life standards. Two recent comparative shelf life studies on industrial bread have highlighted the potential to significantly reduce packaging weight (by about 20%) of sliced durum wheat bread characterized by a long shelf life, without affecting the shelf life standards (Licciardello, Cipri, & Muratore, 2014; Licciardello et al., 2017). A change in the packaging system, from thermoformed to flow-pack, allowed a further reduction of packaging but also reduced the commercial life of the product, which could still fulfil the shelf life requirements for the short-range distribution. These case-studies highlight that the spotlight on packaging optimization should be kept turned on, despite the simplicity of the problem which, however, does not assure that the problem itself is being addressed; moreover, these examples emphasize the importance of shelf life assessment in packaging reduction and the need for a close-knit collaboration between producers and food packaging scientists in order to synergically address food packaging sustainability.

Among packaging innovations offering the possibility for reducing materials thickness, are nanotechnologies: even if they have not yet reached widespread application in food packaging due to some toxicological concern, nanotechnologies offer a great potential for the improvement of key features of packaging, especially barrier and mechanical properties (Wyser et al., 2016). The application of nanotechnologies to packaging polymers is generally performed by nanocoatings applied on the polymer surface or by dispersion of nano-objects or nanophases within a polymer matrix. These approaches are aimed at enhancing gas and water vapour barrier, mechanical and/or other functional properties of the packaging materials. Actually, nanoclaypolymer and biopolymer composites (Kuorwel, Cran, Orbell, Buddhadasa, & Bigger, 2015; Lavorgna et al., 2014; Aloui et al., 2016) and graphene (Loryuenyong, Saewong, Aranchaiya, & Buasri, 2015; Barletta, Puopolo, Tagliaferri, & Vesco, 2016) offer a high potential for the development of packaging materials with improved performance and reduced thickness.

2. Packaging relative environmental impact

Not only the common belief has neglected packaging positive role in the safeguard of products and food loss reduction, but it has generally overestimated its environmental impact, which, in fact, is often minimal compared to overall products impact (Hanssen, 1998).
Various studies have assessed the life cycle environmental impact of different food products, part of which have highlighted the contribution of packaging to overall environmental load, which will be hereafter referred to as "**packaging relative environmental impact" (PREI)**. A literature survey brings out variable figures: for instance, while some studies have pointed out that packaging impact represents 1-10% of overall burden (Silvenius et al., 2014), others have stated that it is among the most relevant impacts in the food chains (Manfredi and Vignali, 2015). In fact, PREI is tightly dependant on the food impact, but also on the packaging solution adopted for that product. The environmental contribution of packaging for meat and dairy products is usually low, as a result of the high environmental impact in the primary production and processing stages: this is the case of milk, whose environmental load in the agricultural phase masks other impacts from the whole life cycle (Meneses, Pasqualino, & Castells, 2012), thus representing a special case among beverages (see after). On the other hand, PREI is usually higher for those products containing high amounts of water and/or whose ingredients originate from lower-carbon footprint primary stages, such as vegetables and beverages (dairy excluded) (Ardente, Beccali, Cellura, & Marvuglia, 2006; Amienyo, Gujba, Stichnothe, & Azapagic, 2013; Manfredi & Vignali, 2015; Cimini & Moresi, 2016).
However, products packed in glass or tinplate usually show high PREI, irrespective of the food category. A survey of publications reporting environmental data of food products and their packaging is shown in **Table 1**. It has to be noted that sources which grouped the impacts arising from packaging materials and operations into subsystems including other phases (such as transport, distribution etc) have not been considered herewith. In this review, Global Warming Potential (GWP) data have been considered for comparative purposes, since this environmental category is the most widely used in scientific papers. The considered studies usually adopted a cradle-to-gate approach, however, for those studies performed on a cradle-to-grave basis, the

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

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

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

These data suggest that food products can be categorized into *high, average and low-PREI products* (**Figure 1**): such simplification is proposed with the sole aim of focusing the reader's attention on the low relative importance of packaging as environmental burden, in some cases, and on the need for strategies for packaging optimization, reduction and/or innovation in other cases. For instance, products packed in glass jars or in tinplate cans are characterized by very high PREI, irrespective of the food nature. In these cases, the reduction of the packaging weight, obtained either by reducing the glass/steel thickness or by changing the package geometry, and the shift to alternative materials, such as plastic for retort packaging, could be effective strategies for the improvement of environmental performances. Similarly, the challenge for the soft drink industry, which suffers high PREI, is to maximize the CO_2 barrier performances of the bottle while minimizing the PET preform weight (Coriolani et al., 2006; Licciardello et al., 2016). On the other hand, the sustainability improvement for products characterized by low PREI, has to take into consideration measures able to minimize the possibility that food turn into a waste.

