Sustainable Packaging

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SUSTAINABLE PACKAGING

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1 Introduction

Food packaging materials are traditionally nonrenewable ones, except for paper-based products. In effect, fossil resources could be considered as bio-based and renewable materials but it takes more than a million years to convert biomass into oil used for plastic production. Since the use of crude oil is faster than the replacement of biomass, an imbalance in the carbon cycle is recorded.

From the beginning of the 20th century, increasing interest is being given to environmental concerns, racing the replacement of petrochemical-based resources by biologically derived resources. Plant-derived products and by-products obtained from their fermentation were the most interesting candidate for plastics packaging production. Such products, named bio-based packaging materials, have been defined by Robertson (2013a) as "materials derived from primarily annual renewable sources." Starch and cellulose films, polymers obtained from fermented organic materials together with edible films and coatings are included in this definition. At present, the term bio-based plastics means plastics obtained from bio-based materials. Both academia and industry are interested in such materials but their commercial use is still in progress with the hope that in the next decade the situation will change (Peelman et al., 2013). In 2010, the consumption of bio-based packaging materials was about 125,000 tonnes, very far from the 100 million tonnes of petrochemical-based plastics used for the same packaging purpose (40% of the 250 million tonnes produced every year). It takes many years to replace petrochemical plastics with bio-based materials. The driving force of this development could be the interest for a more sustainable packaging industry. Solid waste and litter problem together with the terrestrial and

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marine environmental pollution coming from the use of plastic materials could be the key of the bio-based packaging materials development. Since the production of packaging represents one of the most consistent causes of material-related environmental impacts, innovative tools have been designed for improving the environment as well as the economic performance of packages. At a global level, there is a strong interest in bio-based materials as a tool to address the food industry needs, to control the production chain, first of all by reducing material wastes. The aim is to assess and consequently reduce the environmental impact associated with the production, use and disposal of food packaging materials. In particular, edible, bio-based, and biodegradable materials obtained from renewable resources are driving ambitions to replace the packaging materials, coming from nonrenewable resources, to achieve a more sustainable development of the packaging industry.

2 Packaging Materials in the Food Industry

Various shapes of packaging materials are present in the food market, with a wide range of functions correlated to their properties. As reported in Fig. 1, a good balance between shape and function is required.

Taking into consideration that the most important feature is to preserve, contain, and protect food during the whole shelf life, the choice of the most suitable packaging material is dependent on several factors. The possible shape could be between a rigid (bottle, jar, can, cap, tray, and tank), a flexible (bag, foamy trays, shrink, bubble, cling wrap, squeezable tube, stand-up packet, and vacuum bag), and a semiflexible packaging (caps and closure, box, tetrapack, and multimaterial). Packaging must show several functions such as protecting food from oxygen, temperature fluctuation, moisture, light, preserve foods from biological microorganism's attack, physical protection from damage while reporting information about the food product, and its identification. Obviously the chemical-physical properties, mechanical performances, gas barrier behavior, and optical characteristics are the key factors in the choice of the most suitable material.

Among the different materials present in the food market, synthetic plastics packaging coming from petroleum resources are the most used thanks to their several positive features such as low-cost, easily processability, economic starting resources, light weight, flexibility, transparency, impermeability, easy of sterilization, and so on. The most common synthetic polymers used for food packaging application are the well-known polyolefins

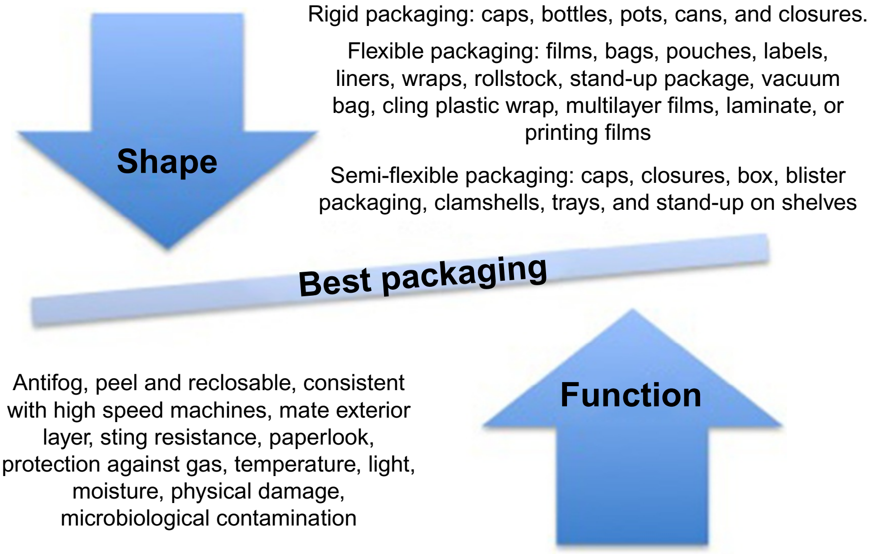

Fig. 1 Balance between shapes and functions of packaging materials.

such as high-density polyethylene, low-density polyethylene, and polypropylene, the substituted olefins such as polystyrene and oriented polystyrene, polyvinyl alcohol, polyvinylchloride, the polyesters such as polyethylene terephthalate and polyethylene naphthalate, and their copolymers, the ethylene polymers such as ethylene vinyl alcohol, ethylene vinyl acetate, and polyamides such as nylon and aramids.

As reported from PlasticsEurope (2016), the main market sector for plastic materials demand is related to packaging (Fig. 2):

Considering that petroleum-based polymers are not degradable and not eco-friendly, bio-based plastic materials are gaining even more attention as a possible food packaging substitute. At a global level, there is a strong interest in developing new sustainable packaging solutions with the principal focus being in reducing wastes while assessing the environmental impact associated with its production, use, and final disposal.

3 Bio-Based and Biodegradable Food Packaging Materials

According to the definition of European Bioplastics, polymers obtained from renewable resources could be classified into three categories, depending on the origin of the raw materials and on the method of production (Siracusa, 2016; Robertson, 2013a):

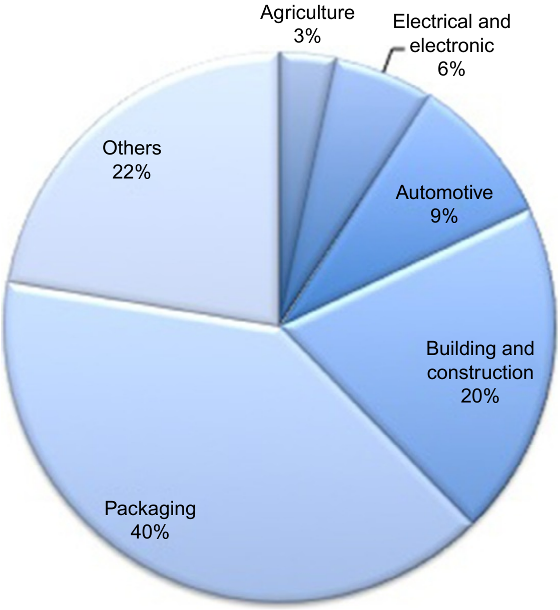

Fig. 2 Main sectors of plastics materials demand. Data from www.plasticeurope.org.

1. Polymers extracted directly from biomass such as polysaccharides obtained from starches of potatoes, rice, corn, maize, and wheat, from hemicelluloses of barley, from gums of guar, alginate, carrageenan and pectin, and from chitosan and chitin, and polymers extracted from animal proteins (such as casein, whey, collagen, and casein) and from plant proteins (such as zein, soy, and gluten).
2. Polymers obtained from monomers synthesized from renewable resources (named bioderived monomers) such as polylactic acid, bio-polyethylene terephthalate, and bio-polyolefins such as bio-polyethylene.
3. Polymer obtained directly from microorganisms such as the family of polyhydroxyalkanoates such as polyhydroxybutyrate, polyhydroxyvalerate, and polyhydroxybutyrate-*co*-valerate copolymers.

In this classification could be also included biodegradable materials obtained from monomers coming from petroleum resources such as polybutylene adipate and its copolymers with polyethylene terephthalate, polybutylene succinate and its copolymers with polybutylene adipate, polycaprolactone, polyglycolic acid, and polypropylene carbonate; that could be considered as the fourth category. It must be kept in mind that biodegradability depends on the final chemical composition of the polymer chain and not on the origin of the raw material. Consequently a biodegradable polymer could be obtained from monomer coming from renewable or petrochemical resources.

The biodegradation of plastics depends on the chemical structure of the polymers or copolymers, as well as on their crystallinity and molecular weight, and of environmental factors such as temperature, oxygen, moisture, sunlight, and so on. In general, bio-based polymers contain ester, amide, or carbonate hydrolyzable groups in the polymer backbone, which are susceptible to the degradation process by the action of natural microorganisms, converting the material into water, carbon dioxide and biomass (Siracusa et al., 2008).

As reported from European Bioplastics (2013) the worldwide capacity of bio-based plastics is expected to increase from 1.4 Mt (2012) to above 6 Mt (2017). The most important products in terms of production volumes were bio-polyethylene terephthalate (about 39% of global production), followed by bio-polyethylene, polylactic acid, and other biodegradable polyesters (each category sharing 13%–14% of the total market) (Fig. 3).

3.1 Polymers From Biomass

These materials, coming from marine and agriculture resources, are characterized by a high crystallinity and strong intermolecular interaction. Therefore, a right combination of temperature, mechanical shear, and additives such as plasticizers is necessary to avoid degradation phenomena during the thermo-plasticization process.

