6 Green Polymer-Based Biodegradable Packaging

Ruchi Sharma, Aparna Agarwal, and Rizwana

Abstract

With the decline in natural resources and increasing environmental waste concerns due to nonbiodegradable packaging materials, there is a need for novel approach of biopolymer-based packaging in order to enhance the quality as well as shelf life of food products. The biopolymer-based packaging involves active and intelligent packaging technology which helps in preventing the migration of moisture, controlling the respiration rate, retarding the oxidative damage, and enhancing the shelf life of the food products. Biopolymer-based packaging materials are considered at a wider pace as they are cheaper, biodegradable, environment-friendly and renewable. These are obtained from various sources including plant or animal protein, chitosan, cellulose, and starch. This review highlights the concept of biopolymers, its sources, characteristics, benefits, and limitations. It focuses on the types of biopolymers such as active and intelligent packaging. Also, it enlightens on bio-nanocomposites, green packaging, and application of biopolymers in other relevant areas.

Keywords

Green packaging · Biodegradable · Intelligent packaging · Food applications

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A. Dutt Tripathi et al. (eds.), *Biodegradable Polymer-Based Food Packaging*,
https://doi.org/10.1007/978-981-19-5743-7_6

6.1 Introduction

Foods are an essential component of life and its protection play a vital role in maintaining the health of the consumers. For the protection of food products, various types of packaging materials are utilized such as glass, plastic, metal, paper, and paperboard. Along with the protection, packaging also helps the consumers in providing them beneficial information regarding the nutritional content and the way the product should be handled or stored. The use of plastics over other packaging materials increased from the long back time due to its low cost (Tang et al. 2012). Packaging is a vital component of the food sector which helps in enhancing the quality and safety of the food products. Its aim is also to provide safe, leakage proof, sound, clean, and contaminated free food products. Also worldwide, food packaging comprises of around 50% of the total other packaging sales which makes the packaging sector the heart of the food industries and led to the concentration over the importance of polymers in the food applications. Polymers play a vital role in the development of the country as from the past 50 years plastics are widely utilized in the manufacturing of packaging materials. During 2014–2015, India produced approximately 8.3 million tons of plastics and in 2018 about 99% of the plastics produced are mainly from petrochemical industries. Although these petroleum-derived plastics has been utilized in the manufacturing of packaging materials from a long back period, the production of these plastics leads to the release of various harmful gases, especially greenhouse gases which adversely affect the ecosystem and cause global warming (Yadav et al. 2018). This has led to the shift towards biopolymer-based packaging materials as it helps in providing protection, preservation, and enhancing shelf life by utilizing natural compounds. The nature-derived biopolymer also has the advantage of being biocompatible, biodegradable, flexible, barrier to gases, stable, chemical-resistant, and safe which provide the consumers an environment-friendly packaged food product (Gabor and Tita 2012).

In view of the discussed beneficial properties of biopolymer-based packaging materials over petroleum based nonbiodegradable plastics, this chapter highlights the novel approach of biopolymer based packaging materials by focusing on active and intelligent packaging for food products.

6.2 Biopolymers, Its Sources, and Characteristics

Biopolymers are derived from living matter and are present in the chain-like structure in the form of linear or branched cross-linked molecules. These usually constitute amino acid proteins, saccharides from sugars, or nucleic acid of nucleotides. These are made up of different monomers and can be considered as heteropolymers. The monomers are arranged in such a fashion to develop secondary structures and even a three-dimensional network to form tertiary structure (George et al. 2020). Biopolymers are effective substitute of harmful and nonbiodegradable conventional packaging materials. Biopolymers are considered as biodegradable, and thus it can be disposed in several ways including composting, decomposition in