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

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

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

Avoidable food losses over the whole food value chain in Europe have been estimated to range around 280 kg per capita per year (Gustavsson, Cederberg, Sonesson, & van Otterdijk, 2011), 45% of which are generated at the household level (Beretta, Stoessel, Baier, & Hellweg, 2013). It has been reported that most of the losses occurring at the processing level are unavoidable, while those occurring in households are mainly avoidable (Beretta et al., 2013). Also, losses occurring at the process level are usually less relevant from an environmental point of view, since they are often fed to livestock; in contrast, losses occurring at home and in restaurants do not find an alternative use and are usually entirely lost (Beretta et al., 2013). Interestingly, Williams et al. (2012) found that 20-25% of household food wastes are packaging-related, highlighting the need for improving packaging systems and investing on packaging research and innovation transfer. A survey (Monier et al., 2010) carried out on EU27 reported that the annual losses across the food value chain, except agricultural production stage, range from about 50 kg to more than 500 kg per capita, as a function of the country, with an average of 180 kg per capita: also this study confirmed that the major contribution is represented by household wastes (42%). Similarly, Kranert et al. (2012) estimated annual food losses in Germany as 100-180 kg per capita, excluding the phases of agricultural production. Data collected since 1974 demostrate that food waste has increased by 50% and has assumed such proportions that it has to be regarded as a global problem (Caronna, 2011).

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

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

3.1. Packaging innovation for shelf life extension and food waste reduction.

Packaging represents the ultimate defense of food products: its role of protection has evolved into an active function with the development of functional packaging materials, which has been regulated by European legislation. In particular, Regulation 450/2009 (EU, 2009) defines active materials as “*materials and articles that are intended to extend the shelf-life or to maintain or improve the condition of packaged food; they are designed to deliberately incorporate* *components that would release or absorb substances into or from the packaged food or the environment surrounding the food*". Active packaging can be classified into emitters and scavengers: the first class, in turn, comprises antimicrobial and antioxidant packaging, while scavengers (or absorbers) usually include oxygen, carbon dioxide and ethylene absorbers (Lee, Yam, & Piergiovanni, 2008). Far from presuming to analyze the scientific panorama on functional packaging, which has been thoroughly reviewed by many comprehensive articles (De Azeredo, 2013; Gómez-Estaca, López-de-Dicastillo, Hernández-Muñoz, Catalá, & Gavara, 2014; Lee, 2016; Fang, Zhao, Warner, & Johnson, 2017), this paragraph aims at highlighting the potential of active packaging at extending food shelf life and reducing food wastes.

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

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

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

4. Future trends and conclusion

Packaging is generally considered by consumers as somewhat superfluous and, at worst, a serious waste of resources and an environmental menace: this is caused by the misconsideration or unawareness of its many important functions (Robertson, 2013). While continuing to address innovation, packaging scientists should rehabilitate the packaging image to public opinion, by highlighing its positive effects and enormous potential. Sustainable packaging, hence, should be both efficient, aiming at minimizing materials, energy and resources depletion, and effective, i.e. it should maximize its positive role of protection towards food. Overall, the “packaging” environmental issue should not be generalized, and it would be more appropriate to focus on the “packaging-product system” instead on packaging alone. Developments in active packaging significantly contribute to widening the available tools for shelf life extension. However, strategies for quality maintenance after package opening (secondary shelf life) have not received the same attention and could be further developed, with promising potential for food wastes reduction at the household level. The estimation of food waste reduction associated with packaging scenarios and its contributiion to sustainability represents the actual challenge of the whole issue, due to the complexity characterizing the food supply chains. The optimization of packaging systems, aimed at reducing packages thickness and weight, also shows wide margins for improvement especially for small and medium-sized food companies. This would require more collaboration between companies decision-makers and food packaging researchers, in order to ensure that the change of packaging system does not affect the product shelf life standards. Most studies on packaging sustainability have correlated the eco-profiles to materials production, transport and disposal; however, food waste reduction potential associated with packaging technologies should always be included in the environmental assessment of food packaging systems: this novel approach is increasingly being applied and will significantly contribute in the discussion on food products sustainability. If food losses are included in the environmental assessments, then an increase, rather than a reduction, of the packaging impact could often result in a decrease of the overall impact of productions.

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

Acknowledgments

This study was supported by the Italian Ministry of Education, University and Research (MIUR, Prot. 957/ric, 28/12/2012), through the Project 2012ZN3KJL "Long Life, High Sustainability".

References

Almeida, C., Vaz, S., & Ziegler, F. (2015). Environmental Life Cycle Assessment of a canned sardine product from Portugal. *Journal of Industrial Ecology, 19 (4),* 607-617.