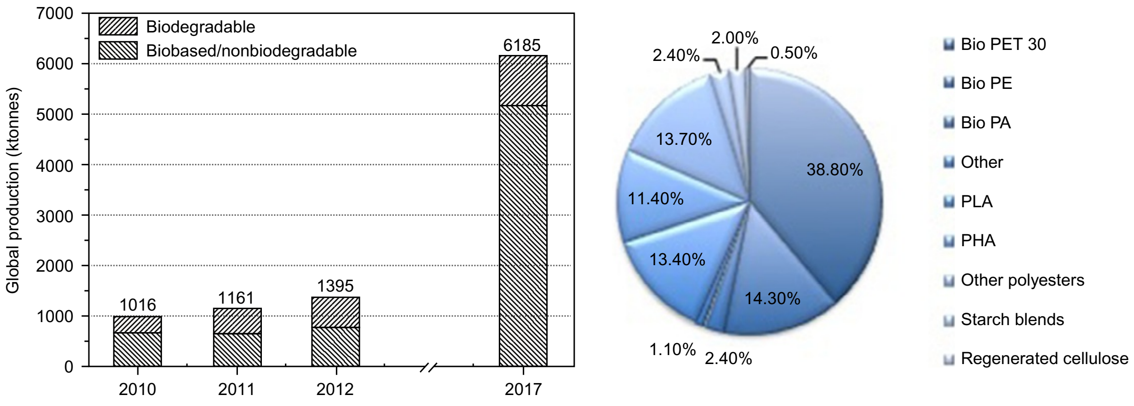

Fig. 3 Global production capacities of bioplastics (European Bioplastics, 2013) by material type. Data from www.plasticeurope.org.

The most used materials are those based on *starch* extracts from cereals such as wheat, corn, rice, and tubers like potatoes. To be used as packaging materials, starch products must be converted into thermoplastic starch materials (TPS). In this case, as the petroleum thermoplastic polymers, TPS can be extruded, injection molded, and blow molded at a temperature between 90°C and 180°C, under shear and in the presence of plasticizers. But, due to the large time required for the stabilization of its properties (several weeks), to the high sensitivity to water vapor and to the low mechanical performance, TPS are unsuitable for several applications. To improve their performance several approaches have been used. The blending with biodegradable petroleum-based polymers such as polycaprolactone, polybutylene adipate-*co*-terephthalate and polyvinyl alcohol improves their processability as well as their biodegradability, giving rise to acceptable barrier and mechanical properties and relative water resistance. The decrease of the water sensitivity was achieved by the chemical modification of the starch polymer chain, after the introduction of less hydrophilic acetate groups.

Cellulose films, obtained by chemically replacing the hydroxyl group with other functional groups, are used for packaging application. Cellulose is biodegradable but not a bio-based material because, being derived from trees, it does not meet the definition of a sustainable material. The commercial name of cellulose film is cellophane, which is a regenerated cellulose film (RCF). In the past, it was substituted by biaxially oriented polypropylene film but, due to the growing interest versus sustainable packaging, it is becoming again popular. RCF is not a plastic material because it cannot be hot pressed and melted. To be used as packaging materials it must be chemically modified or treated with different type of coating. Nitrocellulose is the most common film utilized to provide moisture barrier properties but also it could be used in combination with a polymer coating. Polyvinyl chloride-*co*-vinyl acetate coating is used to obtain a medium film barrier to water vapor, gases, and aromas, approved also for an oven and microwaves use up to 200°C. Polyvinylidene chloride coating is used as moisture barrier material and it could be also metallized. Low-density polyethylene coating is used for high O_2 permeability films for fresh meat packaging application. If three hydroxyl groups of the cellulose are replaced by acetate ones, the cellulose acetate is obtained, which can be formed as films, semirigid containers, and thermoformed blisters. Cellulose acetate is used for fresh fruits and vegetables because it has a high rate of water vapor and gas transmission. In recent years increasing interest was generated on the use of micro and nanofibrilles of cellulose

(MCF and NCF) for packaging application due to the fact that used in composite materials or in coatings and films they impart positive performance such as improved gas barrier properties, mechanical properties, and biodegradability (Spence et al., 2011; Sirò & Plackett, 2010). There is also a growing interest on *hemicellulose* (Hansen & Plackett, 2008) as bio-based food packaging materials, obtained from hard wood and barely but until now they are not present into the market.

Chitin and chitosan are two of the most studied chemical substances used to produce edible films and coatings with antimicrobial activity, for fresh fruits and vegetables. They present poor mechanical and water resistance. Polymers coming from proteins have not yet used as food packaging materials due to the difficulty in their processing, low thermal stability, incompatibility to the most polymers and high costs. They are very interesting as bio-based materials owing to their inherent biodegradability so their future application could be their application as edible films. The most commercialized protein packaging materials are that obtained from collage sausage casings while the most recent biodegradable thermoplastics is obtained from methyl acrylate graft polymerization of chicken feather, rich in β-keratins. Feather films obtained showed higher tensile properties than other soy protein and starch acetate bio-based films (Jin et al., 2011).

3.2 Polymers From Renewable Resource

Today, both academic and industrial researches are oriented versus bio-based alternatives to petroleum derivative materials, with enhanced properties for several applications such as the food's packaging field. The number of companies producing, processing, or using biomaterials is considerably expanding. As reported in Fig. 4, bioplastics are already employed in many different fields, ranging from rigid and flexible packaging to agriculture, from medicine and pharmacology to building and automotive.

The use of renewable resources is growing but, the obtained polymers, present several problems compared with the synthetic ones. In particular, they cannot be processed with traditional technologies and their functional and structural properties present less performance (Mensitieri et al., 2011). By tailoring their chemical-physical properties they become adaptable to specific processing and structural demands. For this purpose, additives such as stabilizers, plasticizers, antioxidant, fillers, and so on have to be added during the polymerization process. Further, blends, composites, and laminates between synthetic polymers and

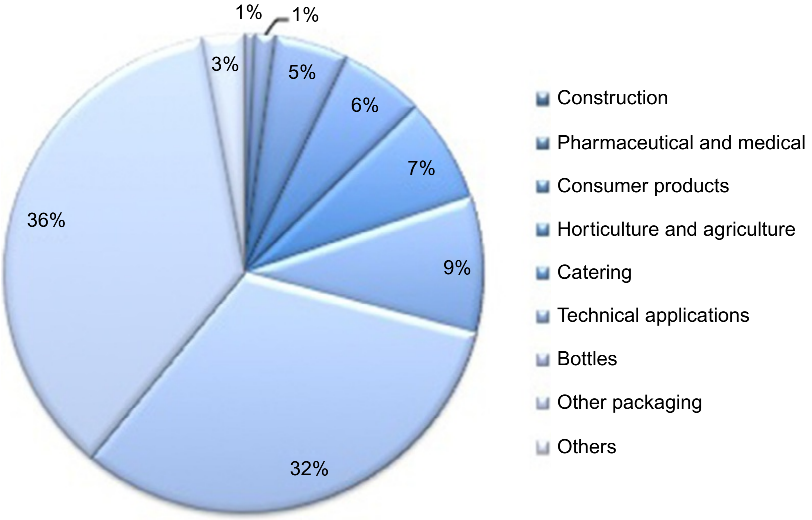

Fig. 4 Plastic materials demand of bioplastics in 2012 by market segments. Data from www.plasticeurope.org.

polymers obtained from renewable resources, have been studied, with the aim to expand the range of application (Siracusa et al., 2008; Mahalik & Nambiar, 2010).

Between all the bio-polyesters produced and present into the market, polylactic acid is the most commercialized one owing to its potential if compared with the synthetic polymers coming from petroleum (Auras et al., 2010). Polylactic acid is a linear aliphatic polyester that could be synthesized from lactic acid monomers obtained from the fermentation of glucose extract from starch in biomass (corn and wheat), from lactose in whey and from sucrose in molasses (Siracusa et al., 2012; Siracusa & Ingrao, 2016). The monomer could be also obtained by petrochemical route. Lactide monomer is a mix of L(+), D(−) and *meso*-lactide stereoisomers. The synthesis could be achieved by direct condensation or by ring-opening polymerization (ROP). The first approach, being an equilibrium reaction, gives rise to a low molecular weight polymer, due to the difficulty in removing the water during the last stage of polymerization where the molecular weight increases. The second approach, ROP, is a solvent free process, catalyzed by tin and zinc oxides or chlorides or by stannous-2-ethylhexanoate. The properties of polylactic acid, as well as the final molecular weight value, vary according to the ratio and distribution of the isomers. While the poly(L-lactide) and the poly(D-lactide) are semicrystalline polymers, the atactic polymer poly(D,L-lactide) is amorphous. The ratio between the crystalline and amorphous phase is determinant for the corresponding appearance of the polymer. The amorphous phase gives up a clear material while the crystalline phase of an opaque and white material. The corresponding transition temperature (T_g) and melting temperature (T_m) are important for commercial application of polylactic acid. The polymer is rigid due to the high-T_g value (50–60°C) but by the use of plasticizers additives the T_g could be lowered giving rise to polymer with a lower stress at yield and higher elongation at break, at room temperature (Siracusa & Ingrao, 2016). Polylactic acid is biodegradable at temperatures above the T_g and compostable in industrial composters.

Bio-polyethylene and bio-polyethylene terephthalate are two of the emerging polymers obtained from renewable resources. They are not biodegradable but they have the same properties, processing, and performance as polyethylene and polyethylene terephthalate made from natural gas or oil feedstocks. Bioethylene is produced starting from bioethanol obtained from the fermentation of sugarcane, sugar beet, and wheat grain. Bioethanol from sugarcane is produced mainly from Braskem with Toyota Tsusho Corporation and from Dow Chemical Company with Crystalsev. Recently, bio-propylene has produced bio-polypropylene (Robertson, 2013a).