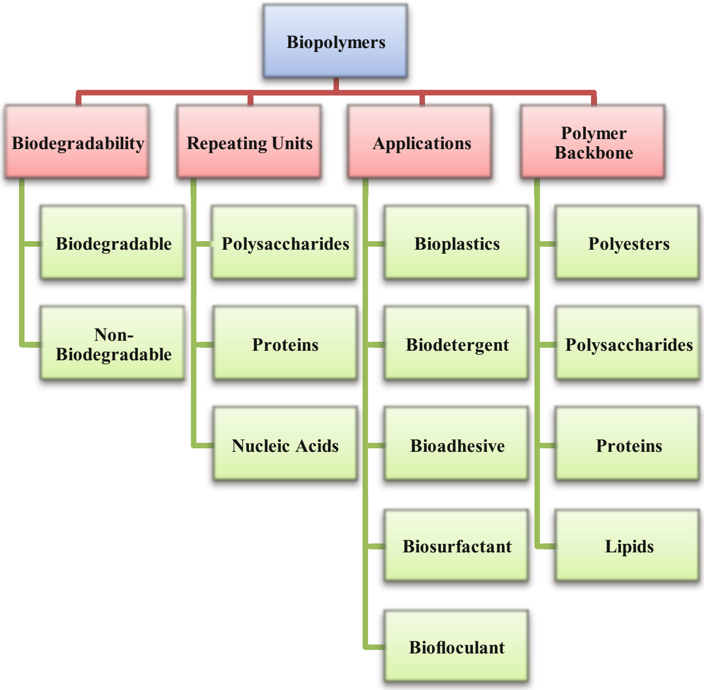

Fig. 6.1 Classification of biopolymers (Mohan et al. 2016)

soil or landfills, anaerobic digestion to produce useful byproducts, thermomechanical recycling, littering, dissolving in water, and carbon dioxide neutral incineration (Ilyas and Sapuan 2020). The main difference between the biopolymers and fossil fuels is that biopolymers are more sustainable and while degrading from bacteria they resulting in less amount of greenhouse gas emissions leading to the prevention from global warming. Biopolymers are majorly classified into four broad categories as shown in Fig. 6.1.

Firstly, they are divided on the basis of their biodegradability, i.e., biodegradable and nonbiodegradable. Also, as an alternative to biodegradability, they are classified as bio-based and non-bio-based. Secondly, they are divided on the basis of repeating units, namely, polysaccharides, proteins, and nucleic acids. Third, they are classified on the basis of application in different areas including bioplastics, biodetergent, bioadhesive, biosurfactant, and biofloculant. And last, biopolymers are categorized on the basis of polymer backbone involving polyesters, polysaccharides, polyamides, polycarbonates, and vinyl polymers (Mohan et al. 2016). Majorly three types of biopolymers for packaging materials are utilized in food applications, namely, polysaccharides, proteins, and lipids. These biopolymers provide a thin coating which is applied over the surface of the food product in order to enhance its quality as well as shelf life. Some biopolymers can also act as a carrier of colorings, flavors, antioxidants, nutrients, and antimicrobial agents which can enhance the organoleptic characteristics as well as nutritional characteristics of the food product (Kraśniewska et al. 2020). Polysaccharide biopolymers are alginate, cellulose, carrageenan, chitin, gellan, curdlan, starch, xanthan, pectin, and pullulan, whereas protein biopolymers include gelatin, collagen, soy protein, whey protein, and zein. Furthermore, polylactic acid (PLA) and polyhydroxyalkanoates (PHAs) fall under the category of aliphatic polyesters (Gabor and Tita 2012).

Starch is considered as a hydrocolloid biopolymer which is extracted from the plants such as corn, potatoes, and rice, in small sizes. It constitutes of 70% amylopectin and 30% amylose with less than 1% lipids and proteins. It is used in the food industry as a thickening agent, gelling agent, and textural agent (Gabor and Tita 2012). It possesses benefits of having cost-effective and abundantly available biopolymer used in the manufacturing of sustainable packaging material (Mangaraj et al. 2019). Starch, when converted into foam through water steam, can also be used to replace the polystyrene foam in the packaging material (Siracusa et al. 2008).

Cellulose is an abundant amphiphilic biopolymer present in the nature. Nowadays, it is widely obtained from the green algae as well as from brown algae (Gabor and Tita 2012). It is a linear polymer containing macromolecular chains of cellobiose. Furthermore, it is crystalline and insoluble which makes it feasible to be converted into processable form (Vroman and Tighzert 2009).