Aloui, H., Khwaldia, K., Hamdi, M., Fortunati, E., Kenny, J. M., Buonocore, G. G., & Lavorgna, M. (2016). Synergistic effect of halloysite and cellulose nanocrystals on the functional properties of PVA based nanocomposites. *ACS Sustainable Chemistry and Engineering, 4 (3),*794-800.

Amienyo, D., Gujba, H., Stichnothe, H., & Azapagic, A. (2013). Life cycle environmental impacts of carbonated soft drinks. *The International Journal of Life Cycle Assessment, 18,* 77-92.

Ardente, F., Beccali, G., Cellura, M., & Marvuglia, A. (2006). POEMS: a case study of an Italian wine-producing firm. *Environmental Management, 38,* 350-364.

Avadí, A., Bolaños, C., Sandoval, I., & Ycaza, C. (2015). Life cycle assessment of Ecuadorian processed tuna. *International Journal of Life Cycle Assessment, 20 (10),* 1415-1428

Barletta, M., Puopolo, M., Tagliaferri, V., & Vesco, S. (2016). Graphene-modified poly(lactic acid) for packaging: material formulation, processing and performance. *Journal of Applied Polymer Science, 133(2),* article no. 42252

Beretta, C, Stoessel, F, Baier, U, & Hellweg, S. (2013). Quantifying food losses and the potential for reduction in Switzerland. *Waste Management, 33(3),* 764-773.

Bevilacqua, M., Braglia, M., Carmignani, G. & Zammori, F. A. (2007), Life cycle assessment of pasta production in Italy. *Journal of Food Quality, 30*, 932–952.

Bonamente, E., Scrucca, F., Rinaldi, R., Merico, M.C., Asdrubali, F., & Lamastra, L. (2016). Environmental impact of an Italian wine bottle: Carbon and water footprint assessment. *Science of The Total Environment, 560–561,* 274-283.

Büsser, S., & Jungbluth, N. (2009). The role of flexible packaging in the life cycle of coffee and butter (2009) *International Journal of Life Cycle Assessment, 14 (SUPPL. 1),* S80-S91.

Caronna, S. (2011). Report on how to avoid food wastage: strategies for a more efficient food chain in the EU. European Parliament, Committee on Agriculture and Rural Development.

Cimini, A., Moresi, M. (2016). Carbon footprint of a pale lager packed in different formats: Assessment and sensitivity analysis based on transparent data. *Journal of Cleaner Production, 112,* 4196-4213.

Coriolani, C., Rizzo, V., Licciardello, F., & Muratore, G. (2006). Dependance of the shelf-life of carbonated soft drinks from PET performances as required by "The Coca-Cola Company". *Italian Journal of Food Science (Special Issue),* 453-455.

De Azeredo, H. M. C. (2013). Antimicrobial nanostructures in food packaging. *Trends in Food Science and Technology, 30 (1),* 56-69.

Del Borghi, A., Gallo, M., Strazza, C., Del Borghi, M. (2014). An evaluation of environmental sustainability in the food industry through Life Cycle Assessment: the case study of tomato products supply chain. *Journal of Cleaner Production, 78,* 121-130.

De Marco, I., Miranda, S., Riemma, S., Iannone, R. (2016). Life cycle assessment of ale and lager beers production. *Chemical Engineering Transactions, 49,* 337-342.

Dolci, G., Nessi, S., Rigamonti, L., & Grosso, M. (2016). Life cycle assessment of waste prevention in the delivery of pasta, breakfast cereals, and rice. *Integrated Environmental Assessment and Management, 12 (3),* 445-458.

Dwivedi, P., Spreen, T., & Goodrich-Schneider, R. (2012). Global warming impact of Florida's Not-From-Concentrate (NFC) orange juice. *Agricultural Systems, 108,* 104-111.

EU, 2009. Commission Regulation (EC) No 450/2009 of 29 May 2009 on active and intelligent materials.

Eurostat. http://ec.europa.eu/eurostat/web/environment/waste/database

Fang, Z., Zhao, Y., Warner, R. D., & Johnson, S. K. (2017). Active and intelligent packaging in meat industry. *Trends in Food Science and Technology, 61,* 60-71.

FAO, 2013. Food Wastage Footprint. Impacts on natural resource.

Fusi, A., Guidetti, R., & Benedetto, G. (2014). Delving into the environmental aspect of a Sardinian white wine: from partial to total life cycle assessment. *Science of the Total Environment, 472*, 989–1000.

Gazulla, C, Raugei, M, Fullana-i-Palmer, P. (2010). Taking a life cycle look at Crianza wine production in Spain: where are the bottlenecks? *International Journal of Life Cycle Assessment*, *15,* 330–337.