For the production of bio-polyethylene terephthalate, the bioethylene glycol coming from sugarcane was used. The first product was commercialized from The Coca-Cola Company with the trade name of PlanBottle, where a 30% of bio-ethylene glycol was used by weight for the production of polyethylene terephthalate. To obtain a 100% bio-based materials the researchers are working on the synthesis of bio-terephthalic acid. PepsiCo also announced the use of a polyethylene terephthalate bottle made entirely with renewable resources coming from waste carbohydrate biomass obtained from the food industry such as orange peels, oat hulls, corn husks, and potato scraps.

Avantium company is developing a new 100% bio-based polyester with the same structure as polyethylene terephthalate obtained from bio-ethylene glycol and bio-terephthalic acid but also replacing the terephthalic acid by 2,5-furandicarboxylic acid, coming from the dehydration of carbohydrates, to produce the polyethylene furanoate (Smith, 2015). Polyethylene terephthalate is one of the most studied polymers to be transformed in commercial bio-based plastics. The interest gives life to a Technological Collaboration between Coca-Cola, Ford, Heinz, Nike, and Proctor & Gamble, with retailers and enterprises such as Avantium and Micromidas, to develop commercial processes for the production of bio-based polyethylene terephthalate and polyethylene furanoate.

3.3 Polymers From Microorganisms

This kind of polymers, obtained from microorganisms belong to the family of polyhydroxy alkanoates (Peelman et al., 2015). They came from renewable resources such as sugars and are biodegradable and biocompatible linear polyesters. In anaerobic environment, the degradation products are carbon dioxide and methane gases. The most common is the polyhydroxybutyrate, the polyhydroxyvalerate and their copolymers Polyhydroxybutyrate-*co*-valerate. The ratio between hydroxybutyric and hydroxyvalerate determines the final mechanical and physical properties such as flexibility, tensile strength, and melting point. If a high percentage of hydroxybutyrate is present, the copolymer is similar to polypropylene while if a high percentage of hydroxyvalerate is used, the corresponding polymer is similar to high-density polyethylene. Polyhydroxybutyrate-*co*-valerate copolymers have a good oxygen and aroma barrier behavior, good chemical and moisture performance. The mechanical behavior could be improved by copolymerization with other polymers and by inorganic materials. Thanks to the innovation in the production technologies, the price is lowering, becoming even closer to that of other biodegradable polymers such as polylactic acid. The most expensive phase is the carbon substrate production but researchers are currently working on low-cost substrates such as whey, wastewaters from olive mills, molasses, corn steep liquor, starchy wastewaters, and palm oil effluents (Koller et al., 2010). Bacterial synthesis is very expensive too, so genetically modified crops are taken into consideration for the production of polyhydroxyalkanoate that could be extracted from plant materials. This procedure is more difficult than those from microorganisms so this technology is still in progress.

An emerging technology is associated with the production of polymer films for food packaging industry from bacterial cellulose (BC). The corresponding polymers have a very low permeability to gases in the dry state but the permeability drastically changes if in wet ambient. To improve the barrier properties a chemical modification could be performed, such as acetylation, nitration, amination, and hexanoylation. Until present they are not commercialized and are studied only on a lab scale. They are also used as bio-reinforcement in nanocomposites.

3.4 Polymer From Petrochemical Resources but Biodegradable

In this category are included polymers coming from monomers obtained from nonrenewable petroleum resources, can be aliphatic polyesters or aliphatic-aromatic copolyesters and are biodegradable. Between them, the most common and commercial available are the Polycaprolactone, polybutylene adipate-*co*-terephthalate, polybutylene succinate and its copolymers, polyglycolic acid and polypropylene carbonate. Polycaprolactone is obtained by ROP of ε-caprolactone, which is obtained from the oxidation of cyclohexanone. Owing to its high cost it is not used for large-scale packaging application. The most commercialized one is under the trade name of Mater-Bi from Novamont where, to increase the biodegradability and lower the cost, it is mixed with starch. Starch-polycaprolactone copolymers with up to 20% of polycaprolactone content show good oxygen barrier behavior but by increasing the content of the gas barrier properties deteriorate while the water vapor barrier improves.

Polybutylene adipate-*co*-terephthalate in obtained by polycondensation of 1,4-butanediol, Adipic acid and Terephthalic acid. It is an aliphatic-aromatic copolyester with mechanical performance similar to those of polyethylene. The commercial name is Ecoflex, commercialized by BASF, and used as food packaging material for fresh meats, fruits, and vegetables. It could be blended with other biodegradable polymers such as polylactic acid or starch to tailor the physical-chemical, mechanical and barrier properties (Wang et al., 2016).

Polybutylene succinate and poly(butylene succinate-*co*-adipate) are obtained by polycondensation of succinic acid (or dimethyl succinate) or adipic acid with ethylene glycol or 1,4-butanediol. The monomer could be obtained from both renewable and nonrenewable resources. The trade name is Bionolle and is commercialized from Showa Highpolymer. Thanks to their excellent processability using conventional equipment they can be injected, extruded, and blown. When terephthalic acid is used the corresponding polybutylene succinate-*co*-terephthalate is obtained while if succinic acid and 1,3-propanediol is used instead of ethylene glycol or 1,4-butanediol, the poly(butylene succinate-*co*-propylene succinate) is obtained. Recently a bio-1,3-propanediol was obtained from aerobic fermentation of corn glucose to synthesize the poly(butylene succinate-*co*-propylene succinate) copolyester (Liu et al., 2010).

Polyglycolic acid is obtained by polycondensation or ROP of glycolic acid. It is an interesting biodegradable thermoplastic aliphatic polyester, with superior barrier performances to both oxygen and carbon dioxide and excellent mechanical properties. It is employed in multilayer bottles with polyethylene terephthalate, for carbonated drinks. In combination with polylactic acid it was observed an enhancement of the biodegradable properties such as the barrier behavior. The trade name is Kuredux, commercialized in the United States, is certified as biodegradable material, with a rate of biodegradation similar to that of cellulose (1 month in compost) releasing water and carbon dioxide.

Polypropylene carbonate is an aliphatic polymer containing C—O—C bonds and C═O groups. It is a hydrophobic, amorphous polymer, with low T_g and thermal stability. To improve its mechanical and thermal properties, it is used for blending with other polymers. In this case biodegradable polymers such as polylactic acid, polybutylene succinate, poly(butylene adipate-*co*-terephthalate) and starch or nanoparticles such as montmorillonites could be used.

4 Edible Food Packaging Materials

The functions of edible packaging materials are very similar to those of synthetic and not edible ones. They have to be selective as barrier materials to control and limit the migration of moisture, gases, oil, fat, volatile flavor compounds and aromas from food, they have to enhance the nutritional and organoleptic properties of packed food while improving or at least maintaining the mechanical performance. But, the most important feature is their resistance to the migration of water vapor to preserve the food deterioration. Due to the fact that these materials have a biodegradable nature, which is the most important benefit, there is a strong limitation on their use. In fact, they cannot replace the traditional packaging materials but they are used to improve the overall food quality to extend the shelf life of packed foods. As reported from Gennadios (2002), they present several positive features. They can be eaten together with the food because they are made with edible ingredient, they are useful to add elements such as flavor, colour, and sweet taste to the food, they can be used to add additional food nutriments such as proteins and, further, they can act as carrier for antioxidant and antimicrobial agents and as controller for the diffusion of preservatives from the surface to the inside of the packed food.

Edible packaging materials could be in the form of edible films, sheets, pouches, and coatings. While the first three types are stand-alone structure that could be placed on food or sealed into pouches, edible coatings are formed directly on the food surface as very thin layers (Falguera et al., 2011a,b).

To obtain the best edible materials several chemical parameters have to be controlled. First of all, the molecular weight of the polymer is very important, that must be high enough for a self-standing film. To improve the cohesion between film and food, long chain polymers with high polarity are required to increase the number of hydrogen bonds and ionic interactions.

Further, to enhance the properties of such edible bio-based materials, several additives are incorporated in the formulation. First of all plasticizers additives, such as saccharides (glucose, fructose, and sucrose), glyceryl derivatives (glycerol, sorbitol, and polyethylene glycols) and lipids derivatives, added to improve the film flexibility and strength. Emulsifiers additives, used to improve the films surface wettability and lipid dispersion. Antimicrobials additives, used to increase and prolong the shelf life of packed foods. In this case, much attention has to be given on the choice of the best agent because their interaction with biopolymer materials and the processing condition could alter their functionality. These additives could be used also to improve the nutritional value of food when used as carriers of substances. The most common are organic acids, chitosan, nisin, and essential oils (Sirocchi et al., 2017). It must be taken in mind that these agents are not a substitute for correct food manufacturing, but they are adjuvant for improving the overall food quality. Antioxidant additives are used on edible films to inhibit or delay the food oxidation process. They can act as oxygen scavengers, oxygen deactivation, and UV absorbing radiation or as a promoter of antioxidant activity of the antioxidant incorporated into the films. Citric and ascorbic acid, tartaric acid, herbs such as rosemary, sage, thyme, tea, and oregano are the most used. These additives are gaining even more attention by the researchers as well as from the industry as substitute on synthetic preservatives to achieve a more sustainable films formulation. Already carried out in the United States, the future could be the commercialization, of edible films obtained from fruits and vegetables (Martin-Belloso et al., 2009) such as broccoli, carrot, tomato, mango, apple, banana, peach, and pear.

