Packaging and food sustainability

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Chapter outline

1. Introduction

Food packaging is a crucial unit of operation within the food production processes, as it provides the food products with suitable conditions able to prevent mechanical damage and slow-down biochemical deterioration, as well as changes caused by microorganisms. Food-packaging's primary protective role is mainly exerted by controlling gas and vapor exchanges with the external environment and by preventing microbial and chemical contamination, thus extending shelf life and preventing food safety issues. In other words, packaging can maintain the beneficial effects of processing after the process is complete (Marsh and Bugusu, 2007) and increase the storage life of fresh foods, such as meats, fruits, or vegetables.

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Much research has been dedicated to the improvement of packaging materials performances which has made available a wide range of materials for any purpose, able to respond to the specific requirements of different food products. Indeed, packaging systems should be designed specifically for each food product, taking into consideration: the food characteristics (specific quality parameters), the events which lead to quality loss (i.e., gas exchange, light transmittance, etc.), distribution specifications, and marketing needs; food-packaging systems should comply with food-contact materials regulations. Modern food packaging must face up to another requirement: it must be environmentally sustainable. Indeed, packaging contributes to the sustainability of a food product and should be designed holistically together with that product to optimize the overall environmental performance and minimize the risk of product spoilage, damage and wastage. A great deal of effort must be addressed to make the packaging system "greener", but still able to protect food and to retard degradation phenomena. To date, the concept of sustainability of packaging has been markedly influenced by the evil reputation of plastics, being one of the major concerns in environmental pollution. Actually, there is a strong need for a more objective consideration of packaging, which balances the undoubtful environmental drawbacks linked to packaging production and end-of-life, with the enormous benefits in terms of food products safeguard and waste reduction potential. Indeed, consumers have the common belief that food packaging represents an additional economic and environmental cost, an unnecessary solid waste rather than a valuable means for waste reduction. According to Cox and Downing (2007), 75%−90% consumers agree that discarded packaging is a greater environmental issue than the wasted food. Sustainability is one of the factors which guide consumers in food products choice. Recent studies (Grunert et al., 2014), however, have pointed out that packaging-related sustainability factors (i.e., the amount of packaging used, food waste and the recyclability of packaging) represent elements of choice for specific products categories, such as ready meals and soft drinks. In general, there is growing awareness on packaging role and what is clear to everyone is that modern food cannot exist without its packaging. Nevertheless, significant improvements are possible, and the food industry should target packaging systems which are more efficient and more effective, i.e., more performing and more sustainable at the same time.

2. Environmental aspects of packaging materials for food use

Plastic packaging, which represents the largest application of plastics, accounts for about 40% of the total volume (PlasticsEurope, 2017). The continuous increase in the share of plastic packaging within the global packaging volumes is to be attributed to the several advantages of plastics as packaging materials: they are inexpensive, lightweight, versatile and high performing.

The assessment of the environmental impact of packaging has recently become a hot topic. This is because packaging materials, especially plastic, have been blamed as primary responsible for environmental pollution. A case which has recently shocked the public opinion is that of plastic recovered in the oceans and in the tissues of fish. Plastic packaging which leak out of collecting and sorting systems, can end up in the soil and in the sea, slowly degrading to micro- and nanoplastics which can reach the food chain through the accumulation into marine organisms, with dramatic long-term consequences (United Nations Environment Program (UNEP), 2011) (European commission, 2011). It is estimated that about 32% of plastic, which is the fraction not suitably recovered by the collection system, pollutes the environment and that 8 million tons end up in the oceans every year: this figure is equivalent to one garbage truck dumping in the ocean every minute, and is estimated to grow to four trucks per minute by 2050 (Ellen MacArthur Foundation, 2016). In Europe, the total packaging waste collected has increased by 12% in the last 10 years. Of the collected plastic packaging waste, 41% is recycled, 39% ends up to energy recovery, while around 20% is still landfilled, however this last fraction has been halved (−53%) between 2006 and 2016 (PlasticsEurope, 2017).

However, the environmental responsibility of packaging materials is not only related with its end-of-life destiny, but also with the fossil resources depletion: indeed, conventional plastic packages (i.e., polyehtylene, PE; polypropylene, PP; polyethylene therephthalate, PET, polyvinyl chloride, PVC, etc.) are made from fossil oil-derived raw materials, implying the consumption of resources which are nonrenewable (actually, they are renewable but in a very long timeframe), thus creating an overall resource imbalance. However, we must be aware that the overall plastic production consumes about 4%−6% of the fossil resources and, therefore, plastic packaging accounts for much less (about 1%−3%); on the other hand, electricity, heating and transport are responsible for 87% of fossil resources depletion (PlasticsEurope, 2017). The new concepts of "green packaging," "eco-friendly packaging," or "sustainable packaging" have, thus, permeated the society, even if they have not been precisely defined and may cause some confusion in the consumers (Herbes et al., 2018).

Life Cycle Assessment (LCA) is, worldwide, the reference tool for the identification and quantification of the environmental impacts associated with a product life cycle (Ingrao et al., 2015). This methodology is ruled by the International Standards 14040 and 14044 (ISO, 2006a,b) and considers representative environmental indicators, such as global warming, nonrenewable energy, respiratory inorganic matter, acidification and eutrophication, eco-toxicities, and land occupation. The adoption of Life Cycle Thinking, i.e., the approach to becoming really aware of how and to what extent everyday life affects the environment, in the food chain particularly has strongly impacted the availability of information on the actual burdens associated with the various phases and such data represent a reference for environmentally-responsible choices. LCA studies have successfully been applied to packaging, highlighting the impacts associated with its production and disposal (Büsser and Jungbluth, 2009; Ingrao et al., 2017; Siracusa et al., 2014; Zabaniotou and Kassidi, 2003).

A comparison with results from LCA studies of packaging revealed a number of discrepancies between consumer perception and facts on the environmental impact of different packaging options: indeed, apparently less environmentally friendly packaging options may be, in fact, more sustainable because they prevent food losses better than other solutions (Herbes et al., 2018). Moreover, several organizations, active in the packaging field, have put on the market, or made available to their associates, simplified and specifically packaging-oriented software, useful for an impact assessment of different packaging options. It is worth mentioning, for instance, the Compass (comparative packaging assessment) offered by the Sustainable Packaging Coalition [https://greenblue.org/work/compass/] and Piqet (packaging impact quick evaluation tool) provided by the Sustainable Packaging Alliance [http://piqet.com/].

3. Impact of food wastes on the overall sustainability

The environmental load of the food industry is function of the resources and emissions associated with both the food and the packaging, including the amount of food that is lost. Indeed, resources and emissions associated with nonconsumed food account for unnecessary impact, whose prevention might significantly improve the overall sustainability. Thus, food loss and waste is not just an important ethical issue, but also a matter of sustainability. Food losses occurring at the end of the food chain (retail and final consumption) are rather called "food waste," which relates to retailers' and consumers' behavior (Parfitt et al., 2010).

A study by the FAO (Gustavsson et al., 2011) highlighted that in medium- and high-income countries a high fraction of food is thrown away, even if it is still suitable for human consumption. Much more food is wasted in the industrialized countries than in developing ones, in particular, food waste at the consumer level in industrialized countries (222 Mton) is almost as high as the total net food production in sub-Saharian countries (230 Mton).

Food wastage is always bad, but some types of waste are even worse than others: this depends on two factors. First, the stage of the value chain at which they occur: indeed, a possible alternative use is possible for losses occurring at the processing stage, while food wasted after distribution is often lost without any alternative. Moreover, as the environmental impacts build up with each step in the production cycle, wastage of finished products implies the maximum level of unnecessary impact and, as a consequence, the reduction of losses occurring in the consumer phase is of paramount importance (Williams and Wikström, 2011). Secondly, the food category determines the importance of the waste: it is well known that certain food types (i.e., animal and dairy) are characterized by higher production impacts, as a consequence, their wastage results in higher resources consumption and higher emissions compared with the wastage of lower-impact foods (vegetables, beverages). For instance, Venkat (2012) estimated that beef accounted for the largest impact contribution of wasted food (16% of the total emissions), even though the amount of waste for this product was less than 2% (by weight) of total waste. Recently, a study conducted on the US food system, with the aim of estimating the actual environmental weight of food wastes, highlighted that the emissions associated with just producing wasted food equal the emissions from 33 million vehicles driven for 1 year (Heller and Keoleian, 2015).