Gómez-Estaca, J., López-de-Dicastillo, C., Hernández-Muñoz, P., Catalá, R., & Gavara, R. (2014). Advances in antioxidant active food packaging. *Trends in Food Science and Technology, 35 (1),* 42-51.

González-García, S., Castanheira, E. G., Dias, A. C., & Arroja, L. (2013). Environmental life cycle assessment of a dairy product: The yoghurt. *International Journal of Life Cycle Assessment, 18 (4),* 796-811.

Gustavsson, J., Cederberg, C., Sonesson, U., & van Otterdijk, R. (2011). Global food losses and food waste; Extent, causes and prevention. Swedish Institute for Food and Biotechnology (SIK), Gothenburg (Sweden), and FAO, Rome (Italy).

Gutierrez, M. M., Meleddu, M., & Piga, A. (2017). Food losses, shelf life extension and environmental impact of a packaged cheesecake: a life cycle assessment. *Food Research International 91*, 124-132.

Hanssen, O. J. (1998). Environmental impacts of product systems in a life cycle perspective: a survey of five product types based on life cycle assessment studies. *Journal of Cleaner Production 6*, 299-311.

Høgaas Eide, M. (2002). Life cycle assesswment (LCA) of industrial milk production. *International Journal of Life Cycle Assessment, 7 (2),* 115-126.

Hospido, A., Moreira, M.T., & Feijoo, G. (2003). Simplified life cycle assessment of galician milk production. *International Dairy Journal, 13 (10),* 783-796.

Hospido, A., Vazquez, M. E., Cuevas, A., Feijoo, G., Moreira, M. T. (2006). Environmental assessment of canned tuna manufacture with a life-cycle perspective. *Resources, Conservation and Recycling, 47 (1)*, 56-72.

Huang, C. C., & Ma, H.-W. (2004). A multidimensional environmental evaluation of packaging materials. *Science of The Total Environment, 324*, 161-172.

Ingrao, C., Lo Giudice, A., Bacenetti, J., Mousavi Khaneghah, A., Sant'Ana, A. D. S., Rana, R., & Siracusa, V. (2015a). Foamy polystyrene trays for fresh-meat packaging: Life-cycle inventory data collection and environmental impact assessment. *Food Research International, 76*, 418-426.

Ingrao, C., Tricase, C., Cholewa-Wójcik, A., Kawecka, A., Rana, R., & Siracusa, V. (2015b). Polylactic acid trays for fresh-food packaging: A Carbon Footprint assessment. *Science of The Total Environment, 537*, 385-398.

Iribarren, D., Hospido, A., Moreira, M. T., & Feijoo G. (2010). Carbon footprint of canned mussels from a business-to-consumer approach. A starting point for mussel processors and policy makers. *Environmental Science & Policy, 13*, 509-521.

Jeswani, H. K., Burkinshaw, R., Azapagic, A. (2015). Environmental sustainability issues in the food-energy-water nexus: Breakfast cereals and snacks. *Sustainable Production and Consumption, 2,* 17-28.

Jo, H., Park, K., Na, J. H., Min, S.C., Park, K.H., Chang, P., & Han, J. (2015). Development of anti-insect food packaging film containing a polyvinyl alcohol and cinnamon oil emulsion at a pilot plant scale. *Journal of Stored Products Research, 61,* 114-118.

Kim, D., Thoma, G., Nutter, D., Milani, F., Ulrich, R., & Norris, G. (2013). Life cycle assessment of cheese and whey production in the USA. *International Journal of Life Cycle Assessment, 18,* 1019-1035.

Kim, I.-H., Song, A. Y., Han, J., Park, K. H., & Min, S. C. (2014), Indian Meal Moth (*Plodia interpunctella*)–resistant food packaging film development using microencapsulated cinnamon oil. *Journal of Food Science, 79,* E2023–E2030.

Kim, J., Park, N., Na, J. H., & Han, J. (2016). Development of natural insect-repellent loaded halloysite nanotubes and their application to food packaging to prevent *Plodia interpunctella* infestation. *Journal of Food Science, 81(8),* E1956-E1965.

Koroneos, C., Roumbas, G., Gabari, Z., Papagiannidou, E., Moussiopoulos, N. (2005). Life cycle assessment of beer production in Greece. *Journal of Cleaner Production, 13 (4),* 433-439.

Kranert, M., Hafner, G., Barabosz, J., Schneider, F., Lebersorger, S., Scherhaufer, S., Schuller, H., & Leverenz, D. (2012). Ermittlung der weggeworfenen Lebensmittelmengen und Vorschläge zur Verminderung der Wegwerfrate bei Lebensmitteln in Deutschland. Institut für Siedlungswasserbau, Wassergüteund Abfallwirtschaft, Universität Stuttgart, Bandtäle 2, 70569 Stuttgart.