One of the main problems of an edible coating for minimally processed fruits and vegetables is that the food surface is wet and remains like this for a long time. As a result there is a very low adherence of those films on the food surface with a consequent loss in efficacy. One possibility is to obtain dry films as for example by infrared drying technic (Martin-Belloso et al., 2009).

Several polysaccharides, proteins, and lipid coming from plants and animals could be used alone or in mixture to obtain the desired materials (Robertson, 2013a). In recent study, the tendency to produce edible films by combining various elements such as polysaccharides, proteins and lipids was expressed with the aim of taking advantage of the properties of each component.

Obviously, the final performance, such as mechanical and barrier behavior as well as transparency for consumer's acceptability, will depend on the compatibility and type used in the polymer matrix. The choice of the best edible film composition is one of the most important fields of research because it must be formulate according to the properties of fruits and vegetables to which it has to be applied, during the storage time (Rojas-Grau et al., 2009). Thereby, microbiological stability, adhesion, cohesion, wettability, solubility, transparency, mechanical, and permeability behavior to water vapor and gases, could be tailored and adapted to the final application by the optimization of their composition.

4.1 Polysaccharides Edible Films

Polysaccharide edible films are the most commercialized ones owing to their good mechanical performance, good gas barrier behavior and oils and lipids barrier, low-cost, being easy to handle and process. Due to their intrinsic nature, they are susceptible to humidity and low water resistant, which make them biodegradable materials.

Starch, a mixture of amylose and amylopectin, is the major compound studied. To improve water solubility, the esterification of amylose with propylene oxide, to give the corresponding hydroxypropylated materials, is used. They are mainly used for bakery, confectionary (such as chocolate), batters, and meat (Janjarasskul & Krochta, 2010). From the hydrolysis of starch a low molecular weight carbohydrate, named dextrin, is obtained and used as an edible coating, glue, and sealant.

Cellulose is the most abundant primary material. Before to be processed for packaging application, it must be chemically modified by substitution of the numerous hydroxyl functions with acetate or methyl groups. As a result, the reduction of the physical network and the decrease of the number of hydrogen bonds make it easier to process and be transformed into films. Being dependent on the chemical modification several types of cellulose materials could be obtained, with tailored properties such as solubility, mechanical properties, and oxygen and lipid barrier behavior. The most common are methylcellulose, hydroxypropyl cellulose, hydroxypropyl methylcellulose and carboxymethyl cellulose, with good film-making properties (Robertson, 2013a).

Hemicelluloses, polysaccharides coming from sugars such as glucose, xylose, mannose, galactose, rhamnose, and arabinose extract from barley, oats, corns, and maize brans are principally used as edible coatings.

Chitin, present in the exoskeleton of arthropods and in the cell walls of insects, which is an acetylated polysaccharides and *chitosan*, obtained by deacetylation with alkalis of the chitin, are nontoxic polysaccharides approved to be used as food additives and as coating materials. Their properties depend on their molecular weight and on the degree of acetylation. Aider (2010) described well the characteristics of these materials and their potential application in the field of food packaging, particularly owing to their antimicrobial properties while Tamer and Çopur (2010) described the use of chitosan as edible coating for fresh-cut fruit and vegetables could increases the food shelf life while reducing the microbial activity.

Alginated coatings obtained from brown seaweeds are used to protect food against oxidation owing to their good oxygen barrier properties. *Carrageenan films* and *Agar films*, obtained from red seaweeds, is used thank to its properties to reduce moisture loss, oxidation and as carrier of antimicrobials for meat food.

Pectin coatings are used as retardant of water loss from food because when moisture evaporates they act as a sacrificial material. They also retard the lipid migration from food enhancing the appearance and handling of foods. Cagri et al. (2004) in their paper on edible films and coatings reviewed the various types of polysaccharide-based (cellulose, chitosan, alginate, starch, pectin, and dextrin), edible films that can be used as films to enhance the safety and shelf life of ready-to-eat foods.

4.2 Proteins Edible Films

Several proteins, proposed for the production of thermoplastic polymers, could be available as by-product from agricultural activities but also from biofuel processing for the production of bioethanol (Falguera et al., 2011a,b; Cuq et al., 1998).

Protein edible films and coatings are obtained from proteins coming from animals and plants such as collagen and gelatin, wheat gluten, corn zein, soy, rice, pea and whey protein, casein, egg white, fish, and so on. They present good flexibility due to the presence of large amount of hydrophilic substances such as glycerin and sorbitol. Naturally, they show good mechanical properties, optical performance, and barrier behavior against oxygen, carbon dioxide, and aroma. Due to their inherent hydrophilicity, and consequently good biodegradability, their mechanical performance and water vapor permeability could be compromized by changes in environmental moisture content. Those properties could be improved by chemical or physical cross-linking.

Collagen films are used for reducing beef exudation when defrosted to avoid colour depletion or lipid oxidation. When used for cooked meat they reduce shrink loss, absorbing exudate and increase juiciness.

Gelatin films are used for encapsulating oil-based and low moisture food ingredients owing to their ability in reducing oxygen and water vapor permeability and oil migration.

Milk protein edible films and coatings present reduced oxygen permeability, very important to avoid rancidity and lipid oxidation in fat food such as roasted peanuts, salmon, peanuts butter, mayonnaise, and chicken breasts.

Cereal protein edible films coming from zein, with high performance as barrier materials against oxygen, moisture and lipid, are used commercially for confectionery product such as candies, chocolate, and so on. As reported by Lia and Padua (1999), it is a better moisture barrier material than other protein material such as casein or polysaccharides such as starch, owing to its high content of nonpolar amino acid groups, with its hydrophobic behavior.

4.3 Lipids Edible Films

Since these materials have a low molecular weight and are not polymers, they cannot be used as films with defined characteristics. Thanks to their low polarity they are used as moisture barrier material. Wax from natural products such as carnauba, rice bran, bees, synthetic wax such as paraffin and mineral, and vegetable oils have been used to protect fresh fruits and vegetables. Despite the fact that they are used to protect the food surface, they can confer a waxy or a rancid taste to the food. Further, transparency could be affected as well as mechanical performance of the final polymer matrix. To overcome the poor mechanical strength, lipid compound can be used in combination with hydrophilic materials, forming an emulsion compound, or with a hydrocolloid film lipid layer by lamination. But, despite emulsion films are less efficient than laminated films due to the fact that lipids are not homogeneously dispersed, they have good mechanical performance and require simple processes for their manufacture and application. The smaller are the lipid particle size, the more homogeneously are distributed, with lower water vapor permeability (Falguera et al., 2011a,b; Cagri et al., 2004). Multilayer films are difficult to processes, depending also on the number of coatings. Shellac edible coating was used for confectionary and fresh products (Baldwin, 2007).

5 Bio-Composites Materials

To improve the mechanical and barrier properties of bio-based materials to make them competitive with petrochemical-based polymers, the most used tool is to mix them with nanoparticles, obtaining the corresponding bio-nanocomposites materials. In this case, inorganic and organic fillers with particular chemical functionalities, geometry and size are mixed with biopolymers, enhancing their properties and lowering their price (Sorrentino et al., 2007; Chivrac et al., 2009). The most affected properties are the mechanical, thermal, and gases permeability. In this case, it is very important to obtain a uniform dispersion of the nanofillers to assure a great polymer matrix versus nanofiller interfacial area and higher reinforcing effects. The most used nanocomposites for bio-based polymers are nanoclays and polysaccharides for polylactic acid, polycaprolactone, polybutylene succinate, poly(butylene adipate-*co*-terephthalate), polypropylene carbonate, poly(hydroxubutyrate-*co*-valerate), and polyvinyl alcohol (Tang et al., 2008). Gordon in its book described the use of such chemical on bio-based polymers, reporting the corresponding improvement on the chemical-physical, mechanical, and gas barrier properties (Robertson, 2013a). Several parameters have to be controlled to achieve the best affinity between the polymer and fillers. The most promising reinforcing materials are nanobiofillers such as cellulose nanowhiskers with large surface-to-mass ratio, high mechanical strength, flexibility, lightness, and also edibility, considering that they are obtained from hydrocolloids (Lagaron & Lopez-Rubio, 2011). A future application in the field of food packaging is not excluded (Azeredo et al., 2009; De Moura et al., 2009). Further, nanoparticles can be used as a carrier for antimicrobials and antioxidant additives, for increasing stability during storage, for reducing food spoilage, for maintain flavor, aroma, colour, texture, and so on.

6 Performances and Packaging Applications

The most important properties of bio-based materials for food packaging applications are the barrier and mechanical properties. Regarding the barrier properties, biopolymers show several problems, especially in high moisture condition. To improve such behavior one possible route is to coat them with synthetic polymers, limiting drastically their use as bio-based materials. It must be underlined that in literature several information are present about the water vapor transmission rate (WVTR) and gas transmission rate (GTR) but these information lack in precision due to the fact that most of the time data on sample thickness, temperature, and humidity at which measurements were made and variation in test methodology, crystallinity, amorphous content, and films preparation are missing. Therefore data reported in literature have to be used with caution for food packaging application. As an example, Siracusa and Ingrao (2017) reported a full gas barrier behavior study performed on several biaxially oriented polypropylene films, of different thickness, at different temperature, used for food packaging application. In this case, the influence of both temperature and thickness on the final polymer performances was reported and fully described. The same research could be performed on bioplastics materials because it was demonstrated that it is not always easy to compare data present in the literature with the experimental ones. The variation of data is correlated to several factors such as thickness, molecular weight, density, crystallinity/amorphous phase percentage of polymer matrix, and so on. Also, slight change in polymer formulation due to change in process conditions, should not be overlooked to not over or lower estimate the packaging performance requested to extend the food shelf life.