Chitin is a biodegradable, nontoxic, biocompatible, and most abundant biopolymer present in nature after cellulose. It is available in the crystalline form and make up the structure of the cell walls of yeast and fungi (Malathi et al. 2014). Upon the deacetylation of chitin, a copolymer chitosan is produced which has antimicrobial and antibacterial properties and utilized in the form of coatings on various fruits and vegetables including peppers, strawberries and cucumbers (Wróblewska-Krepsztul et al. 2018).

Polyhydroxyalkanoates (PHAs) is a nontoxic polyester of hydroxyalkanoates which is obtained through microbial fermentation. It possesses low melting point, biocompatibility with UV light, better physical property, and better chemical property but lower mechanical property (Zhong et al. 2020). These biopolymers give excellent packaging films alone or in combination with synthetic packaging materials. On such type of PHAs is polyhydroxybutyrate (PHB), which provides similar functional properties to that of polypropylene, but it is more stiff and brittle in nature (Siracusa et al. 2008).

Polylactic acid (PLA) is a hydrophobic polymer which is usually produced from polycondensation of D- or L-lactic acid or through the ring opening polymerization of lactide (Vroman and Tighzert 2009). With the increased utilization, it has limitations of being less thermally stable and brittle in nature. This limitation can be overcome by plasticizing of polylactic acid which thus improves the crystallization (Pawar and Purwar 2013).

Plants extracts can also be utilized in enhancing the functionality of biopolymer-based packaging materials. Plant extracts consists of various functional and bioactive properties which help in improving the physicochemical properties of the packaging materials. One study revealed that the addition of star anise, cinnamon,

Table 6.1 Properties of biopolymers with their roles/applications (Mangaraj et al. 2019)

S. no.	Properties of biopolymers	Roles/applications
1.	Density	If density is high, it results in high transportation cost and thereby alters the mechanical properties
2.	Gas barrier property	Packaging materials should have the excellent barrier properties against gases in order to prevent the fruits and vegetables which are oxidative in nature from degradation
3.	Glass transition temperature	The biopolymers should have high glass transition temperature for the foods stored at lower temperatures and should have high melting point for the foods stored at high temperature
4.	Mechanical properties	For the ease of handing and transportation with no damage to the products, the biopolymers should have excellent mechanical properties such as strength, toughness, and viscoelasticity
5.	Biodegradability	The biopolymers should be biodegradable in order to provide eco-friendly and sustainable environment

and clove extracts increased the tensile strength and reduced the water vapor permeability of the partially hydrolyzed gelatin film (Wang et al. 2012; Hoque et al. 2011). There are various other properties of biopolymers which have specific roles and applications as described in Table 6.1 (Mangaraj et al. 2019).

6.3 Bio-nanocomposites

Although biopolymer-based packaging materials possess various functional and environmental benefits, but they also constitute many limitations. The biopolymer-based packaging materials have poor thermal, barrier, and mechanical characteristics when compared with the petroleum-derived plastic packaging materials. In order to combat these drawbacks, nanocomposites can be utilized which can improve the mechanical and barrier properties of the biopolymer-based packaging materials (Othman 2014). Bio-nanocomposites are a rising approach towards the development of packaging materials as they are well equipped with improved thermal, rheological, barrier, as well as mechanical properties. These properties are because of their high aspect ratio and greater surface area of the nanoparticulates (Rhim et al. 2013).

Nanotechnology is an important element in enhancing the functionality of packaging material. This technology involves the characterization and preparation of structures having 1–100 nm length. The nanomaterials are broadly classified into three categories, namely, platelets, particulates, and fibers. The nanocomposites due to their nano-size exhibit large surface-to-volume ratio and possess good mechanical, electrical, and thermal properties (Youssef and El-Sayed 2018). For the production of bio-nanocomposites, four different types of nanofillers are utilized, namely, carbon nanotubes, cellulose nanofillers, functional nanofillers, and nanoclays. Carbon nanotubes is a segment of carbon nanostructures which also involve other structures including carbon nanofibers, fullerene, grapheme nanosheets, and carbon nanoparticles, whereas cellulose is the cheaper, renewable, and nonbiodegradable material which is utilized as a nanofillers in the production of bio-nanocomposites. Furthermore, for the preparation of clay-based nanocomposites, nanoclays, also referred as layered silicates are utilized, especially phyllosillicates. Also, functional nanofillers including hydroxyapatite, cellulose nanofibers, and silica nanoparticles are used in biomedical as well as biotechnological applications (Reddy et al. 2013). The major bio-nanocomposites utilized for packaging materials include polyhydroxybutyrate, polylactic acid, starch, aliphatic polyester, and poly(butylene succinate) (Sorrentino et al. 2007). Among the various natural polymers utilized, chitosan is one of the widely utilized biopolymer which has applications in food packaging material, artificial skin, and water engineering. Chitosan is widely used due to its functional properties including biodegradability, solubility, mechanical properties, functional groups, and biocompatibility. In order to enhance the functionality of chitosan, it is combined with the nanoparticles such as titanium dioxide. The bio-nanocomposites involving chitosan, titanium dioxide, and polyvinyl alcohol can be used as a packaging material for soft white cheese in order to enhance its antimicrobial activity and sustainability (Youssef et al. 2015).