It has been estimated that 35%−60% of food waste is avoidable and that 45% of the avoidable losses (which, in turn, represent 26% of the wasted food in Switzerland), occurs at households (Beretta et al., 2013). In 2012, the European Commission (EC) set a target to reduce by 50% the food waste in Europe by 2025. Indeed, it is widely accepted that food waste reduction must be attempted both for reducing the environmental burden of food chains and as a food security strategy, which would allow to increase the availability of food worldwide.

Wikström and Williams (2010) established the need to utilize a functional unit based on the food eaten in order to account for consumer-level food losses in the assessment of the environmental performances of foods, this concept was also adopted by (Heller et al., 2018). The same authors proposed that it could be environmentally reasonable to increase the impact of packaging with the adoption of new design and innovation that contribute to reduce food losses. Following studies (Silvenius et al., 2014; Verghese et al., 2015; Williams and Wikström, 2011) strengthened this achievement and it is now consolidated that an increase in packaging impact is acceptable when it is counterbalanced by an impact reduction due to shelf life extension and/or improved protection along the product chain.

Fig. 6.1 reproduces some of the results from (Williams and Wikström, 2011) showing the maximum increase in environmental impact from the packaging as a function of the reduction of food losses. T is the environmental impact to produce the package for one unit of purchased food to the consumer, inclusive the waste handling of the packaging, and T_2 and T_1 are the impacts referred to two different packaging systems, the former with increased impact. As it can be inferred, a reduction

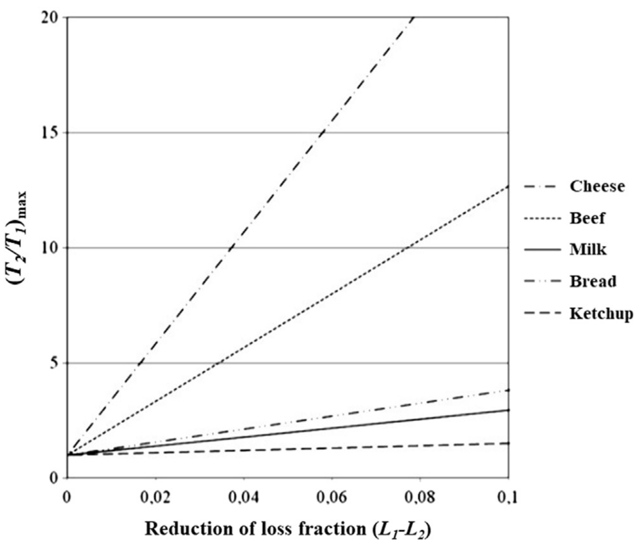

Figure 6.1 Maximum increase in environmental impact from the packaging as a function of the reduction of food losses.
Reproduced from Williams, H., Wikström., F., 2011. Environmental impact of packaging and food losses in a life cycle perspective: a comparative analysis of five food items. J. Clean. Prod. 19 (1), 43−48 https://doi.org/10.1016/j.jclepro.2010.08.008.

of food losses justifies the impact increase of packaging, especially for cheese and beef which are characterized by much higher production impacts and higher loss rates.

Wikström et al. (2018) recently contributed to consolidate the growing awareness on that the impact of packaging is not as high as that of food waste for different products; in their paper, the authors showed the greenhouse gas distribution between the consumed food, wasted food and packaging materials of: (1) meat, fish and eggs; (2) dairy; (3) fruits, vegetables, and nuts. The greenhouse gas of consumed food was 80%, 75%, and 60% for the three categories, respectively; the impact of wasted food was as high as 18%, 13%, and 22%, much higher than the impact arising from packaging materials (2%, 10%, and 12%, respectively). This study confirmed that, for the considered food categories, packaging accounts for the least environmental impact compared to the food itself.

Overall, it should be noted that it is possible to measure the environmental load of food and packaging, while the correct estimation of the waste level for specific products remains the major challenge within this area. Those few studies which consider food wastes usually refer to general data, while the actual waste level is very product-specific and is strongly dependent on the specific food-packaging configuration and socioeconomic factors.

Consumer behavior has the largest potential to decrease food waste, but packaging may influence behavior through new information and/or technical solutions. Some of the reasons for food to turn into waste at the consumer level are packaging-related: packaging role to prevent food from turning into a waste is linked to the main packaging functions (i.e., protection, convenience, communication), which should be further implemented in the direction of waste reduction. In particular, packaging should protect the food from physical damage and biochemical degradation; it should be easy to reseal, thus extending secondary shelf life; it should be easy to empty completely, it should be provided in suitable sizes that avoid leftovers and it should also provide the correct information (content, best-before-date, etc.) to avoid that food that is still suitable for consumption is thrown away (Williams and Wikström, 2011).

The wastage of packaged food, occurring during the distribution and at the household level, brings about another issue: not only the food is wasted, with unnecessary impact arising from resource consumption and emissions, but also this waste is enclosed in its package and a correct disposal would imply the package opening and separation of the food from its package, which should follow two separate recovery paths (i.e., the organic fraction and the plastic fraction, respectively). When the two items are not correctly separated, which is the current scenario due to the lack of suitable sorting plants, this waste is collected as unsorted waste and is likely to end up in landfill or incinerated (Garcia-Garcia et al., 2015; Vitale et al., 2018).

4. The contribution of packaging to the sustainability of food chains

Packaging reputation by consumers can be inferred from a study by Tanner and 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". The role of packaging in the sustainability of food chains has been controversial and it appears that the different considerations of packaging under the sustainability point of view raise from the attempt to generalize its role. As an example, in one paper on the theme (Silvenius et al., 2014) it was stated that "the significance of packaging production and post-consumer life on environmental impact is low and represents 1%−10% of the total environmental impact generated by the food chains", while, on the other hand, another work (Manfredi and Vignali, 2015) reported that "the impacts of the packaging materials life cycle are very often among the most relevant environmental burdens". The understanding of the contribution of packaging to overall food sustainability, however, should consider each specific food case and should be based on considerations on the environmental impact connected to the production of both packaging and food.

Recently the Packaging Relative Environmental Impact (PREI) was proposed as an indicator able to assess the role of packaging in the sustainability of a specific product (Licciardello, 2017). PREI is the ratio of the environmental impact related to the packaging, $\mathbf{EI}_{(pack)}$, to the overall environmental impact of the food, $\mathbf{EI}_{(food)}$. Impacts are conveniently expressed as Global Warming Potential (GWP), since this impact category is the most widely used and the less affected by other factors.

$$\mathbf{PREI} = \mathbf{EI}_{(pack)}/\mathbf{EI}_{(food)}$$

This simple index represents a balance between the actual environmental load of packaging and that of a specific food product and could be used as a tool to support improvement strategies. In particular, high-PREI values suggest that actions aimed at reducing the environmental impact of packaging materials may result in the sustainability improvement of the system, while low-PREI values suggest that food wastes, for the specific product, have a significant impact on the environmental performances: therefore, investments aimed at reducing food wastage may be positive, even when they imply some increase of the packaging impact.

PREI can assist in packaging design and optimization and does not require to perform full LCA studies. However, the source of data (i.e., LCA studies on food products) should display the impact of packaging production, while studies which group the impact of packaging together with other phases (usually, transportation, storage, distribution) are not suitable for this aim.