Between all the biopolymers, polylactic acid, and polyhydroxyalkanoates are the two materials with the lower dependence to the ambient humidity (Auras et al., 2004, 2006; Almenar & Auras, 2010; Bao et al, 2006; Thellen et al., 2008). Polylactic acid has a WVTR three to five times higher than the commercial polymers such as polyethylene terephthalate, high-density polyethylene, low-density polyethylene, and oriented polystyrene, while polyhydroxy alkanoates have a WVTR very similar to those of petrochemical ones. Polylactic acid has better O_2-TR properties than polystyrene but not as polyethylene terephthalate while polyhydroxybutyrate is better than polyethylene terephthalate and polypropylene with good fat and aroma barrier properties for food with short shelf life. To improve the barrier properties several techniques were proposed such as mono- or biaxially orientation, coating with organic layer such as SiO_2, metallization, blending with nanofillers for nanocomposites preparation (Cushen et al., 2012).

The most important parameters influencing the mechanical performance are the molecular weight, the chain backbone architecture such as the presence of linear and/or branched polymer chains, the ratio between the crystalline phase and the amorphous phase. Mono- or bi-orientation of the polymer chains improves the mechanical strength as well as the heat stability.

Change in crystallinity and molecular weight could allow to changes between soft and elastic to stiff and strength material. The most studied material was the polylactic acid, the most commercialized biomaterial. Plasticizers such as water, polyols, polyethylene glycol, and citrates were used to pass from a brittle to a ductile behavior for polylactic acid polymers, to produce a flexible films (Vieira et al., 2011; Cairncross et al., 2005; Almenar & Auras, 2010; Holm et al., 2006). McCarty et al. (1999) is the author of a patent describing the results obtained when PLA was blended with 20% of any biodegradable aliphatic copolyesters such as polycaprolactone, Ecoflex, Bionolle and polyhydroxyalkanoates. By tailoring the copolymer composition is possible to modulate the corresponding mechanical as well as thermal and barrier properties.

Also the mechanical performance of the polyhydroxyalkanoates can be modulated by changing the molecular structure and the copolymer composition, changing from hard crystalline plastic material to elastic rubber material.

Despite the considerable amount of research and results obtained on the study of bio-based materials, their commercial use is still limited (Gontard et al., 2011). At present, they are used for short shelf life food stored at chill temperature and dry ambient, due to their inherent biodegradability, which is manifested especially in moisture ambient. Potential application could be for fresh fruit and vegetable minimally processed, due to the high CO_2/O_2 permeability ratio, useful for respiring food. For moist food there are some limitation due to their sensitivity for humidity and consequently low water vapor barrier property. Polylactic acid remains still the most utilized biopolymer for food packaging application. Several results were published regarding its use for fresh salmon packaging (Pettersen et al., 2011) in the form of oriented polylactic acid and for blackberries packaging (Joo et al., 2011), comparing its performance with synthetic polymers such as polyethylene terephthalate, low-density polyethylene and oriented polystyrene.

Edible films and coatings are studied by researchers as possible tools for the reduction in fried food products, as means for active compounds migration and shelf life extension of high perishable foods such as fresh-cut fruits and vegetables and for meats and fishes. Consumers, more conscious in their health, are driving the interest to the reduction of oil incorporation during frying process (Freitas et al., 2009). Consumers are more interest for fresh and minimally processed food, enriched with natural substances and not with chemical substances, while maintaining their nutritional and sensory characteristics (Falguera et al., 2011a,b).

Considering that taste and flavor must be maintained during food storage, the encapsulation of aromatic compounds such as ethyl acetate, ethyl butyrate, ethyl octanoate, 2-pentanone, and so on (Marcuzzo et al., 2010) could be used as a strategy to reduce degradation reactions such as oxidation. Lastly, various active compounds such as antioxidants, flavorings, antibrowning, antimicrobials, vitamins, and enzymes, as transport and release means, are the future of edible films and coatings, while nanotechnology is an emerging technology that could be used to release, in a controlled manner, the encapsulated bioactive compounds from the matrix to the product (Rojas-Grau et al., 2009). The main limitation on the commercial use of edible films and coating are the problems related to the poor mechanical and barrier properties. Improving their performance by adding reinforcing nanocompound is not always possible due to safety concerns. While the properties of macromolecules are well-known about their eventual toxicological effects, scientific data about the effect of nanostructures for human health must be still followed, for any future commercialization. The positive feature is that edible films and coatings fit several environmental parameters suggested by US Environmental Protection Agency (EPA) (Dangaran et al., 2009) like:

- to be "green packaging," because they improve municipal waste management and waste reduction,
- to reduce the amount of toxic materials in packaging, making easier the reuse or composting them,
- to reduce the amount of food wastes owing to the reduction of damage and/or spoilage on food products.

7 Food Packaging Sustainability

According to Marsh and Bugusu (2007), food packaging is one of the principal causes of waste productions in fact it is ~50% of the total packages sold, being the two-third of total packaging waste by volume. The result is that the assessment and reduction of the environmental impact associated with the production, use and final-end of these materials are one of the most important priorities of the food packaging industries. Further, different life cycle phases associated to food packaging, such as production, transport, use, solid waste disposal, and so on causes different environmental impacts, correlated also to the consumption of nonrenewable and renewable resources such as materials and energies, air, and water emissions (James et al., 2005).

The massive consumption of plastics packaging materials is related to different causes (Verghese, 2008). The first is that, according to the change in human nutrition and life habits, the request of small package size is increasing, giving a great contribution to the increase of plastics wastes. Secondary, a difficulty in the recycling process due to the use of different packaging materials requested by industry and by consumers to satisfy economic, health, quality and new cooking styles needs, is increasing even more the production of solid wastes.

To take into consideration the growing environmental concern, packaging industries are working on reducing the weight and volume of packaging eliminating the unnecessary component, while assuring the correct shelf life, safety, and protection functions of the packaging. Further, improvement of the recyclability, reusability, composting, and energy recovery are other tools considered by industries to reduce wastes production. Using new materials such as biopolymers and improving the product shelf life could give a great contribution for sustainable development due to the fact that the longer the shelf life is, the lower food and packaging wastes are (Restuccia et al., 2016). The world's largest retailer, the US WalMart Store, is a leader on sustainable initiatives such as the promotion of the Packaging Scorecard, which is a tool introduced to evaluate the performance and the efforts of the suppliers to work on and select the best packaging with reduced environmental impacts (Robertson, 2013b). Further, the European Organization for Packaging and the Environment (European) support that is better to talk about packaging and sustainability rather than sustainable packaging. They consider packaging not as a problem but as part of the environmental solution for a sustainable development. From this point of view a packaging gives a considerable contribution to economic, environmental and social sustainability because it protects the food products while reducing wastes (food and material wastes). Following the European's vision (European, 2009), to minimize the impacts and maximize the benefits, for a sustainable development a packaging should:

- be designed holistically with the product to optimize overall environmental performance
- be made from responsibility sourced materials
- be designed to be effective and safe throughout its life cycle
- meet market criteria for performance and cost
- meet consumer choice and expectations
- be recovered efficiently after use.

A packaging material impact not only during its production and disposal but also during the packing, in the food chain, and its distribution. Johnson in his work (Johnson, 2009) discussed the eight criteria reported from the US-based Sustainable Packaging Coalition (SPC) (SPC, 2011) for identifying what a sustainable packaging material must display. In particular:

- it must be beneficial, safe, and healthy for individuals and communities throughout its life cycle;
- it should meet market criteria for performance and cost;
- it must be sourced, manufactured, transported, and recycled using renewable energy;
- it optimizes the use of renewable or recycled source materials;
- it must be manufactured using clean production technologies and best practices;
- it is made from materials healthy throughout the life cycle;
- it is physically designed to optimize materials and energies;
- it is effectively recovered and utilized in biological and or industrial closed-loop cycle.

It must be taken into consideration that the choice of packaging material could respect one or more criteria but could be contradictory for others. For example, a packaging could be produced using renewable resources but more energy is utilized to produce and transport it than a material produced by a nonrenewable resources.

In 2009, the Consumer Goods Forum (CGF) was created with the aim to connect retailers, manufacturers, service providers, and stakeholders from all over the world to discuss and assess the packaging sustainability. In 2010, they published *A Global Language for Packaging Sustainability* while in 2011, they published the Global Protocol on Packaging Sustainability (GPPS, 2011), giving the possibility to standardize the questions about the packaging sustainability, within a company or between business partners.