Bio-nanocomposites have good mechanical, barrier, gas, and antimicrobial properties towards the moisture, oxygen, and flavors in order to protect the food materials and maintain its storage life. To highly preserve the food materials, maintaining its quality, safety, and freshness along with preventing the food from the attack of microorganisms, antimicrobial bio-nanocomposite packaging is the major approach. Also, antimicrobial packaging is a form of active packaging which helps in extending the shelf life of the stored and packaged food products. Various types of antimicrobial bio-nanocomposites are utilized in the food packaging depending on the type of filler incorporated (Sharma et al. 2020).

6.4 Active Packaging

Active packaging is a type of packaging in which there is a linkage between the product, environment, and the packaging material. This type of packing helps in enhancing the shelf life of the food product by maintaining its nutritional and functional properties. Active packaging also involves another class of packaging, i.e., antimicrobial packaging which further ensures the protection of the food products from invading microorganisms (Miteluț et al. 2015). The use of synthetic petroleum-based packaging materials which are nonbiodegradable leads to the environmental degradation. Thus, in order to mitigate this problem, active packaging based on the biopolymers derived from renewable sources including agro-industrial waste is an emerging trend. This can be achieved by extraction and isolation of nanoparticles from the renewable sources and further incorporating in the active packaging. Cellulose nanoparticles are widely used due to its nontoxic nature, lower thermal expansion, and greater binding properties with other binding agents such as chitosan.

In biopolymer-based active packaging, antimicrobial and antioxidant agents are widely incorporated to enhance the functionality of food products along with refining the film properties with antimicrobial and antioxidant characteristics. One such antimicrobial and antioxidant agents are zinc oxide and curcumin, respectively. The combined addition of zinc oxide and curcumin increases the film properties against UV light, water, and gases. Also they help in providing the antibacterial activities against pathogenic microorganisms and thus ensuring the safety and improving the storage stability of packaged food products (Roy and Rhim 2020). Another antimicrobial and antioxidant agent is anthocyanin which can be incorporated inside the biopolymer-based active packaging films in the form of anthocyanin extract and thus act as a reducing agent and extend the shelf life of the packaged food product (Yong and Liu 2020). Furthermore, antioxidant active packaging can be employed in the meat products to prevent lipid oxidation. Lipid oxidation can cause off-odor, off-color, and undesirable textural changes as myoglobin oxidize and changes the color of the meat products and ultimately affect the purchase decision of consumers. Thus, it is essential to incorporate the antioxidant agents, especially natural antioxidants inside the packaging material help to interact with the headspace and meat product resulting in the prevention of lipid oxidation. Also, the antioxidant active packaging functions in two ways, first to use the emitters which can release the antioxidants inside the food and packaging material, and second is to absorb the undesirable components such as oxygen from the food or packaging material (Domínguez et al. 2018).

6.5 Intelligent Packaging

Intelligent packaging is also another type of essential packaging which helps in monitoring the packaging food in terms of its storage conditions along with informing the quality and safety of the packaged food product to the consumers. This packaging involves the utilization of labels inserted inside the packaging material or displayed over the packaging material in the form of label (Yong and Liu 2020). Furthermore, intelligent packaging systems are categorized into three broad groups including sensors, radio frequency identification system, and indicators. Among these, sensors are more widely used that can also help in determining the quality and history of the food product in terms of the variation in the color of the food product. The sensors developed from biopolymers are sodium alginate, sodium caseinate, and carrageenan ultraviolet light-activated intelligent packaging system. Among these, carrageenan sensor is the most effective as an oxygen leak indicator in food packaging applications with decrease migration into food products and higher tensile strength (Deshwal et al. 2018).