Kuorwel, K. K., Cran, M. J., Orbell, J. D., Buddhadasa, S., & Bigger, S. W. (2015). Review of mechanical properties, migration, and potential applications in active food packaging systems containing nanoclays and nanosilver. *Comprehensive Reviews in Food Science and Food Safety, 14 (4),* 411-430.

Lavorgna, M., Buonocore, G. G., Tescione, F., Capezzuto, F., Yan, N., & Amendola, E. (2014). Multifunctional chitosan nanocomposites: the effect of silver supported on montmorillonite platelets on barrier. and mechanical properties. *AIP Conference Proceedings 1599(1),* 442–445.

Lee, D. S., Yam, K. L., & Piergiovanni, L. (2008). Food Packaging Science and Technology, CRC Press, Taylor & Francis Group.

Lee, D. S. (2016). Carbon dioxide absorbers for food packaging applications. *Trends in Food Science and Technology, 57,* 146-155.

Licciardello, F., Cocuzza, G. E., Russo, A., & Muratore, G. (2010). Quality maintenance performance and resistance to *Tribolium castaneum* and *Plodia interpunctella* penetration of an alternative packaging material for semolina, *Italian Journal of Food Science, 22(4),* 461-466.

Licciardello, F., Coriolani, C., & Muratore, G. (2011). Improvement of CO_2 retention of PET bottles for carbonated soft drinks. *Italian Journal of Food Science, 23 (SUPPL.),* 115-117.

Licciardello, F., Muratore, G., Suma, P., Russo, A., & Nerín, C. (2013). Effectiveness of a novel insect-repellent food packaging incorporating essential oils against the red flour beetle (*Tribolium castaneum*). *Innovative Food Science and Emerging Technologies, 19,* 173-180.

Licciardello, F., Cipri, L., & Muratore, G. (2014). Influence of packaging on the quality maintenance of industrial bread by comparative shelf life testing. *Food Packaging and Shelf Life, 1*, 19-24.

Licciardello, F., Sapienza, G., Mazzaglia, A., D'Amico, L., Tornatore, G., & Muratore, G. (2016). Packaging reduction to improve the sustainability of carbonated soft drinks. *Italian Journal of Food Science, Special Issue of Vol 28(2),* 1-6.

Licciardello, F., Giannone, V., Del Nobile, M.A., Muratore, G., Summo, C., Giarnetti, M., Caponio, F., Paradiso, V.M., & Pasqualone A. (2017). Shelf life assessment of industrial durum wheat bread as a function of packaging system. *Food Chemistry, 224*, 181-190.

Loryuenyong, V., Saewong, C., Aranchaiya, C., & Buasri, A. (2015). The improvement in mechanical and barrier properties of poly(vinyl alcohol)/graphene oxide packaging films. *Packaging Technology and Science, 28(11),* 939–947.

Manfredi, M., Fantin, V., Vignali, G., Gavara, R. (2015). Environmental assessment of antimicrobial coatings for packaged fresh milk. *Journal of Cleaner Production, 95,* 291-300.

Manfredi, M., & Vignali, G. (2015). Comparative Life Cycle Assessment of hot filling and aseptic packaging systems used for beverages. Journal of Food Engineering, 147, 39-48.

Manfredi, M., & Vignali, G. (2014). Life cycle assessment of a packaged tomato puree: a comparison of environmental impacts produced by different life cycle phases. *Journal of Cleaner Production, 73,* 275-284.

Meneses, M., Pasqualino, J., & Castells, F. (2012). Environmental assessment of the milk life cycle: The effect of packaging selection and the variability of milk production data. *Journal of Environmental Management, 107,* 76-83.

Michaud, J.-C., Laura Farrant, L., Jan, O., 2010. Environmental Benefits of Recycling e 2010 Update. Available at: http://www.wrap.org.uk/sites/files/wrap/ Environmental_benefits_of_recycling_2010_update.3b174d59.8816.pdf (accessed March 8, 2017).

Monier, V., Shailendra, M., Escalon, V., O'Connor, C., Gibon, T., Anderson, G., Hortense, M., & Reisinger, H. (2010). Preparatory Study on Food Waste across EU 27. European Commission (DG ENV) Directorate C-Industry. 2010. Final Report. ISBN: 978-92-79-22138-5.

Mungkung, R., Gheewala, S.H., Kanyarushoki, C., Hospido, A., van der Werf, H., Poovarodom, N., Bonnet, S., Aubin, J., Teresa Moreira, M., & Feijoo, G. (2012). Product carbon footprinting in Thailand: A step towards sustainable consumption and production? *Environmental Development, 3 (1),* 100-108.