7.1 Life Cycle Assessment

To consider all the environmental impacts, a life cycle thinking (LCT) approach is the most used tool, with the definition of the environmental burden of a food packaging. All environmental, social, and economic impacts through the whole life cycle of a product have to be considered. Different LCT tools could be used to perform an environmental study such as life cycle assessment (LCA), life cycle costing (LCC), social LCA, the eco-design, carbon, water, and ecological footprint. Between them, the most utilized and accepted methodology is the LCA for measuring the environmental performance of products and processes. The LCA methodology is useful for the identification and assessment of potential impacts associated with a material, product, service, and/or process, from raw material extraction and processing to manufacturing, transport, use and final disposal, throughout the entire life cycle (Guinée, 2002). It is applied in accordance with the indication of the International Organization for Standardization (ISO) standards (ISO14040, 2006; ISO14044, 2006). It is usually referred to a "cradle-to-grave" analysis but also a "cradle-to-gate" analysis could be performed. Typically two or more products with the same use are compared. According to ISO standards, a LCA study is divided into four steps:

1. Goal and scope definition
2. Life cycle inventory (LCI)
3. Life cycle impact analysis (LCIA)
4. Life cycle interpretation

Goal and scope definition. This is the step where the intended motivation for conducting the study is defined. Results, audience, geographical area, functional unit, system boundaries, data, procedure for handling the data, limits, are well identified in this step. The functional unit, that is, the unit of product that will be the object of the LCA study, have to be chosen to avoid losing time and to well compare the results obtained. All input and output data are related to this functional unit. In general, for food packaging application, it is a defined volume of materials such as, for example, 1 kg of polymer. The goal and scope can also be adjusted during the LCA study if the initial choice is not optimal. In this step could be drawing a diagram of the system, starting to identify the boundaries. Also, in this step the model used must be indicated. Is it possible to use a consequential model or an attributional model? The consequential model is used when the scope is to investigate the consequences of a change of a starting situation. The attributional model is used when the environmental impacts assessment of a product, a process or a comparison with two products with the same functional unit is required. All the environmental inputs and outputs data are expressed for the raw materials extraction (from cradle) to the gate of the product or supplier or to the final disposal of the material (grave).

Life cycle inventory (*LCI*). In this step the data collection is very important and could be classified as primary and secondary ones. Primary data are obtained directly from the original source as for example the food industry. The secondary data are extrapolated from official databases, included in the LCA software, recognized from the research word. The primary data that are necessary to well describe the system under study are called "Foreground data" while the secondary data which are referred to a generic materials, energy, transport, and waste management and that can be found in databases or literature are called “background data.” Foreground data could be collected following the questionnaires described in the ISO standards that contain in a simple way, generic information, and explanation for each data requested, data sections, data quality, and allocation. The use of background data requires much attention because they have to fit with the requirement of the goal and scope of the LCA study. The two most important data sources are the Ecoinvent database and the Input-Output database. The first ones have been created by several Swiss organizations and cover over than 10,000 processes while in the second ones data are collected per economic sector rather than per processes.

The LCI quantifies the use of resources and materials, the consumption of fuels and energies, the involved transportation. All data that cannot be identified and expressed quantitatively are not included in the study. All input and output data are described as a framework. These data are referred to the involved materials and energies used for the production of a product or for a process. Several individual units operations are identified, each well described from several input and output data.

Life cycle impact analysis (*LCIA*). In this step, all data collected and described during the LCI analysis are converted in several indicators. To do that different method could be used, depending on the audience addressed and on the ability of the audience to understand the results. Each method contains from 10 to 20 impact categories which are grouped in Damage Categories such as Resources, Climate Change, Human Health, Ecosystem Quality, and so on, internationally accepted, scientifically valid, and environmentally relevant. Some of these could be aggregated in single score and some do not. Until now, there is no indication on what the best method is. For each damage category, several impact categories are identified. For example for the damage category Ecosystem Quality the following Aquatic ecotoxicity, Terrestrial ecotoxicity, Terrestrial acidification/nitrification, Aquatic acidification, Aquatic eutrophication, Land occupation impact categories are considered. The aim of this phase is to understand and evaluate the magnitude and significance of the environmental impacts.

Life cycle interpretation. In this last step, a conclusion and a solution of the environmental study must be performed. Results obtained from LCI and LCIA phases are combined together to identify the most impacting categories. Opportunities to reduce the environmental impacts of the product system investigated must be given, with the subsequent indication of limitations and recommendations. Results obtained from this last phase are used for direct applications on product development and improvement, for strategic planning, for marketing, for social policy making, and so on.

7.2 Application of LCA to Food Packaging

A comparison between multilayer and monolayer packaging could be performed. It is obvious that the multilayer material is not an environmentally friendly solution in respect to the single-layer where less material and energy is used. But, if the longer food shelf life is also included in the study, with a multilayer packaging less energy is used during storage and distribution of the packed food and also a minor food waste could be supposed (Lee & Xu, 2005). It can be concluded that a multilayer material could have a less environmental impact.

Biodegradable material or bio-based materials are of course considered as environmental friendly polymers than synthetic ones, but if they are mixed with traditional polymers to improve their thermal, mechanical, and barrier properties and if their end-of-life phase is included in the LCA study, then they become not environmental sustainable. The bio-based polymers with greater difficulty will biodegrade while the synthetic polymer will lose their recyclability (ExcelPlas Australia, Centre for Design, RMIT & NolanITU, 2004).

With the new technologies is possible to reduce over certain limits the volume and weight of the packaging materials, with a considerable saving on raw material consumption (both renewable than nonrenewable ones) and reduction on solid wastes. But the problem could be the increase on the food damage due to inadequate protection and safety with a consequential increment on the food wastes (Oki & Sasaki, 2000).

To reduce the amount of packaging material one possible solution could be to increase the food packaging size. In this case, more food is packed with reduced use of materials. The problem could be that food could deteriorate faster that in small size packaging, increasing the food wastes, making a less eco-compatible choice (Grönman, 2013).

Thanks to the improvement of the LCA methodology, a large number of research studies were done and published, making the food packaging field the most investigated system (Siracusa et al., 2014). So, in this field, studies can be focalized on the LCA study of food and drink products, food and drink packaging, on alternative food packaging technologies and on food waste, and/or packaging wastes management options, focalized on the end-of-life phases.

Flanigan et al. (2013) as well as Ror et al. (2009) and Grönman (2013), reported several cases studies of LCA analysis for food and beverages and for packaging materials, giving the possibility to understand the environmental performance of this methodology. They compare several studies focalized on food and packaging materials, with the analysis of the end-of-life scenarios, and in same case implementing the comparison between different kinds of alternative materials solution (conventional packaging versus novel packaging). All found that food, especially as wasted food, has more impact than the packages but several articles do not take into consideration the food waste. If the package is seen as a fundamental strategy to reduce the food losses, then food waste must be taken into account. In fact, Williams and Wikström (2011) and Hanssen et al. (2012) write that a real connection between food losses and packaging is very important to stress the important role of the packaging to avoid food wastes.

Biodegradable polymers, recycled materials such as polyethylene terephthalate, biopolymers, edible films, lightweight packaging, and so on have been the object of LCA study in these recent years. In this context, very interesting studies were reported in 2013 by Yates and Barlow (2013), Hottle et al. (2013), and Pawelzik et al. (2013). Leceta et al. (2013) reported a case study of comparison between a 1 m^2 of chitosan film with 1 m^2 of conventional polypropylene film used for packaging application. All phases such as material extraction, film manufacture, and end of life were considered. It was evidenced that the raw material extraction phase for the production of the polypropylene film was more environmentally impacting on carcinogen and fossil fuel categories while for chitosan films the phases with most impact were respiratory inorganics, land use, and mineral categories, associated with the nonoptimized film manufacturing phase, which enhanced the consumption of electricity and additives. However, the end-of-life composting scenario was more favorable for the chitosan than for the polypropylene film.

Few articles are present in literature regarding the LCA study on nanomaterials. As an example de Figueirêdo et al. (2012) reported a case study on two cellulose nanowhisker from coconut and from white cotton fibers, with a low environmental impact recorded from the prime films rather that from the latter.

But, not only is packaging the principal contributor to the environmental impacts of a food product. Agricultural production and processing must also be taken into consideration. Erlov et al. (2000) reported that the energy used for processing bread, tomato juice, milk, and yogurt was 68% greater than the energy used for the packaging system. Indeed, as reported by Silvenius et al. (2011), 2%–5% of the total environmental impact could be attributed to the packaging for greenhouse emission, eutrophication, and acidification impacted categories. An opposite tendency is recorded for soft drinks bottle and for low-value food packaging where the materials used for packaging exhibit the greater environmental impact.

7.3 Limits of the LCA Analysis

To best represent the environmental LCA study results, diverse methodological aspects should be improved. First of all, correct strong interaction between food and packaging has to be taken into account. This is to avoid an over or lower estimation of the packaging, to evaluate the correct influence of the packaging in the product life cycle, to evaluate the influence of different packaging materials and packaging technologies (Restuccia et al., 2016). Then, considering that the main feature of a packaging material is to protect, to ensure the food safety and quality and to extend the food shelf life, these aspects must be encountered in the choice of the packaging functional unit. Finally, the most difficult task, a good balance between quality, health, economic, social, and environmental factors must be included in the study. One possibility could be to perform together with the LCA study, a LCC analysis. On this new methodology, called life cycle sustainability assessment, several researchers are already working.

Despite the increase in popularity of this methodology, several other efforts have to be made to overcome its limitations. First of all the study of a product or a package is geographically related, with very different environmental effects. The various packaging functions have to be considered when an LCA study is performed comparing different packaging materials, for the same product, as for example: if one package is reusable or not, if it provides a greater shelf life than the other, if one is more commercial communicative than the other (branding), and so on. The final cost, related to extraction of raw materials, manufacturing, transport, recovery, or disposal is also a very important tool if not of primary importance. Another time, it is necessary to correlate the LCA study with the LCC analysis. The LCA results are most of the time related to the specific system under study and could not be generalized and adapted for every situation. In general the consumer's behavior is not taken into consideration in LCA studies.

Despite these limitations, the LCA methodology is a very helpful tool in the identification of the most used resources and wastes production, on the identification of emission into air, water, and soil. Further it serves as the decision-maker's tool for selecting the best product or process with lower environmental impact. LCA assesses the waste management options and serves as a valuable decision support tool for policy makers and the industry.