Various chemical sensors are utilized in the food packaging which are categorized under active and passive sensors depending upon the external power required or not for the detection. Biosensors are one such sensors that fall under chemical sensors, but their biological components are different from chemical sensors. Biosensors basically utilized the isolated and purified cells, antibodies, fungi, plant cells, animal cells, enzymes, and bacteria in the form of detectors (Nemes et al. 2020). Nowadays, there is an emerging need for the utilization of natural pigments such as betalains, anthocyanin, and curcumin as a natural antioxidants that can be combined with the starch-based films to enhance the antimicrobial as well as antioxidant properties of the meat, milk, and seafood. It thus acts as an intelligent packaging system which detects and retains the freshness of the food products (Qin et al. 2020). Furthermore, intelligent packaging films are also produced by combining the biopolymers with various extracts of fruits and vegetables including berries, dark purple and black vegetables, sweet potato, and red cabbage (Wu et al. 2021).

However with the utilization of biopolymer-based intelligent packaging systems, it possesses various benefits and limitations in the food products. The major advantage is that the pigments containing intelligent films are temperature, pH, light, and ammonia-sensitive which helps in monitoring the deterioration of the food products. Also, the pigment-based intelligent system is cost-effective with improved sensing abilities and are safe as well as nontoxic for the food packaging systems. In addition to this, it has some limitations such as the pigment-based intelligent system is not feasible for a longer duration and also are more prone to thermal degradation (Bhargava et al. 2020).

6.6 Green Packaging and Its Characteristics

Nowadays there is an emerging concern regarding the environmental disruption by using plastic materials. Green packaging materials serves as an alternative towards the non-biodegradable materials so as to reduce the environmental pollution to a wider extent. Green materials help in replacing the petroleum derived plastics and also reduce the dependency on fossil fuels. These materials are produced from non-toxic components and are widely distributed in the nature such as chitin and cellulose (Darder et al. 2007). The green packaging is 100% biodegradable as compared to petroleum-based plastic packaging materials. It can be degraded from microorganisms or marine water through aerobic or anaerobic fermentation as illustrated in Fig. 6.2 (Moustafa et al. 2019). There are three major tests which can be employed for detection of biodegradability of the polymer, namely, laboratory tests, field tests, and simulation tests. Laboratory tests include clear zone test, enzyme test, and Sturm test. Field tests carried out in nature, water, soil, and landfill, whereas simulation tests involve laboratory reactor, landfill, water and soil. Laboratory and simulation tests are conducted in synthetic and complex environment, respectively, with defined conditions. On the other hand, field tests are conducted in complex environment with variable conditions (Mangaraj et al. 2019).

Green packaging is also referred to as an ecological packaging which is reusable, recyclable, and harmless to the humans, environment, as well as livestock. It is purely obtained from natural plants and provides a sustainable development to the packaged product throughout its life cycle. The main aim of green packaging is divided into four R and one D, namely, reduce, reuse, recyclable, reclaim, and degradation (Zhang and Zhao 2012).

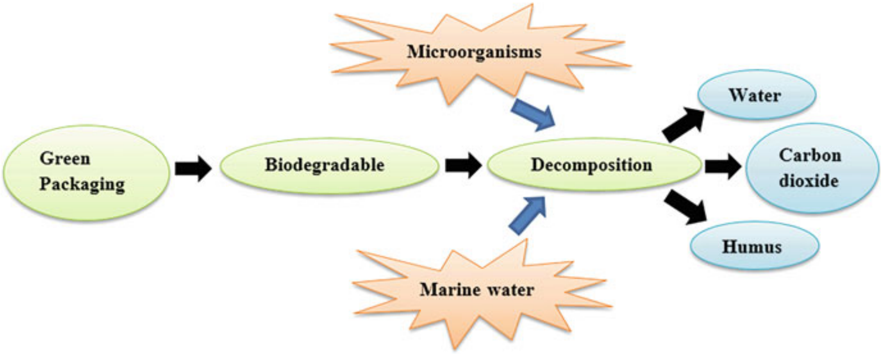

Fig. 6.2 Decomposition of green packaging (Moustafa et al. 2019)