In some cases, which are hereafter exemplified, may be useful to understand the potential of this indicator. Based on data collected by the author (Licciardello, 2017), beverages such as beer, wine and carbonated soft drinks are characterized by a high-PREI, ranging from 45 to 80, as to testify the higher environmental impact generated by the packaging production, usually glass bottle, PET bottle or aluminum can, compared with the impact generated by the production process of the beverage itself. For such products, actions aimed at minimizing the impact of packaging, with special regards for the material reduction (lighter bottles and caps, new shapes) and at improving the recyclability of materials represent the right strategies for sustainability improvement. A similar consideration applies to canned vegetables and fish or tomatoes in glass jars, whose impact is highly affected by the packaging. On the other hand, dairy product (milk, cheese, butter) and beef meat are characterized by low and very low-PREI values, ranging from about 1 to less than 15, as a result of high impacts related to the food production and raw materials primary production, compared to which the environmental load of packaging becomes, in some cases, negligible. For such products, packaging is usually polymeric (HDPE or PS bottles and jars, PS or PET trays with lid film) or composite (multilayer laminated carton) and environmental improvement strategies should be based on actions aimed at extending the product shelf life and reducing product losses. Indeed, food losses, however generated, represent unnecessary impact. A previous study (Williams and Wikström, 2011) compared the environmental impact from food (F) and from packaging (T) for five different food categories. The environmental impact related to cheese and beef was much higher than the impact of packaging, thus resulting in the highest F/T ratio (or lowest PREI). Similar considerations arose from this study: large increases from the cheese packaging could be justified for a new packaging reducing cheese losses, while the low F/T ratio for ketchup indicates that it is just as important to find packaging systems with less environmental impact as it is to develop packaging that lead to lower losses (Williams and Wikström, 2011).

Similarly to PREI, the Food-to-Packaging (FTP) environmental impact indicator proposed by (Heller et al., 2018) gives useful information for assessing the actual weight of packaging and food on overall food sustainability, but its interpretation is, of course, inverse compared with PREI. FTP ratio is calculated as [("agricultural (farm-gate) production/kg food" + "food processing/kg food")/"packaging materials/kg food".

Based on the established awareness of the impacts of food waste, packaging environmental assessment needs to be reconsidered to include the indirect effects due to packaging-related food waste. Both PREI and FTP can be also used to estimate the influence of food waste on the overall system environmental performance. When FTP ratios are high, food waste is likely to have a strong influence on system environmental performance and changes in packaging design that lead to food waste reduction are likely to determine net decreases in environmental impact; on the other hand, low FTP ratios indicate that investments should be better addressed at reducing the impact of the packaging itself. Based on a survey of LCA studies performed by (Heller et al., 2018), the FTP ratio (for GHG emissions) ranges from 0.06 in wine to 780 in beef. High ratios for cereals, dairy, seafood, and meats, which correspond to the low-PREI values estimated by Licciardello (2017), suggest that net impact reductions can be achieved through packaging-based food waste reduction innovations.

Often, the agricultural production stage is responsible for the highest impacts in food life cycles (Ingrao et al., 2018), however processing or packaging can also play a significant role, depending on the product. A survey of LCA studies on food products has brought to light large differences in the environmental load caused by the packaging and by the production (primary production + processing) of the food. Fig. 6.2 reports different food products with their calculated PREI, as an estimate of the weight of packaging on the overall environmental impact generated in the product chain.

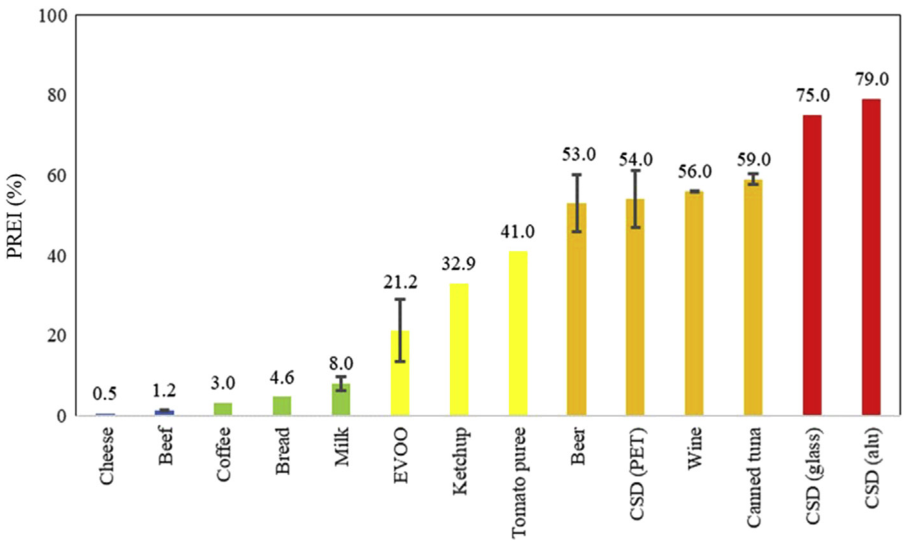

Figure 6.2 Packaging relative environmental impact (PREI) calculated for different food products. *CSD*, Carbonated soft drinks; *EVOO*, Extra virgin olive oil. Where multiple data are available, the mean calculated value is reported with standard deviation. Sources of data for PREI calculation are reported in Table 5.1.

As it can be inferred, based on the literature data considered (Table 6.1), food products can be classified into very low-PREI (cheese, meat, coffee, bread), low-PREI (milk), moderate-PREI (extra virgin olive oil, ketchup, tomato puree), high-PREI (beer, wine, carbonated soft drinks bottled in PET and canned tuna), and very high-PREI products (carbonated soft drinks packed in aluminum cans and in glass bottles).

Based on the above consideration that for systems characterized by a low-PREI (or a high FTP ratio) the adoption of packaging systems able to reduce food waste would improve the overall sustainability, in some cases the best and simplest solutions could be to pack the products in smaller package sizes, despite the increase in packaging materials.

There remains the challenge to estimate food wastes related to specific scenarios. Only a few studies have attempted to consider food waste in the sustainability assessment of packaging systems and have calculated the waste reduction that can be achieved with a new packaging, while in most cases waste reduction scenarios were only hypothesized. The study by (Heller et al., 2018) analyzes a group of foods with the aim of demonstrating the influence of food waste on product system environmental performance. This paper considered 13 foods in their typical packaging configurations applied waste rates provided at the food commodity level as an estimate for product-specific waste rates. The environmental balance between food waste and food packaging can be delicate, and a careful measurement of waste levels, which is the actual challenge in the theme, is the fundamental step for demonstrating the environmental benefits which can be achieved.

Table 6.1 Data sources (LCA studies) for the PREI calculation (Fig. 5.1).

Food product	Data source
Cheese	Williams & Wikström (2011)
Beef	Williams and Wikström (2011); Zhang et al. (2015)
Coffee	Büsser & Jungbluth (2009)
Bread	Williams & Wikström (2011)
Milk	Williams and Wikström (2011); Hospido et al. (2003); Manfredi et al. (2015)
EVOO	Pattara et al. (2016)
Ketchup	Williams and Wikström (2011)
Tomato puree	Manfredi and Vignali, 2014
Beer	Cimini and Moresi, 2016
CSD	Amienyo et al., 2013
Wine	Fusi et al., 2014; Bonamente et al., 2016
Canned tuna	Avadì et al., 2015; Hospido et al. (2003)