8 Conclusions

Over the past 20 years, many results have been achieved in the study of bio-based materials for food packaging application. Despite that, many of the studied materials remained at the laboratory scale due to several reasons. First of all, the higher cost is compared with synthetic polymers derived from petroleum resources. It is obvious that if the production capacity increases, the costs can fall down. One possibility will be to substitute the production of raw materials with biofuels. The second reason is related to the material performances. Many attempts have been made to improve their properties but, taking into consideration that the main feature must be their degradation, very often it is not possible to improve their properties over a certain limit. Further, as a result of their inherent biodegradation behavior, their functions are active for a short period of time, shorter than conventional packaging, and not adequate to the shelf life request from manufacturers and consumers. Melt extrusion for thermoplastics preparation is sometimes not possible for bio-based polymers, which have to be prepared by a casting procedure, especially for edible films. Inadequate water vapor barrier behavior has limited their application in the food's packaging field but this is an inherent property essential to confer the biodegradability behavior to these materials.

So, to adequately address the stability of these materials to the intended storage and use conditions, much more investigation is mandatory. It is indisputable that the use of bio-based materials will increase in the near future owing to their improved performance such as mechanical and barrier properties. Probably the near future will see these materials blended with other polymers and nanoparticles, obtaining bio-nanocomposite materials, to meet the demand of the food packaging industry for achieving the desired performances required for commercial application.

Further, considering that consumers are asking vociferously for sustainable and environmental friendly food packaging materials, an additional effort is required by the suppliers. The modern industrial economy must be characterized by the development of efficient processes and products, with reduced energy and resources consumption, and decrease in material and energy content. Additional research is required from industries, consumers, and governments to ensure a more sustainable society with a minimum impact on the environment and future generations.

References

Aider, M., 2010. Chitosan application for active bio-based films production and potential in the food industry: review. LWT Food Sci. Technol. 43, 837–842.

Almenar, E., Auras, R., 2010. Permeation, sorption, and diffusion in poly(lactic acid). In: Auras, R., Lim, L.T., Selke, S.E.M., Tsuji, H. (Eds.), Poly(Lactic Acid): Synthesis, Structures, Properties, Processing and Applications. John Wiley & Sons, New York, pp. 155–179.

Auras, R., Harte, B., Selke, S., 2004. Effect of water on the oxygen barrier properties of poly(ethylene terephthalate) and polylactide films. J. Appl. Polym. Sci. 92, 1790–1803.

Auras, R., Harte, B., Selke, S., 2006. Sorption of ethyl acetate and D-limonene in poly(lactide) polymers. J. Sci. Food Agric. 86, 648–656.

Auras, R., Lim, L.-T., Selke, S.E.M., Tsuji, H. (Eds.), 2010. Poly(Lactic Acid): Synthesis, Structures, Properties, Processing, and Application. John Wiley & Sons, New York.

Azeredo, H.M.C., Mattoso, L.H., Wood, D., Williams, T.G., Avena-Bustillos, R.j., McHugh, T.H., 2009. Nanocomposites edible films from mango puree reinforced with cellulose nanofibers. J. Food Sci. 74, N31–N35.

Baldwin, E.A., 2007. Surface treatments and edible coatings in food preservation. In: Rahman, M.S. (Ed.), Handbook of Food Preservation. CRC Press, Boca Raton, FL, pp. 478–508.

Bao, L.B., Dorgan, J.R., Knauss, D., Hait, S., Oliveira, N.S., Maruccho, I.M., 2006. Gas permeation properties of poly(lactic acid) revisited. J. Membr. Sci. 285, 166–172.

Cagri, A., Ustunol, Z., Ryser, E.T., 2004. Antimicrobial edible films and coatings. J. Food Prot. 67 (4), 833–848.

Cairncross, R.A., Becker, J.G., Ramaswamy, S., O'Connor, R., 2005. Moisture sorption, transport, and hydrolytic degradation in polylactide. Appl. Biochem. Biotechnol. 129 (132), 774–785.

Chivrac, F., Pollet, E., Avérous, L., 2009. Progress in nano-biocomposites based on polysaccharides and nanoclay. Mater. Sci. Eng. R67, 1–17.

Cuq, B., Gontard, N., Guilbert, S., 1998. Proteins as agricultural polymers for packaging production. Cereal Chem. 75, 1–9.

Cushen, M., Kerry, J., Morris, M., Cruz-Romero, M., Cummins, E., 2012. Nanotechnologies in the food industry—recent developments, risks and regulation. Trends Food Sci. Technol. 24, 30–46.

Dangaran, K., Tomasula, P.M., Qi, P., 2009. Structure and function of protein-based edible films and coatings. In: Embuscado, M.E., Huber, K.C. (Eds.), Edible Films and Coatings for Food Applications. Springer, New York.

de Figueirêdo, M.C.B., Rosa, M.D.F., Ugaya, C.M.L., Souza Filho, M.D.S.M.D., Silva Braid, A.C.C.D., Melo, L.F.L.D., 2012. Life cycle assessment of cellulose nanowhiskers. J. Clean. Prod. 35, 130–139.

De Moura, M.R., Aouada, F.A., Avena-Bustillos, R.J., McHugh, T.H., Krochta, J.M., Mattoso, L.H.C., 2009. Improved barrier and mechanicl properties of novel hydroxypropyl methylcellulose edible films with chitosan/tripolyphosphate nanoparticles. J. Food Eng. 92, 448–453.

Erlov, L., Lofgren, C., Sora, A., 2000. Packaging—A Tool for the Prevention of Environmental Impact. Packforsk, Kista.

European, 2009. What is Sustainable Packaging? Our Vision, www.european.be.

European Bioplastics, 2013. Bioplastics—Facts and Figures. European Bioplastics, Berlin.

ExcelPlas Australia, Centre for Design (RMIT) and NolanITU, 2004. The impacts of degradable plastic bags in Australia: Final report to department of the environment and heritage. Department of the Environmental and Heritage, Commonwealth Government of Australia, Canberra.

Falguera, V., Pagan, J., Ibarz, A., 2011a. Effect of UV irradiation on enzymatic activities and physiochemical properties of apple juices from different varieties. LWT Food Sci. Technol. 44 (1), 115–119.

Falguera, V., Quintero, J.P., Jiménez, A., Muñoz, J.A., Ibarz, A., 2011b. Edible films and coatings: structures, active functions and trends in their use. Trends Food Sci. Technol. 22, 292–303.

Flanigan, L., Frischknecht, R., Montalbo, T., 2013. An Analysis of Life Cycle Assessment in Packaging for Food & Beverage Applications. UNEP Life Cycle Initiative, UNEP DTIE Sustainable Consumption and Production Branch, Paris, France.

Freitas, D.D.G.C., Berbari, S.A.G., Prati, P., Fakhouri, F.M., Queiroz, F.P.C., Vincente, E., 2009. Reducing of fat uptake in cassava product during deep-fat frying. J. Food Eng. 94, 390–394.

Gennadios, A., 2002. Protein-Based Films and Coatins. In: Gennadios, A. (Ed.), CRC Press, Boca Raton, FL.

Global Protocol on Packaging Sustainability, 2011. Available from: http://globalpackaging.mycgforum.com.

Gontard, N., Angellier-Coussy, H., Charlier, P., Gastaldi, E., Guillard, V., Guillaume, C., Peyron, S., 2011. Food packaging applications of biopolymers-based films. In: Plackett, D. (Ed.), Biopolymers—New Materials for Sustainable Films and Coatings. John Wiley & Sons, Chichester, pp. 213–232.

Grönman, K., 2013. Importance of Considering Food Waste in the Development of Sustainable Food Packaging System. Acta Universitatis Lappeenrantaensis 559. Diss. Lappeenranta University of Technology ISBN 978-952-265-534-9, ISBN 978-952-265-535-5 pdf.

Guinée, J.B., 2002. Handbook of life cycle assessment operational guide to the ISO standards. Int. J. Life Cycle Assess. 7 (5), 311–313.

Hansen, N.M.L., Plackett, D., 2008. Sustainable films and coatings from hemicelluloses: a review. Biomacromolecules 9, 1493–1505.

Hanssen, O., Møller, H., Svanes, E., Schakenda, V., 2012. Life Cycle Assessment as a tool in food-waste reduction and packaging optimization, packaging innovation and optimization in a life cycle perspective. In: Curran, M.A. (Ed.), Life Cycle Assessment Handbook: A Guide for Environmentally Sustainable Products. John Wiley & Sons/Scrivener Publishing LLC, New Jersey/Massachusetts, pp. 345–367.

Holm, V.K., Ndoni, S., Risbo, J., 2006. The stability of poly(lactic acid) packaging films as influenced by humidity and temperature. J. Food Sci. 71, E40–E44.

Hottle, T.A., Bilec, M.M., Landis, A.E., 2013. Sustainability assessments of biobased polymers. Polym. Degrad. Stab. 98 (9), 1898–1907.

ISO 14040:2006, 2006. Environmental Management—Life Cycle Assessment—Principles and Framework. International Organization for Standardisation, Geneva.

ISO 14044:2006, 2006. Environmental Management—Life Cycle Assessment—Requirements and Guidelines. International Organization for Standardisation, Geneva.

James, K., Fitzpatrick, L., Lewis, H., Sonneveld, K., 2005. Sustainable packaging system development. In: Leal Filho, W. (Ed.), Handbook of Sustainability Research. Peter Lanf Scientific Pubishing, Frankfurt.

Janjarasskul, T., Krochta, J.M., 2010. Edible packaging materials. Annu. Rev. Food Sci. Technol. 1, 415–448.

Jin, E., Reddy, N., Zhu, Z., Yang, Y., 2011. Graft polymerization of native chichen feathers for thermoplastic application. J. Agric. Food Chem. 59, 1729–1738.