For a packaging to be considered under green packaging category, it should possess certain characteristics including strength, barrier properties against light, heat, moisture, printing capabilities, and other chemical resistance which can accomplish the goal of food safety among the finished products. One such packaging material consists of poly (lactide), i.e., PLA which has the capability of barrier properties, recyclable properties, easily composting benefits, and natural resemblance (Ahmed and Varshney 2011). However, the higher cost utilized during the production of PLA creates a limitation towards its usage. However, cost-effective raw materials including agricultural waste helps in mitigating the higher cost barrier in the usage of PLA as a packaging material. Furthermore, polyhydroxyalkanoates (PHAs) have improved oxygen barrier and mechanical properties as compared to poly (lactide), but possess one limitation of being costly. Thus, reduction in the cost of producing PHAs generates a sustainable and effective green packaging with improved characteristics as compared from non-sustainable polypropylene packaging (Rabnawaz et al. 2017).

6.7 Application of Biopolymers in Other Areas

There are various applications of biopolymers in several fields including 3D printing technology, textiles, and other relevant areas. 3D printing is an emerging technology which is also referred as additive manufacturing to create three-dimensional materials through layer by layer placing of materials over each other such as plastics, metal, cells, and ceramics. This technology is widely utilized in various sectors such as food industry, textiles, healthcare, aeronautics, and architecture. However, there are many limitations while adopting this technology including sustainability, environment friendly, cost-effective, bio-based materials, and printer-friendly (Liu et al. 2019). Biopolymers derived from wood including cellulose, lignin, and hemicellulose are also utilized in 3D printing technology. These biopolymers derived from wood are bio-inert as well as possess biocompatibility with the environment. Thus, wood derived biopolymers can be utilized in formation of bio-inks through tissue engineering technology (Xu et al. 2018).

Textiles is another area which is gaining a lot of attention in various industries including medicine, textile, and pharmaceutical. Due to the increased demand of textiles, various chemicals are added during production to provide antimicrobial characteristics to the textile materials. However, the chemicals utilized such as antibiotics, phenols, synthetic dyes, and inorganic salts possess harmful and toxic effects on the human health. Also, chemically manufactured textile materials are not environment friendly and non-sustainable. Thus, this creates the opportunity for the development of eco-friendly and bio-based textile materials (Shahid and Mohammad 2013).

There are different types of biopolymers which possess applications in different areas. Polyhydroxyalkanoates (PHAs) are widely utilized in the manufacturing of biomedical instruments, disposable films, and gloves. Poly-(ether ester) is employed in the medical areas for slow tissue healing procedure. Poly-(hydroxy acid) find their application in the development of food packaging materials, containers, floor mats, medical surgery devices, pharmaceutical products, and cutlery items. Poly-(alkylene dicarboxylate) is used in the manufacturing of food packaging materials, containers, bottles, pharmaceuticals, disposable sheets, and plastic bags. Polyamides such as nylon is used in the manufacturing of plastic materials and textile materials. Furthermore, vinyl polymers are used in paper manufacturing, textile industries, and manufacturing of packaging bags. Polyurethanes finds the application in the biomedical areas, foaming materials, and shock absorbing materials (George et al. 2020).

6.8 Conclusion

Biopolymers have unique opportunity to provide a greener and sustainable environment which does not only possess harm to environment, humans, and livestock but also creates a novel opportunity for a safer future. The biopolymers can be utilized in food packaging materials in the form of active as well as intelligent packaging. However, with the increased benefits of biopolymers in the packaging industry, there is one limitation, i.e., cost which needs to be considered while moving further towards the improvement and inclusion of biopolymers in the packaging as well as other areas. Furthermore, with the cost-effectiveness, future studies should also focus upon utilizing the evolving technology to create and add value to the food packaging materials by using smart sensors and nanomaterials and utilizing the bio-waste in the development of packaging materials.

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