Navarro, S., Dov, Z., Sam, A., & Finkelman, S. (2007) Natural nontoxic insect repellent packaging materials, Chapter 10; p. 201-236. In Charles L.Wilson, (Ed) Frontiers of "Intelligent" and "Active' Packaging For Fruits and Vegetables, CRC Press, Taylor & Francis Group, Boca Raton, FL.

Nilsson, K., Flysjö, A., Davis, J., Sim, S., Unger, N., & Bell, S. (2010). Comparative life cycle assessment of margarine and butter consumed in the UK, Germany and France. *International Journal of Life Cycle Assessment, 15 (9),* 916-926.

Pattara, C., Raggi, A., & Cichelli, A. (2012). Life cycle assessment and carbon footprint in the wine supply-chain. *Environmental Management, 49 (6),* 1247-1258.

Peelman, N., Ragaert, P., De Meulenaer, B., Adons, D., Peeters, R., Cardon, L., Van Impe, F., & Devlieghere, F. (2013). Application of bioplastics for food packaging. *Trends in Food Science & Technology, 32(2),* 128-141.

Robertson, G. L. (2013). Food Packaging: Principles and Practice. Third Edition, CRC Press.

Riudavets, J., Salas, I., & Pons M. J. (2007). Damage characteristics produced by insect pests in packaging film. *Journal of Stored Product Research 43,* 564-570.

Roy P., Nei D., Orikasa T., Xu Q., Okadome H., Nakamura N., & Shiina T. (2009). A review of life cycle assessment (LCA) on some food products. *Journal of Food Engineering, 90,* 1-10.

Shiina, T. (1998). Optimization of food supply chain to minimize the environmental load. In: Proceedings of the 13th Seminar of the Study Group on Agricultural Structure, Tsukuba, Japan

Silvenius, F., Grönman, K., Katajajuuri, J.-M., Soukka, R., Koivupuro, H.-K., & Virtanen, Y. (2014). The role of household food waste in comparing environmental impacts of packaging alternatives. *Packaging Technology and Science*, *27*, 277-292.

Siracusa, V., Rocculi, P., Romani, S., & Dalla Rosa, M. (2008). Biodegradable polymers for food packaging: a review. *Trends in Food Science and Technology, 19 (12),* 634-643.

Siracusa, V., Ingrao, C., Lo Giudice, A., Mbohwa, C., & Dalla Rosa, M. (2014). Environmental assessment of a multilayer polymer bag for food packaging and preservation: An LCA approach *Food Research International, 62,* 151-161.

Sorrentino, A., Gorrasi, G., & Vittoria, V. (2007). Potential perspectives of bio-nanocomposites for food packaging applications. *Trends in Food Science & Technology, 18,* 84-95.

Speck, R., Selke, S., Auras, R., & Fitzsimmons, J. (2015). Choice of life cycle assessment software can impact packaging system decisions. *Packaging Technology and Science, 28,* 579–588.

Stejskal, V., Bostlova, M., Nesvorna, M., Volek, V., Dolezal, V., & Hubert, J. (2017). Comparison of the resistance of mono- and multilayer packaging films to stored-product insects in a laboratory test. *Food Control, 73,* 566-573.

Svanes, E., Vold, M., Møller, H., Pettersen, M. K., Larsen, H., & Hanssen, O.J. (2010). Sustainable packaging design: a holistic methodology for packaging design. *Packaging Technology and Science, 23,* 161–175.

Tanner, C., & Kast, S. W. (2003). Promoting sustainable consumption: Determinants of green purchases by Swiss consumers. *Psychology and Marketing, 20*, 883-902.

Vázquez-Rowe, I., Rugani, B., & Benetto, E. (2013). Tapping carbon footprint variations in the European wine sector. *Journal of Cleaner Production 43,* 146–155.

Verghese, K., Lewis, H., Lockrey, S., & Williams, H. (2015). Packaging's role in minimizing food loss and waste across the supply chain. Packaging Technology and Science, 28, 603-620.

Wikström, F., & Williams, H. (2010). Potential environmental gains from reducing food losses through development of new packaging – a life cycle model. *Packaging Technology and Science 23,* 403-411.

Williams, H., & Wikström, F. (2011). Environmental impact of packaging and food losses in a life cycle perspective: a comparative analysis of five food items. *Journal of Cleaner Production 19,* 43-48.

Williams, H., Wikström, F., Otterbring, T., Löfgren, M., & Gustafsson, A. (2012). Reasons for household food waste with special attention to packaging. *Journal of Cleaner Production, 24,* 141-148.