5. Sustainability-oriented strategies through the improvement of packaging efficiency

5.1 Packaging lightweighting

Packaging materials, as well as other resources used in the production of a food product, should be minimized. This does not mean that packaging should be avoided, as it is undoubtful that packaging represents an essential element for the quality preservation of food products, and modern foods could not be conceived without their packaging. Packaging should be optimized in order to use as minimum materials as necessary to fulfill its protective functions. Packaging lightweighting, i.e., the adoption of thinner and/or lighter packaging materials, reduces the use of resources and, obviously, represents the first simple strategy toward waste prevention. In the last decades, glass, aluminum and steel containers have been significantly lightweighted, as well as PET bottles and paperboard (Marsh and Bugusu, 2007). Since packaging lightweighting also implies a reduction of costs for the producer, this concept might sound obvious and packaging minimization should be taken for granted; however, many commercial cases demonstrate that this theme still carries significant improvement potential (Licciardello, 2017). Overpackaging, that is the unnecessary use of packaging materials, is, in fact, an underestimated issue. Packaging systems are often oversized, and, in some cases, it has been demonstrated that a significant reduction of thickness is possible, with noticeable economic and environmental benefits, which do not compromise the package performance. The optimization of packaging systems implies the verification of such performances by comparative shelf life testing, whose aim is to prove that the alternative system guarantees the same shelf life standards as the conventional system. As an example, a recent study (Licciardello et al., 2017) evaluated two alternative packaging systems for industrial durum wheat bread, commercially available in a two-piece form-fill-seal packaging system made of a thermoformed bottom and a lid. The packaging system identical to the one in use, but with lower thickness (about 20% lightweighting) was able to guarantee the same shelf life standard, as evaluated by instrumental and sensory analyses. In particular, the two packaging systems had the same barrier to gases, thus allowing the preservation of the modified atmosphere conditions. The other candidate was a flow-pack system with a 62 micron-thick co-extruded film, allowing an even higher lightweighting: in this case the performances of the system were slightly lower, causing a shelf life reduction which could still meet the requirements for a local distribution of the product. Soft drinks companies keep on trying to reduce the preform weight, which might be possible with new PET grades and bottle design (Coriolani et al., 2006; Licciardello et al., 2011): in this case, the comparative shelf life tests are made easier by the mere consideration of carbon dioxide retention inside the bottle, that is the key quality parameter determining the shelf life of such products. Packaging lightweighting remains an underestimated strategy for many food products, but it represents the easiest and more affordable measure for sustainability improvement of food packaging. Lightweighting could be achieved by reducing thicknesses for the same material and/or adopting composite structures with higher performances: however, sustainability-driven packaging reduction should be addressed under an end-of-life perspective, preferring monomaterials instead of composite multilayer materials (wherever possible), which bring higher performances but are less recyclable. Indeed, recyclability could be the downside of lightweighting when alternative multilayer/composite materials are considered.

5.2 *The choice of packaging materials with a focus on recyclability*

According to Peelman et al. (2013), sustainability of food packaging can be achieved at three levels: (1) at the raw materials level; (2) at the production level, through more energy-efficient processes; (3) at the waste management level, considering reuse, recycling and biodegradation. Recycling diverts packaging from the waste stream (incineration or landfill) to recovery, through collection, sorting, processing, and manufacturing into recycled materials and products. Recyclability of plastic packaging depends, in part, on the efficiency of the collection and sorting systems. To these regards, recent data on the end-of-life of plastic postconsumer waste (PlasticsEurope, 2017) demonstrate that in 2016, for the first time, the level of recycling (31.1%) in Europe overcame that of landfilling (27.3%), while the remaining major fraction (41.6%) was addressed to energy recovery. According to these data (very uneven across the EU countries), from 2006 to 2016 the total amount of plastic waste collected increased by 11%, while recycling grew by about 80%. Similarly, the levels of plastic packaging recycling increased by about 75% in the same decade, and the average plastic packaging recycling rate across the EU countries was about 41%, well above the requested 22.5% of the EU Packaging Waste Directive.

The ambitious target to further increase plastic packaging recyclability through improved selection and recovery implies redesigning packaging through an end-of-life thinking approach. The adoption of high-performance composite materials, in the last decades, has contributed to reduce the packaging amounts but, on the other hand, has worsened the end-of-life scenario for plastic packages, whose recyclability is limited to PET and HDPE. Composite multilayer films, which are made up of two or more layers, and are designed to combine the performances of different materials into one single structure: they include materials made of different plastic layers, or combining plastic (especially, polyethylene) with aluminum and paperboard (multilayer cartons). In particular, multilayer structures are designed to improve the gas and moisture barrier of films for application to modified atmosphere- or vacuum-packaged products and to moisture-sensitive foods, allowing the extension of the shelf life by keeping the modified atmosphere (or vacuum) for a longer time and by minimizing the moisture transfer, respectively. Sorting and recycling plants are equipped with optical devices (usually, Fourier Transform Near-Infrared, FT-NIR) able to identify different polymers, however, the coupling of different materials into one structure makes it impossible, at the actual state of technology, to correctly process each component (Ragaert et al., 2017), thus addressing the material to the unsorted fraction and to energy recovery (pyrolysis), in the best scenario.

Lightweighting design of packaging has widespread at the expense of recyclability, in the wrong understanding that reducing the weight of a package is so resource-efficient that its recyclability can be neglected (Scriba and Germany, 2016). However, the most recent innovations in the field (i.e., nanotechnologies) have paved the way to the improvement of packaging performances which might not affect recyclability. The plastic packaging sector, where possible, has the responsibility to revert to materials which guarantee good recyclability, primarily mono-PET. Similarly, the choice to adopt black-dyed plastic trays for some applications (such as meat), driven by market needs, has not taken into consideration the end-of-life of such packages, which cannot be sorted by the current optical sorting equipment due to their color. Based on the above considerations, the choice of mono-materials, with improved recycling potential, as well as lightweighting design, could significantly contribute to the improvement of resource efficiency for packaging materials.

5.3 The shift to biobased plastic materials

The search for packaging materials sources alternative to oil-based materials is another target toward sustainability, and this objective was included among the three levels to tackle sustainability of food packaging proposed by Peelman et al. (2013). The use of synthetic plastic has posed serious ecological problems due to their nondegradability and to the depletion of fossil resources. Bioplastics have recently been proposed as alternatives, at least for certain applications, to fossil-based, nonbiodegradable, plastics. According to the European Bioplastics Organization

(EUBP, www.european-bioplastics.org/), "bioplastic" is the word to be used to indicate plastics (1) which are "biodegradable", (2) which come from renewable resources ("bio-based"), or (3) having both these features, i.e., are biobased and biodegradable. Indeed, bioplastics are not a single kind of polymer but rather a very heterogeneous family of materials.

(1) There actually exist some fossil-based polymers which are biodegradable: it is the case of some PVOH formulas (Polyvinyl alcohol, also named as PVA), an array of water-soluble polymers showing high gas barrier properties, PCL (Polycaprolactone), a polyester with a low melting point widely used in polyurethane adhesive, PBS (Polybutylene succinate), a thermoplastic polymer with properties comparable to polypropylene and few other minor resins. All these polymers, according to the EUBP's nomenclature, deserve to be named as "bioplastics", though they are oil-based.

(2) "Biobased" bioplastics are, instead, materials based on renewable resources and they can be biodegradable or not. The second EUBP class of bioplastics corresponds to biobased, nonbiodegradable, plastics. Nowadays it has become possible to synthetize conventional plastic from precursors obtained from renewable sources. For instance, PP (polypropylene), PE (polyethylene) and other useful resins, can be produced starting from ethanol and other small molecules obtained by biomasses and sugar fermentation. Ethylene, for instance, is obtained by the catalytic dehydratation of bioethanol, followed by normal polymerization to produce low and high-density polyethylene (LDPE, HDPE). The ethylene obtained from bioethanol may be also dimerized to produce n-butene, which reacting with ethylene can lead to PP. These Bio-PP and Bio-PE are exactly alike the conventional polymers obtained through oil cracking and chemical synthesis; hence they are not biodegradable but, coming from renewable resources, they are very interesting anyhow. It is worth reminding that these polyolefinic polymers, together, currently account for about 55% of all plastic and 70% of plastics for packaging. Bio-PP and Bio-PE, due to their origin, show carbon neutrality and do not contribute to fossil depletion, making energy recovery even more attractive, and contribute to a circular economy. Among durable plastics obtained from renewable resources, biopolyethylene terephthalate (bio-PET) represents a case of success, which has achieved wide commercial exploitation. PET is a polymer (polyester) obtained mainly by direct esterification of 30% mono-ethylene glycol (EG, $C_2H_6O_2$) and 70% terephthalic acid (TA, $C_8H_6O_4$) or by transesterification of dimethyl terephthalate with EG (Xiao et al., 2015). PET is one of the most widely produced polymers, whose main application is in the food and beverage sector (bottles, trays, films). EG, which represents 30% of the PET composition, can be obtained through direct conversion of lignocellulose in the one-pot process with tungstic catalysts under hydrothermal conditions (Wang and Zhang, 2013): in this process, the carbohydrates of cellulose, hemicellulose, and sugars are selectively transformed into EG with high yields of 60−76%. Unlike the conventional oil-derived EG, the biomass-derived EG (bio-EG) can contain small amount of other diols, as the byproducts in the catalytic conversion of biomass. However, it has been demostrated that bio-PET prepared with bio-EG at purity higher than 95% could be used as widely as the conventional oil-PET resin without significant changes in their performance (Xiao et al., 2015). TA, which accounts for the remaining 70%, is normally obtained from paraxylene, which typically is oil-based, but new technologies (not yet on the market) converts biomasses into paraxylene or muconic acids to obtain bio-TA (Brandvold, 2012) that might make possible a 100% bio-based PET. In 2009 The Coca-Cola Company launched the PlantBottle program, aimed at distributing beverages in fully recyclable PET bottles obtained in part from plant material. By 2015 (Ren et al., 2015) the use of PlantBottle packaging since launch had helped save the equivalent annual emissions of more than 315,000 metric tons of carbon dioxide. Together with the challenge to commercialize 100% plant-based PET, the Coca-Cola Company set the target of having all the new PET packaging containing PlantBottle packaging material by 2020. In every case, being the bioplastic chemically identical to the oil-based polymer, performances and uses remain the same as for the conventional polymer. Currently, the bio-PET market is already quite interesting worldwide, accounting for more than one fourth of the overall bio-based bioplastics (see Fig. 6.3).