Johnson, A., 2009. Sustainable packaging. In: Yam, K.L. (Ed.), The Wiley Encyclopedia of Packaging Technology, third ed. John Wiley & Sons, New York, pp. 1177–1182.

Joo, M.J., Lewandowski, N., Auras, R., Harte, J., Almenar, E., 2011. Comparative shelf-life study of blackberry fruit in bio-based and petroleum-based containers under retail storage conditions. Food Chem. 126, 1734–1740.

Koller, M., Atlic, A., Dias, M., Reiterer, A., Braunegg, G., 2010. Microbial PHA production from waste raw materials. In: Chen, G.Q. (Ed.), Plastic From Bacteria: Natural Functions and Applications. Springer-Verlag, Berlin.

Lagaron, J.M., Lopez-Rubio, A., 2011. Nanotechnology for bioplastics: opportunities, challenges and strategies. Trends Food Sci. Technol. 22, 611–617.

Leceta, I., Guerrero, P., Cabezudo, S., Caba, K.D.L., 2013. Environmental assessment of chitosan-based films. J. Clean. Prod. 41, 312–318.

Lee, S.G., Xu, X., 2005. Design for the environment: life cycle assessment and sustainable packaging issues. Int. J. Environ. Technol. Manag. 5 (1), 14–41.

Lia, H.M., Padua, G.W., 1999. Water vapour barrier properties of zein films plasticized with oleic acid. Cereal Chem. 75, 194–199.

Liu, H., Xu, Y., Zheng, Z., Liu, D., 2010. 1,3-Propanediol and its copolymers: research, development and industrialization. Biotechnol. J. 5, 1137–1148.

Mahalik, P., Nambiar, A.N., 2010. Trends in food packaging and manufacturing systems and technology. Trends Food Sci. Technol. 21, 117–128.

Marcuzzo, E., Sensidoni, A., Debeaufort, F., Voilley, A., 2010. Encapsulation of aroma compounds in biopolymeric emulsion based edible films to control flavour release. Carbohydr. Polym. 80 (3), 984–988.

Marsh, K., Bugusu, B., 2007. Food packaging—roles, materisals and environmental issues. J. Food Sci. 72 (3), 39–55.

Martin-Belloso, O., Rojas-Graü, M.A., Soliva-Fortuny, R., 2009. Delivery of flavour and active ingredients using edible films and coatings. In: Embuscado, M.E., Huber, K.C. (Eds.), Edible Films and Coatings for Food Applications. Springer, New York, p. 295.

McCarty, S.P., Gross, R.A., Ma, W., 1999. Polylactic acid-based blends. U.S. Patent 5883199.

Mensitieri, G., Di Maio, E., Buonocore, G.G., Nedi, I., Oliviero, M., Sansone, L., Inannace, S., 2011. Processing and Shelf life issues of selected food packaging materials and sructures from renewable resources. Trends Food Sci. Technol. 22, 72–80.

Oki, Y., Sasaki, H., 2000. Social and environmental impacts of packaging (LCA and assessment of packaging functions). Packag. Technol. Sci. 13 (2), 45–53.

Pawelzik, P., Carus, M., Hotchkiss, J., Narayan, R., Selke, S., Wellisch, M., Patel, M.K., 2013. Critical aspects in the life cycle assessment (LCA) of biobased materials—reviewing methodologies and deriving recommendations. Resour. Conserv. Recycl. 73, 211–228.

Peelman, N., Ragaert, P., De Meulenaer, B., Adons, D., Teeters, R., Cardon, L., Van Impe, F., Devlieghere, F., 2013. Application of bioplastics for food packaging. Trends Food Sci. Technol. 32, 128–141.

Peelman, N., Ragaert, P., Ragaert, K., De Meulenaer, B., Devlieghere, F., Cardon, L., 2015. Heat resistance of new biobased polymeric materials, focusing on starch, cellulose, PLA, and PHA. J. Appl. Polym. Sci. 132, 42305–42320.

Pettersen, M.K., Bardet, S., Nilsen, J., Fredriksen, S.B., 2011. Evaluation and suitability of biomaterials for modified atmosphere packaging for fresh salmon fillets. Packag. Technol. Sci. 24, 237–248.

PlasticsEurope, 2016. (http://www.plasticseurope.org).

Restuccia, D., Salomone, R., Spizzirri, U.G., Saija, G., Ioppolo, G., Parisi, O.I., Picci, N., 2016. Industrial application: regulatory issues and life cycle assessment of food packaging. In: Barros-Velàzquez, J. (Ed.), Antimicrobial Food Packaging. Academic Press for Elsevier, Cambridge, MA. ISBN: 978-0-12-800723-5, pp. 221–227 (Chapter 16).

Robertson, G.L., 2013a. Edible, biobased and biodegradable food packaging materials. Food Packaging Principles and Practice, third ed. CRC Press, Taylor & Francis Group, Boca Raton, London, New York. (Chapter 3), pp. 49–90.

Robertson, G.L., 2013b. Food packaging and sustainability, Food Packaging Principles and Practice, third ed. CRC Press, Taylor & Francis Group, Boca Raton, London, NewYork. (Chapter 23), pp. 670–667.

Rojas-Grau, M.A., Soliva-Fortuny, R., Martìn-Belloso, O., 2009. Edible coatings to incorporate active ingredients to freshcut fruits: a review. Trends Food Sci. Technol. 20, 438–447.

Ror, P., Nei, D., Orisaka, T., Xu, Q., Okadome, H., Nakamura, N., Shiina, T., 2009. A review of life cycle assessment (LCA) on some food products. J. Food Eng. 90 (1), 1–10.

Silvenius, S., Katajajuuri, J.M., Grönman, K., Soukka, R., Koivupuro, H.K., Virtanen, Y., 2011. Role of packaging in LCA of food products. Towards Life Cycle Sustainability Management. Springer, Netherlands. pp. 359–370.

Siracusa, V., 2016. Packaging material in the food industry. In: Barros-Velazquez, J. (Ed.), Antimicrobial Food Packaging. Academic Press, Elsevier, Cambridge, MA, pp. 95–106 (Chapter 7).

Siracusa, V., Ingrao, C., 2016. The use of polylactic acid in food packaging. In: Reference Module in Food Sciences, first ed. Academic Press, Elsevier, pp. 1–5. ISBN: 9780081005965, https://doi.org/10.1016/B978-0-08-100596-5.03208-X.

Siracusa, V., Ingrao, C., 2017. Correlation amongst gas barrier behaviour, temperature and thickness in BOPP films for food packaging usage: a lab-scale testing experience. Polym. Test. 59, 277–289.

Siracusa, V., Rocculi, P., Romani, S., Dalla Rosa, M., 2008. Biodegradable polymers for food packaging: a review. Trends Food Sci. Technol. 19 (12), 634–643.

Siracusa, V., Blanco, I., Romani, S., Tylewicz, U., Rocculi, P., Dalla Rosa, M., 2012. Poly(lactic acid) (PLA) modified films for food packaging application: physical, mechanical and—barrier behavior. J. Appl. Polym. Sci. 125, E390–E401.

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 Res. Int. 62, 151–161.

Sirò, I., Plackett, D., 2010. Microfibrillated cellulose and new nanocomposite materials: a review. Cellulose 17, 459–494.

Sirocchi, V., Devlieghere, F., Peelman, N., Sagratini, G., Maggi, F., Vittori, S., Ragaert, P., 2017. Effect of Rosmarinus officinalis L. essential oil combined with different packaging conditions to extend the shelf life of refrigerated beef meat. Food Chem. 221, 1069–1071.

Smith, P.B., 2015. Bio-based sources for terephthalic acid. ACS Symp. Ser. 1192, 453–469.

Sorrentino, A., Gorrasi, G., Vittoria, V., 2007. Potential perspectives of bionanocomposites for food packaging applications. Trends Food Sci. Technol. 18, 84–95.

Spence, K.L., Venditti, R.A., Rojas, O.J., Habibi, Y., Pawlak, J.J., 2011. A comparative study of energy consumption and physical properties of microfibrillates cellulose produced by different processing methods. Cellulose 18, 1097–1111.

Sustainable Packaging Coalition (SPC), 2011, www.sustainablepackaging.org.

Tamer, C.E., Çopur, O.U., 2010. Chitosan: an edible coating for fresh cut fruit and vegetables. Acta Hortic. 877, 619–626.

Tang, X., Alavi, S., Herald, T.J., 2008. Barrier and mechanical properties of starch-clay nanocomposites films. Cereal Chem. 85, 433–439.

Thellen, C., Coyne, M., Froio, D., Auerbach, M., Wirsen, C., Ratto, J.A., 2008. A processing, characterization and marine biodegradation study of melt-extruded polyhydroxyalkanoate (PHA) films. J. Polym. Environ. 16, 1–11.

Verghese, H., 2008. Environmental assessment of food packaging and advanced methods for choosing the correct materials. In: Chiellini, E. (Ed.), Environmentally Compatible Food Packaging. Woodhead Publishing Limited, Cambridge, pp. 182–210.

Vieira, M.G.A., da Silva, M.A., dis Santos, L.O., Beppu, M.M., 2011. Natural-based plasticizers and biopolymer films: a review. Eur. Polym. J. 47, 254–263.

Wang, H., Langner, M., Agarwal, S., 2016. Biodegradable aliphatic–aromatic polyester with antibacterial property. Polym. Eng. Sci. 56 (10), 1146–1152.

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.

Yates, M.R., Barlow, C.Y., 2013. Life cycle assessment of biodegradable, commercial biopolymers—a critical review. Resour. Conserv. Recycl. 78, 54–66.