Wyser, Y., Adams, M., Avella, M., Carlander, D., Garcia, L., Pieper, G., Rennen, M., Schuermans, J., & Weiss, J. (2016). Outlook and challenges of nanotechnologies for food packaging. *Packaging Technology and Science, 29 (12),* 615-648.

Zhang, H., Hortal, M., Dobon, A., Bermudez, J.M., & Lara-Lledo, M. (2015). The effect of active packaging on minimizing food losses: Life Cycle Assessment (LCA) of essential oil component-enabled packaging for fresh beef. *Packaging Technology and Science, 28 (9),* 761-774.

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

Packaged product		**PREI (GWP%)**	**Reference**
Beef		6.5	Williams & Wilkström, 2011
Beef		1.2	Zhang et al., 2015
Beer		78.0	Koroneos et al., 2005
Beer		very high	De Marco et al., 2016
Beer	aluminum can 33cl	58.0	Cimini & Moresi, 2016
Beer	glass bottle 33cl	54.00	Cimini & Moresi, 2016
Beer	glass bottle 66cl	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
Butter		very low	Nilsson et al., 2010
Canned sardines		71.1	Almeida et al., 2015
Canned tuna		60.0	Hospido et al., 2006
Canned tuna		58.0	Avadí et al., 2015
Canned tuna		30.0	Mungkung et al., 2012
Carbonated soft drinks	aluminum can 0.33 L	79.0	Amienyo et al., 2013
Carbonated soft drinks	glass 0.75 L	75.0	Amienyo et al., 2013
Carbonated soft drinks	PET 0.5 L	59.0	Amienyo et al., 2013
Carbonated soft drinks	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
Milk		9.2	Hospido et al., 2003
Milk		3.3	Høgaas Eide , 2002
Milk		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
Pasta	pillow-bag	about 18	Dolci et al., 2016
Pasta		about 13	Bevilacqua et al., 2007
Tomato puree		41.0	Manfredi & Vignali, 2014
Tomato puree	carton-based pack	36.3-46.8	Del Borghi et al., 2014
Tomato puree	glass bottle	9.7-12.1	Del Borghi et al., 2014
Tomato, chopped	glass bottle	46.5	Del Borghi et al., 2014
Tomato, chopped	tinplate steel can	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
Wine		34.2	Gazulla et al., 2010
Wine		55.9	Fusi et al., 2014
Wine		56.1	Bonamente et al., 2016
Wine		73.0	Pattara et al., 2012
Yoghurt		about 18	González-García et al., 2013

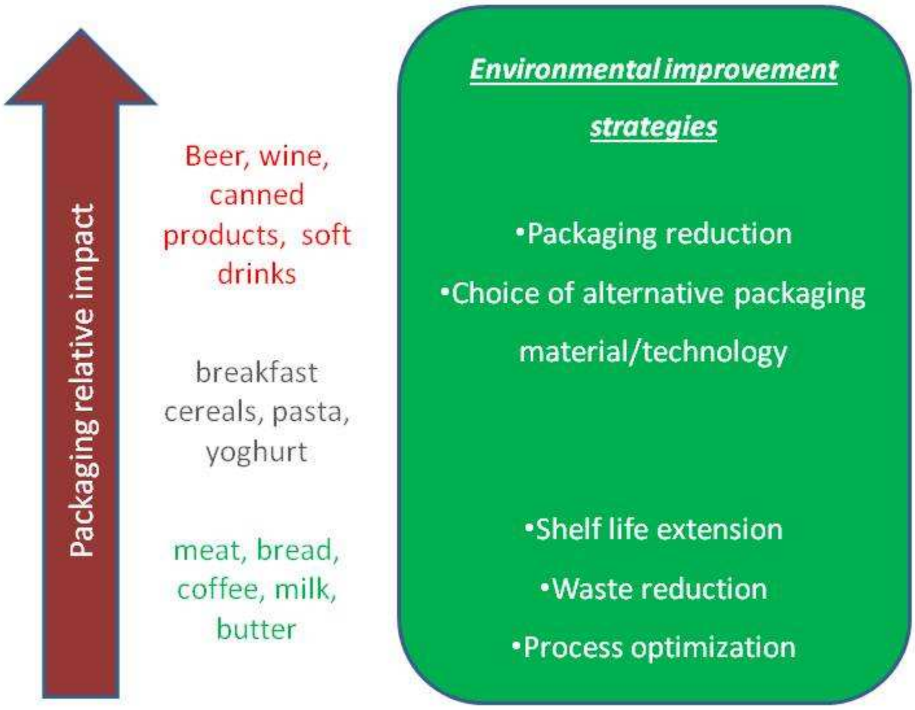


Figure 1. Proposed environmental improvement strategies for different packaged foods categories based on packaging relative impact.