Other biobased, nonbiodegradable materials can be obtained, as well as bio-PET, from monomers produced by bioprocesses employing metabolically engineered microorganisms (so-called "biorefineries") (Chung et al., 2015). These include polyamide precursors (diamines, dicarboxylic acids, amino acids), and polyester precursors (diols and hydroxy acids).

It is worth reminding that all the biobased plastics (biodegradable or not) nominally belong to the category of "bioproducts", which have been already properly defined by various institutions. According to the European Committee for Standardizations (EN 16575) they are "products that are wholly or partly derived from biomass of biological origin, such as from trees, plants or animals", which "may have undergone some kind of physical, chemical or biological treatment before being turned into the intermediate, material, semifinished or final product, called bio-product". In other words, the extent of "biorefinery concept" is huge, and its potential is continuously increasing (Cherubini, 2010). When the production of potential biobased chemicals, and particularly bioplastics, is concerned, elevated costs and long implementation times must be taken into account. In such cases, computational tools can be very useful to explore the biological and technical spectrum of feasibility (Campodonico et al., 2018).

The wide definition of bioproducts, as well as the fast growth of this technological area, poses also a problem of authenticity, i.e., how can we be sure about the biobased nature of the packaging material selected? Indeed, a significant contribution has been offered by the assessment of biogenic carbon derived from biomass, implemented in various standard. A well-established method for measuring the biobased carbon content in a product is the ^{14}C-method, present in official standards in EU and in USA (EN 15440, ASTM 6866). A bioplastic may also be specified by the percentage of the overall biobased mass. This method, complementary to the ^{14}C-method, takes into account other chemical elements such as oxygen, nitrogen, and/or hydrogen. Some certification schemes and derived product labels based on European and US standards are already available (Kale et al., 2007; Tellnes et al., 2017).

(3) The third category, according to European Bioplastics Organization's classification, refers to biobased plastics that are also biodegradable or compostable. It should be emphasized that biodegradability is different from compostability. The term "biodegradability" refers to the possible biodegradation phenomenon, which is a chemical process during which microorganisms in the environment, or other biological means, convert materials into natural and simple substances such as water, carbon dioxide, methane and others. This phenomenon can occur both in aerobic and anaerobic conditions and a number of different factors determine the rate of the process and the final products. Almost all materials are subject to biodegradation processes, but the discriminants are the rate of the process (it can be too low for humans' expectations) and the consequences of such processes. Depending on the material, it is also possible that the biodegradation leads to harmful substances absorbed by the soil. The term "compostability," on the contrary, refers to aerobic process only and its definition, including the timeframe, the level of biodegradation, the surrounding conditions and the safety of final products, is much more precise and useful.

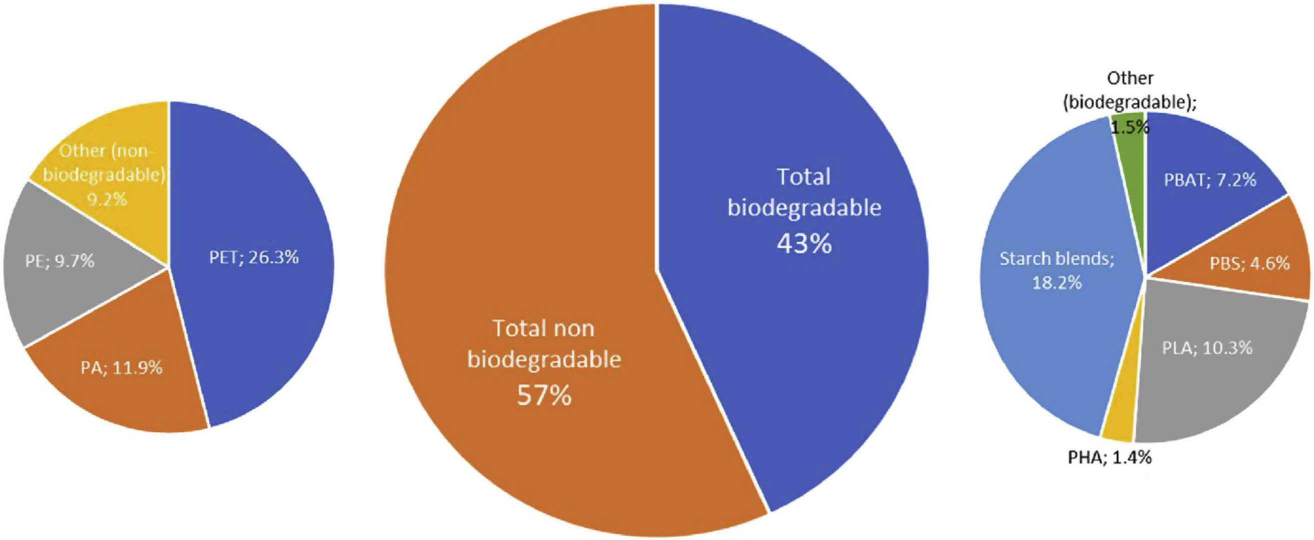

Figure 6.3 Global production capacities of bioplastics.
European Bioplastics—nova institute. http://www.european-bioplastics.org/market.

Moreover, compostability can rely on specific standard references, applicable both to packaging and plastics (ISO 17088, EN 13432, EN14995 or ASTM D6868). In the latter class of bioplastics (biobased and biodegradable) we find PLA (polylactic acid or polylactide) which is a very promising thermoplastic polyester derived from corn starch, cassava roots, or sugarcane. PLA is versatile, compostable and recyclable and it is characterized by very good optical properties, good processability, high resistance to water solubility (Siracusa et al., 2008). PLA also offers the possibility to be thermoformed, and the PLA granule can be expanded, offering a valuable alternative to expanded polystyrene (EPS) to produce trays addressed to the packaging of fresh products (meat, cheese, vegetables). The most common route to PLA is the ring-opening polymerization of lactide with various metal catalysts in solution but a huge number of studies have been carried out on this bioplastic (Farah et al., 2016; Bajpai et al., 2014), trying, in particular, to overcome its poor gas barrier properties by means of nanocomposite technology and green materials (Ortenzi et al., 2015; Gazzotti et al., 2017). A second class of biobased, biodegradable bioplastics, quite interesting for packaging applications, are the PHA polyesters (Polyhydroxyalkanoates), produced through bacterial fermentation of sugars or lipids. More than 150 different monomers are known with extremely different properties, but always biodegradable. In particular, the development of polyhydroxybutyrate-valerate (PHB−V) copolymers, is a promising route both under the technological point of view, since the materials have properties suitable for some food application, and under the sustainability aspect, as these biopolymers can be obtained through microbial fermentation of various substrates, including organic wastes, and are fully biodegradable (Guillard et al., 2018).

No less important is the class of thermoplastic starches (TPS). The characteristics of TPS bioplastics, in fact, can be easily tailored according to specific requirements. Starch-based bioplastics are often blended with PLA or PHA and to this class belongs the well-known brand of Mater-Bi products.

Whether simply biobased or also biodegradable, the use of these last bioplastics may result in environmental advantages in terms of safeguard of fossil resources, end-of-life, or both. Interestingly, it has been demonstrated recently that, also for compostable biopolymers, recycling represents the best end-of-life option showing the highest environmental benefits (Hottle et al., 2017).

Many applications of biodegradable/compostable, biobased bioplastics are already available, even if the commercial diffusion of such materials has been limited by costs and by their lower performances. Indeed, biopolymeric packages are usually more sensitive to high relative humidity, which acts as plasticizer thus compromising the structure and functionality. Anyway, technological limitations can be improved by tailoring the biomaterials to specific purposes. Other issues that limit a wider scaling up and market diffusion of biobased bioplastics are the raw material variability and the narrow processing window compared to conventional oil-based polymers (Guillard et al., 2018).

While the word "bioplastics" has been clearly defined by EUBP's classification (already discussed), there remains some ambiguity between the terms "biopolymers" and "bioplastics". "Biopolymer" relies on chemical and biological general nomenclature. Biopolymers are polymers, i.e., macromolecules containing arrays of monomeric units covalently bonded to form larger structures, produced by living organisms. There are various families of biopolymers, commonly classified according to the monomeric units; the most important and diffuse are: polynucleotides (RNA and DNA, composed of the 13 fundamental nucleotide monomers); proteins and polypeptides, which are polymers of amino acids, linked by peptide bonds; polysaccharides which are linear and branched carbohydrates polymers, such as starch, cellulose, chitin, glycogen. More complex structures (i.e., combined with molecules different from the main monomeric units) are also quite common in the wide category of biopolymers, such as rubber, suberin, melanin, lignin.

Based on the production process, biopolymers are generally classified into polyesters, starch-based polymers, and other polymers. Another classification depends on the source and includes polymers extracted directly from biomass (i.e., proteins, polysaccharides, lipids); materials chemically synthesized by polymerization from renewable monomers (e.g., polylactide, PLA); materials synthesized by microorganisms (polyhydroxyalkanoates, PHAs).

Unfortunately, the currently marketed bioplastics based on renewable resources compete with the food sources since they use corn starch, cassava roots or sugar cane, while a significant improvement, within a circular economy perspective, would be the development of processes for obtaining bioplastics from organic wastes (crop residues, sludges, agro-industrial by-products), fully biodegradable and which do not compete with food sources (European Parliament and Council, 2018a,b). Even though, the current estimates of the land use for bioplastics production (European Bioplastics, 2018) indicate a very small percentage (about 0.02%), less than 1/50 of what is used nowadays for biofuels which, in turn, is 1% of the global agricultural area, the debate about the use of limited resources such as the arable land is absolutely right and proper.

Beside starch, which is really a food biopolymer, our planet is a huge resource for two more carbohydrate biopolymers, which are chitin and cellulose, that mainly come from byproducts and biomass wastes. Both are extensively investigated for possible packaging application but not as such, rather as somehow modified forms of them, according to the bioproducts definition already proposed.

The great interest around the biopolymer chitin is related to its transformation into chitosan. Chitin, a long-chain polymer of N-acetylglucosamine, is a primary component of cell walls in fungi and of the exoskeletons of crustaceans and insects, it is also widely present in parts of molluscs, fish (scales) (Tang et al., 2015) and other living organisms. Chitosan is obtained by the deacetylation of chitin through an alkaline process; the degree of deacetylation ranges from 60% to 100%. Thus, chitosan is an etherogeneous linear polysaccharide, constituted by a randomly distributed β(1−4) linked D-glucosamine (deacetylated unit) and N-acetyl-D-glucosamine (acetylated unit). It has a number of commercial, even biomedical, uses but in the field of packaging it is worthy reminding its film forming ability and the antimicrobial activity which makes chitosan very interesting in active packaging materials. The antimicrobial function is related, very likely, to its positive charge: indeed, chitosan is one of the few natural polycationic polymers available.

The structures of chitin/chitosan are comparable to another polysaccharide, much more diffused and much more easily available than chitin, that is cellulose. Cellulose, unquestionably, is a true protagonist in the world of packaging materials. The packaging industry has always been using cellulose-based materials in huge amount. Currently, cellulosic packagings, include both wrapping materials and containers, primary and secondary packages, flexible and rigid packaging. The biggest part of the whole of packaging materials, is accounted, all around the world, for cellulosic materials with figures around 40% of the total (Li et al., 2015).

The biopolymer cellulose is generally recognized as safe, largely available, cheap and completely biodegradable. However, its most interesting packaging applications deal with modified cellulose. Regenerated cellulose (cellophane) had been the fundamental element in the development of flexible packaging. The clear, resistant and gas barrier thin films of cellophane dominated the flexible packaging scenario for many years, up to the development of plastic films and the affirmation of OPP and OPET films, in particular. The regenerated cellulose, however, in spite of its deep modification introduced by the manufacturing process (Kolpak and Blackwell, 1975), maintains its full biodegradability, at such an extent that cellophane has been used as benchmark in order to estimate the degradability of different packaging materials (Coma et al., 1994). Recently, very likely due to the environmental concerns, a revitalization of the cellophane sector has been noted and new products, certified as compostable, are available. Beside the market growing, also new processes with lower impacts on the environment have been proposed and extensively investigated for cellophane (Hudson and Cuculo, 1980).

However, the most significant innovations in the area of cellulosic materials come from nanotechnology and the production of cellulose nanocrystal (CNC), cellulose microfibrillated (MFC) and cellulose nanofiber (CNF). A discussion and some comments about these cellulose nanoparticles are proposed furtherly.

Both the improved recyclability of plastic packaging and the use of renewable resources for producing biobased and/or biodegradable packaging are complementary strategies targeting the sustainability improvement of packaging through the CO_2 emission reduction and the safeguard of fossil resources (Table 6.2).

6. Sustainability-oriented strategies through the improvement of packaging effectiveness

In the case of packaging, effectiveness can be declined into various meanings, under the common denominator of preventing food from turning into a waste. In this light, effective packaging should protect the food from physical damage and biochemical degradation, thus guaranteeing an adequate shelf life; it should allow an extended secondary shelf life and supply the suitable information to the consumer for domestic storage after opening; it should avoid leftovers and it should be easy to empty completely.

Table 6.2 Synopsis of commercial bioplastics and classification based on source and biodegradability.

Acronym	Full name	Source		Biodegradability
		Renewable	**Fossil**	
PVOH, PVA	Polyvinyl alcohol		CS	+
PCL, PLC	Polycaprolactone		CS	+
PBS	Polybutylene succinate		CS	+
PBAT	Polybutylene adipate terephthalate		CS	+
Bio-PP	Bio-polypropylene	CS		-
Bio-PE	Bio-polyethylene	CS		-
Bio-PET	Bio-polyethylene terephthalate	CS		-
PLA	Polylactic acid, Polylactide	CS		+
PHAs	Polyhydroxyalkanoates	SMO		+
TPS	Thermo-plastic starches	CS		+
Cellophane	Regenerated cellulose	CS		+
Chitosan	Chitosan	DFB		+

DFB: directly from biomass; CS: chemically synthesized from renewable material; SMO: synthesized by microorganisms

6.1 Redesign product-packaging configurations

In the last decades, family-sized packages have been proposed as the most convenient solutions, allowing the consumer to access food products at a lower cost per weight, and to use lower amounts of packaging. Actually, this trend has the hidden aim of increasing products purchase and consumption, since consumers are encouraged to buy larger pack sizes, probably exceeding their needs, because of quantity discounts. This commercial strategy had some merits, but it underestimated the waste increase potential. Indeed, the actual tendencies aiming at reducing food waste are proposing strategies able to minimize food waste potential: among these, the shift to smaller packages or single-serve formats and the adoption of reclosable packages may result in more packaging per serve, but the potential for food waste is reduced, meaning that, for some food categories, the overall environmental impact from the system will decrease (Wikström et al., 2014). Modern food industry is requested to redesign product-packaging configurations to help consumers reduce waste through convenience features (among which, package size); however, pricing policies need to support consumers to ensure they see value in the smaller pack sizes (and that they will not waste product) (Verghese et al., 2015).