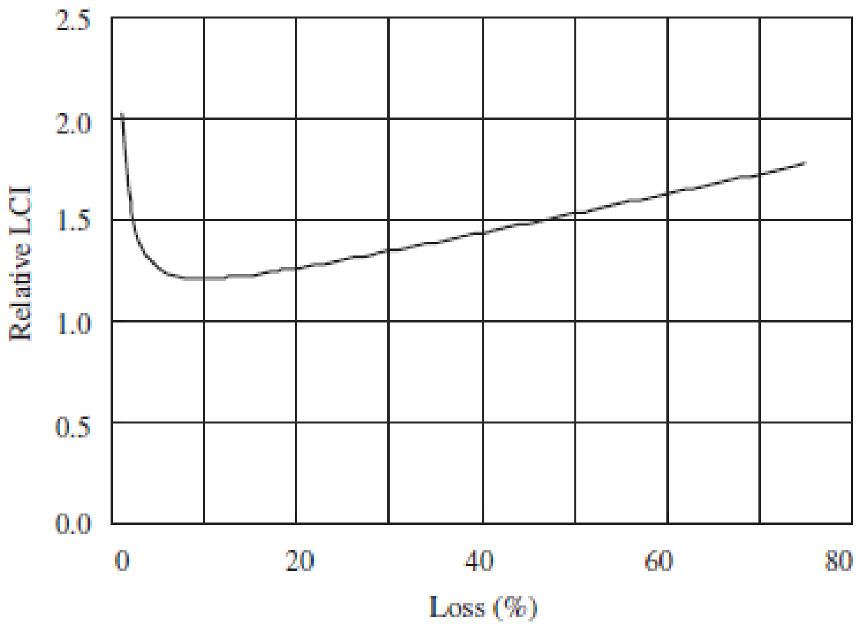


Figure 2. Relation between level of food losses and environmental impact generated. Reprinted from Roy et al. (2009), with permission from Elsevier.

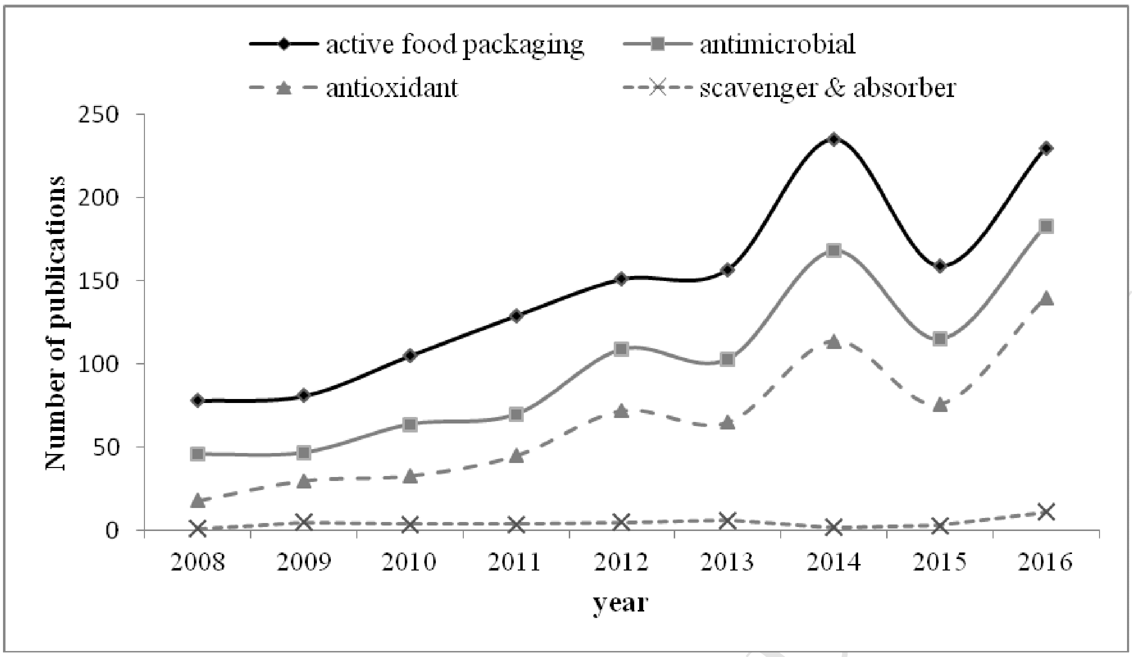


Figure 3. Number of publications in the last 10 years pertaining “Active food packaging”, among which: “antioxidant", "antimicrobial" and "scavenger & absorber" using Scopus. Queries were referred to the Title, Abstract and/or Keywords.

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