6.2 Maximize packaging protective role

The design of packaging systems implies tailoring the packaging functions for the specific requirements of the food. Packaging protective function can be maximized exploiting the new concept of active packaging. This concept includes materials and devices able to offer additional protection to the packaged food by a tailored interaction with the food itself and/or with the package headspace. Active packaging has broadened the packaging potential to maintain food quality and is increasingly drawing the interest of the whole sector as a promising strategy for extending the shelf life of fresh and perishable foods. The European Regulation 450/2009 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*." A very high number of publications have focused on active packaging in the last decades, but the commercial exploitation of the findings has not been satisfactory, to date. An overview on this recent packaging innovation goes beyond the scope of this chapter but detailed information can be retrieved from valuable reviews on the theme (Fang et al., 2017; Francisco et al., 2015; Gómez-Estaca et al., 2014; Han et al., 2018; Ribeiro-Santos et al., 2017). The consolidated assumption that some increase in the impact of packaging could, in some cases, be justified by the achievement of significant waste reduction (Silvenius et al., 2014; Verghese et al., 2015; Wikström et al., 2018; Williams and Wikström, 2011) paves the way toward the commercial adoption of active packaging, especially for food products for which wastes account for a significant part of environmental impact.

Along with active packaging, “responsive packaging” represents an emerging field within packaging technologies, targeting the design of stimuli-response systems enabling real-time food quality and food safety monitoring or remediation (Brockgreitens and Abbas, 2016; Heller et al., 2018). The difference between this type of system and a typical active system based on diffusion and migration of an active compound into the food is subtle, but the distinction is important due to the engineered goal of the packaging. Active packaging systems based on the principles of diffusion are effective as soon as they come in contact with the food and do not respond to any change in food quality or food safety. On the other hand, responsive packaging operates “in response” to specific trigger mechanisms. An example of the former type could be a water-soluble film designed to release antimicrobials into the food only after the build-up of moisture inside the package, while an example of active packaging is a silver particle-embedded film, whose antimicrobial activity only depends on the diffusion of silver ions into the food (Brockgreitens and Abbas, 2016).

6.3 Nanotechnologies for packaging improvement

Nanotechnology deals with the manipulation of materials in the nanoscale (<100 nm). According to the EU definition (EU Recommendation, 2011), “*nanomaterial* means a natural, incidental or manufactured material containing particles, in an unbound state or as an aggregate or as an agglomerate and where, for 50% or more of the particles in the number size distribution, one or more external dimensions is in the size range 1−100 nm”. The application of nanotechnology in polymers involve the design, manufacturing, processing and application of polymer materials including nanoparticles. Nanocomposites are multiphase materials resulting from the amalgamation of matrix (continuous phase) and a nano-dimensional material (discontinuous phase) (Arora and Padua, 2010), the latter generally consists of nanospheres or nanoparticles, nanowhiskers or nanorods, nanotubes and nanosheets, or nanoplatelets (Bratovcic et al., 2015). Nanomaterials are mainly inorganic, such as clay and silicate, organoclays, graphene, and metal nanoparticles (Sharma et al., 2017). They display specific and improved physicochemical properties, owing to the small size of nanoparticles which are characterized by a very high surface-to-volume ratio and surface activity. These nanomaterials applied to packaging result in improved electrical conductivity, optical properties, thermal stability, flame resistance, durability and processability and, especially, they improve the mechanical and barrier properties of food packages, along with offering active packaging functions (Han et al., 2018; Sharma et al., 2017).

Also, organic and biobased nanoparticles, however, are gaining more and more interest in packaging applications. Both chitin and cellulose, the two most abundant biopolymers on the earth, are greatly investigated for their properties at nanoscale; a dimension which is generally reached by a fragmentation-top-down process.

Chitosan is easily obtained following treatment of chitin with an alkaline substance. Chitosan is a linear polysaccharide composed of randomly distributed β-(1 → 4)-linked D-glucosamine (deacetylated unit) and N-acetyl-D-glucosamine (acetylated unit). Chitosan nanoparticles are of particular interest in packaging because they are biodegradable and bactericidal; thus, in the perspective of more sustainable functional packaging materials. Chitosan is already approved as food additives in many countries and this pushes for potential applications since it is expected that its features can be enhanced by the nano dimensions (De Lima et al., 2010; Woranuch and Yoksan, 2013).

Concerning cellulose nanoparticles (CNs), their potential in packaging applications is, very likely, much wider; however, it must be related to their specific properties, which depend on the CNs morphology, their origin and the process used for their obtainment. Two main approaches are used for obtaining CN from cellulosic raw materials which are acid hydrolysis and mechanical treatments. Both the two processes, particularly the mechanical (high pressure homogenization treatments), can be aided by different pretreatments applied on the raw materials, that can be chemical, enzymatic or mechanical refining. The methods based on acid hydrolysis have been extensively investigated for nanocellulose extraction from various natural sources (Dufresne, 2017). The fundamental method is to split the cellulose chains, cleaving preferentially the amorphous parts of cellulose. Since the acid attack occurs much faster on the less dense amorphous parts, the result is the isolation of denser and crystalline particles with shorter chains. The nanoparticles obtained may have different morphologies and dimensions, according to the source of native cellulose broken down, but they are always indicated as cellulose nanocrystals (CNCs). Different acids have been tested and used in CNCs production and together with the acid, quite often, also oxidant species are used to increase the charge density and enhance useful properties for packaging applications (Mascheroni et al., 2016). The prevalently crystalline nature of the nanoparticles obtained by acid hydrolysis must be underlined with reference to potential packaging applications. The crystalline portion, indeed, makes a fraction of polymeric volume practically unavailable for transport phenomena. High crystallinity in polymers means tortuous path and high density to the diffusion of possible permeating gases and migrant substances, resulting in a sharp decrease in permeability and migration. Even a thin layer of crystalline nanocellulose, applied as coating, can provide a significant improvement in gas barrier and in other properties, very useful in packaging applications (Li et al., 2013). As highly hydrophilic biopolymers, however, CNCs have a strong sensitivity to water that can be detrimental for packaging applications with fresh foods or in moist conditions, due to water absorption and to the consequent loss of barrier properties (Fotie et al., 2017; Fotie et al., 2018). However, identical issues concern synthetic polymers like polyvinyl alcohol (PVOH) or ethylene vinyl alcohol copolymer (EVOH), which even show a lower gas barrier than CNCs. Therefore, the same solutions used for these common barrier materials can be used to overcome the limitations of CNCs; i.e., the lamination or the coating with a more hydrophobic layer in order to avoid moisture absorption.

The most common mechanical process used for CN obtainment is high pressure homogenization. The CNs produced in this case are long and very thin fibers with a major presence of amorphous parts. For the higher aspect ratio and the different morphology their properties are quite different in comparison with nanocrystals; these nanoparticles are referred to, depending on the dimensions, as cellulose nanofibers (CNFs), or microfibrillated cellulose (MFC) and mainly addressed to possible applications, different from packaging (Dufresne, 2017).

Nanomaterials carry the potential to develop innovative materials as well as to enhance conventional materials properties. However, an analysis of the state of the art of research on nanomaterials falls beyond the scope of this chapter, which aims at highlighting the potential of this advancing technology in a sustainability perspective. Nanotechnology-based packaging has the potential to tackle both efficiency and effectiveness of packaging. One of the most important issues in food-packaging material science is the improvement of gas or water barrier properties of materials used to package food products: this objective has mainly been pursued with the development of laminated multilayer packaging and composite packaging combining the properties of different materials, but the downside of the creation of such materials consists in the higher production costs and on the difficulties related to their recycling. The use of nanocomposite materials has been proposed for improving film mechanical performances and barrier properties, both in conventional and biopolymeric materials (Angiolillo et al., 2017).

Nanomaterials that play a role in barrier improvement are also referred to as nanofillers and nanocoatings. Nanofillers are a heterogenous class of materials characterized by high ratio of largest to smallest dimension. Due to their specific surface area, nanofillers provide a tortuous path for gas and water molecules, which are forced to travel a longer path to diffuse through the material.

The possible issues of excessive dilution of nanofiller and incompatibility between the matrix material and the nanoparticles may be overcome by coating technology, using very thin coatings of nanoparticles on various conventional and biobased materials. Li et al. (2015) proposed the use of cellulose nanocrystals applied in the form of thin coating on various substrates, dramatically reducing the gas permeability and enhancing other useful properties, such as coefficient of friction, transparency, and antifog properties. These functional coatings may improve, as well, the sustainability of packaging, by reducing the thickness of oil-based conventional plastic films.

Thus, nanoengineered materials would allow packaging lightweighting and performance improvement at the same time, which are two strategies corresponding to the concepts of efficiency and effectiveness, respectively.

Nanotechnologies offer the possibility to compensate for some of the lower performances of biopolymers, which represent one of the factors limiting their widespread adoption. Nanotechnology would also allow to improve conventional packaging performances without worsening recyclability, unlike conventional composite and multilayer materials: this is another aspect which focuses nanobased packaging in the direction of efficiency (recyclability), and effectiveness (packaging performances in food protection), together.

In the European Regulation No 10/2011 on plastic materials and articles intended to come into contact with food, it is established that "substances in nano form shall only be used if explicitly authorized and mentioned in the specifications in Annex I." Indeed, since nanoparticles exhibit chemical and physical properties that significantly differ from those at a larger scale, they "may lead to different toxicological properties and therefore these substances should be assessed on a case-by-case basis by the authority as regards their risk until more information is known about such new technology" (EU 1282/2011). Safety is the major drawback of nanotechnology applied to food and to food packaging: a plethora of studies have highlighted some harmful effects of nanoparticles on human health. In particular, nanoparticles can penetrate the human body by inhalation, ingestion or cutaneous exposure and cause various negative effects. For instance, silver nanoparticles are known to be genotoxic, cytotoxic and carcinogenic, they cause oxidative stress responses and decrease of viability in model cell systems (Pradhan et al., 2015); silica nanoparticles may be toxic through oxidative stress generation, leading to DNA damage and induction of apoptosis (Tarantini et al., 2015), and they have been found to induce allergic immune responses in mice (Yoshida et al., 2011). While, apparently, the cellulose nanoparticles (CNs) maintain the biodegradability of the original biopolymer and show very low ecotoxicity, cytotoxicity and genotoxicity (Li et al., 2013). However, the possible release of whatever type of nanoparticles is still considered with suspect and strongly feared. Nevertheless, it has been recently demonstrated that measurable migration may occur only for nanoparticles up to approximately 3.5 nm in diameter and higher dimensions are practically excluded from any diffusional migration phenomena. For 10 nm diameter particles, an apparent diffusion coefficient (D) of 1.1E-35 $cm^2\ s^{-1}$ was calculated theoretically in an LDPE host matrix and such extremely low diffusivity results in almost null mobility of the migrants and undeterminable risk of migration (Bott et al., 2014).

Despite the numerous positive effects of nanotechnology on food-packaging sustainability, the controversial safety aspects and the unresolved concern lets this technology as a promising perspective.

6.4 Correct shelf life assignment

Shelf life can be defined as a finite length of time after production (in some cases after maturation or aging) and packaging during which the food product retains a required level of quality under well-defined storage conditions (Nicoli and Calligaris, 2018). Shelf life, however achieved, should be objectively determined and effectively communicated.

The correct shelf life assignment has commercial repercussions, since the estimated length of time during which the product retains the required level of quality results in the "use by" or minimum durability date, according to EU regulation (EU 1169/2011). Unfortunately, this timeframe is often estimated without proper objective studies, and the shelf life indicated on the package label does not usually correspond to the actual quality level of the product. Often, small and medium food industries do not perform this evaluation based on reliable and objective shelf life studies but estimate durability following a prudential approach, i.e., assigning a minimum durability date that is shorter than the actual shelf life based on the variation of quality indicators. While this approach is simple, cost-saving and guarantees that consumers purchase products with a high-quality standard, it results in a high amount of food turning into a waste, even when their quality is still within the limits of acceptability. Shelf life underestimation generates food waste and represents an important issue for the whole food system in a sustainability perspective. In this light, the conduction of shelf life studies based on systematic approaches in highly recommended (Nicoli, 2012; Robertson, 2009).

Moreover, consumers are often confused on the terms used on packages labels, and they throw away food right after the minimum durability date, in the belief that they will not be further suitable for consumption. A recent review of the history and current practices of date labeling concludes with a call to action to move toward uniformity in date labeling (Newsome et al., 2014). Food shelf life communication effectiveness and consumer education are as important for food waste reduction as any other strategy discussed above.

Another issue related to shelf life assessment and communication is the durability of products after opening, the so-called secondary shelf life. Again, this represents an underestimated issue (Nicoli and Calligaris, 2018) as far as food waste reduction is concerned. In a variety of situations, both at consumer level and at industrial level, the consumption of food (or the use of ingredients and semimanufactured products) is spread over a certain length of time after pack opening, hence a time period during which the product maintains an acceptable quality level should be defined. Moreover, suitable strategies for the extension of secondary shelf life, such as resealable packages and active packaging systems based on specific trigger mechanisms (moisture or gas changes after opening) would help save food from turning into waste and represent interesting actual research topics.

7. Conclusion

Sustainability of packaging is usually claimed in terms of resources (renewable, biobased) or with respect to the end-of-life (biodegradable, compostable), even if the environmental benefits are not always proved. Other than for the supposed or proved environmental benefit, packaging could be referred to as "sustainable" as a consequence of its improved effectiveness and for its potential to reduce the amount of food that turns into waste. The production of food, whether consumed or not, carries environmental impact, thus, reducing the amount of food that is wasted determines a net reduction of unnecessary impact. Since a significant fraction of food wastage is avoidable and occurs during the commercial phase and in households, there appears with evidence the potential of food-packaging design at reducing the amount of food that turns into waste. Sustainability of food packaging can be pursued through actions focusing on the improvement of efficiency and others targeting effectiveness. Ideally, a fully sustainable packaging should comply with all measures proposed within each category, however, priority strategies should be selected considering the balance between the environmental impact linked to the packaging and that arising from the food production. The estimation of this balance, whether the packaging relative environmental impact or the FTP ratio, gives an immediate indication on whether it is more "environmentally sound" to invest in the reduction of packaging impact, through lightweighting, shift to mono-PET and other fully recyclable materials and adopt biobased materials, or to mainly target food waste reduction, with packaging innovations guaranteeing higher protective performances and/or redesigning the package configuration, even if such measures imply some impact increase. 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.

New technologies and materials are available today and offer enormous potential for sustainability improvement. Biodegradable and/or compostable materials could finally penetrate the markets thanks to the forthcoming legislation banning the use of single-use plastics in Europe, however, no less care should be addressed to the management of biobased materials waste, as recycling seems to be the best end-of-life option. Nanotechnologies which have emerged as a panacea in the food and packaging industry actually carry serious safety concern and, to date, cannot be considered as viable tools for sustainability improvement in the food system, however, nanotechnology-based packaging has the potential to tackle both efficiency and effectiveness of packaging.

Each single actor of the food system holds responsibility in terms of environmental sustainability: consumers are expected to reconsider their attitude toward food waste and packaging, and to adopt more responsible purchasing and waste sorting behaviors; food companies and packaging manufacturers are responsible for the packaging choice and design, especially preferring mono-material and biobased packaging, and for a correct shelf life assignment; the institutions have already undertaken measures to reduce plastic waste and to favor the commercial diffusion of bioplastics, but still have responsibility in consumers education and awareness-rising on the theme.

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