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REVIEW

Food Packaging Materials with Special Reference to Biopolymers-Properties and Applications

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Abstract
Food is an important material for survival. The increasing world population, urbanization, and globalization are responsible for more food. This has increased challenges in food storage and safety. Therefore, it is necessary to preserve food by suitable packaging materials. The packaging materials are useful for giving longer life to the food and improving quality during transportation, storage and distribution. Innovations and developments in food packaging, have become very important in the food industry. Variety of packaging materials such as plastics, paper, metal, and glass are used in food packaging. Most widely used packaging materials are non-biodegradable plastics but these are harmful to environment and human health. Therefore, the food industry is in search of environment friendly replacement of non-biodegradable plastics by biodegradable plastics. However, no systematic literature is available on the subject, so there is a need to summarise the available information in a systematic way. Polymer packaging materials with special reference to biodegradable plastics have been discussed in detail. Different type of biodegradable plastics with their functionality and applications in food packaging have been summarised. Literature available has shown that biodegradable plastics are much better for food packaging as compared to other packaging materials. Increasing fundamental research in the use of biodegradable polymers in food packaging and effort to protect the environment, requires deep understanding and there are lot of challenges for commercialization, which are to be tackled. All these aspects have been discussed in this review article.

Keywords Plastic · Bioplastic · Degradable plastic · Food · Packaging

1 Introduction

Growing population, requires more food. Therefore, production and safety of food is the most important task. Due to urbanization and globalization, food demand and its safety is very important. Food packaging has become important to protect food from contamination, dust, spill, atmospheric conditions and for safe transportation. It also preserves the nutritional value of food and decrease the wastage of food. According to report of centres for disease control and prevention more than 70 million people suffer from food related diseases yearly. It causes the economic burden and deaths. For both storage and safety of food, variety of materials as packaging materials are being used throughout the globe. The main requirement of food packaging is to protect the food from deterioration and maintain the quality for some period of time. Different types of packaging materials like glass, paper, biodegradable polymer, etc., are being used. In current scenario this is shifting towards the development of sustainable packaging material which also get the preference in market. Now-a-days polymeric materials are being used extensively as food packaging materials because of their lightweight, good thermal and mechanical properties. They also possess corrosion-resistant properties and ease in production. Number of publications related to food packaging over the last 15 years is given in Fig. 1 [1]. This number increased considerably.

Polymers are generally used as a matrix and substrates in food packaging. Because of lack of environmental awareness, cost, technological limitations synthetic undegradable polymers "[e.g., high-, low-, and linear low-density

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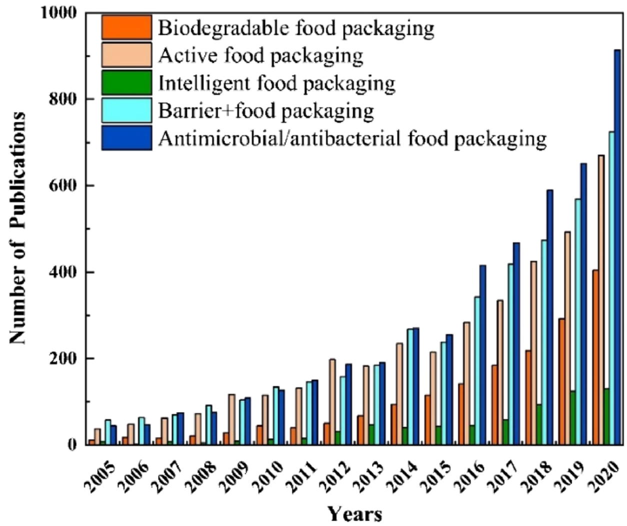


Fig. 1 Publication numbers in the past 15 years related to food packaging [1]

polyethylene (HDPE, LDPE, and LLDPE), polystyrene (PS), polypropylene (PP), polyethylene terephthalate (PET)]" are being used as packaging materials in food packaging industry. Chemical structures of some of these polymeric materials are given in Fig. 2.

Since these polymers are non-degradable, create lot of environmental problems [2, 3]. Due to this, bio-based biodegradable polymers are considered to be a good substitutes for non-degradable polymers [4]. Notably, awareness of the negative impacts of traditional plastics has been the main driving force in the growth of the bioplastic packaging market. As shown in Fig. 3, global production of bioplastics was estimated to be 2.11 million tons in 2020, 47% of which was used by the packaging industry [1].

Due to large demand of food packaging materials, the packaging industry has become one of the most important commercial sectors in the world. Most of the food packaging materials are being made with petroleum-based plastics [5]. However, petroleum-based plastics create lot of environmental problems and because of this, biodegradable polymer with various properties are being now manufactured and used [5]. Several publications have summarized plastics as a food packaging material and their advantages and disadvantages. However, in recent years much emphasis is being made to use biodegradable plastics as food packaging materials but due to high cost, it limits the use. Table 1

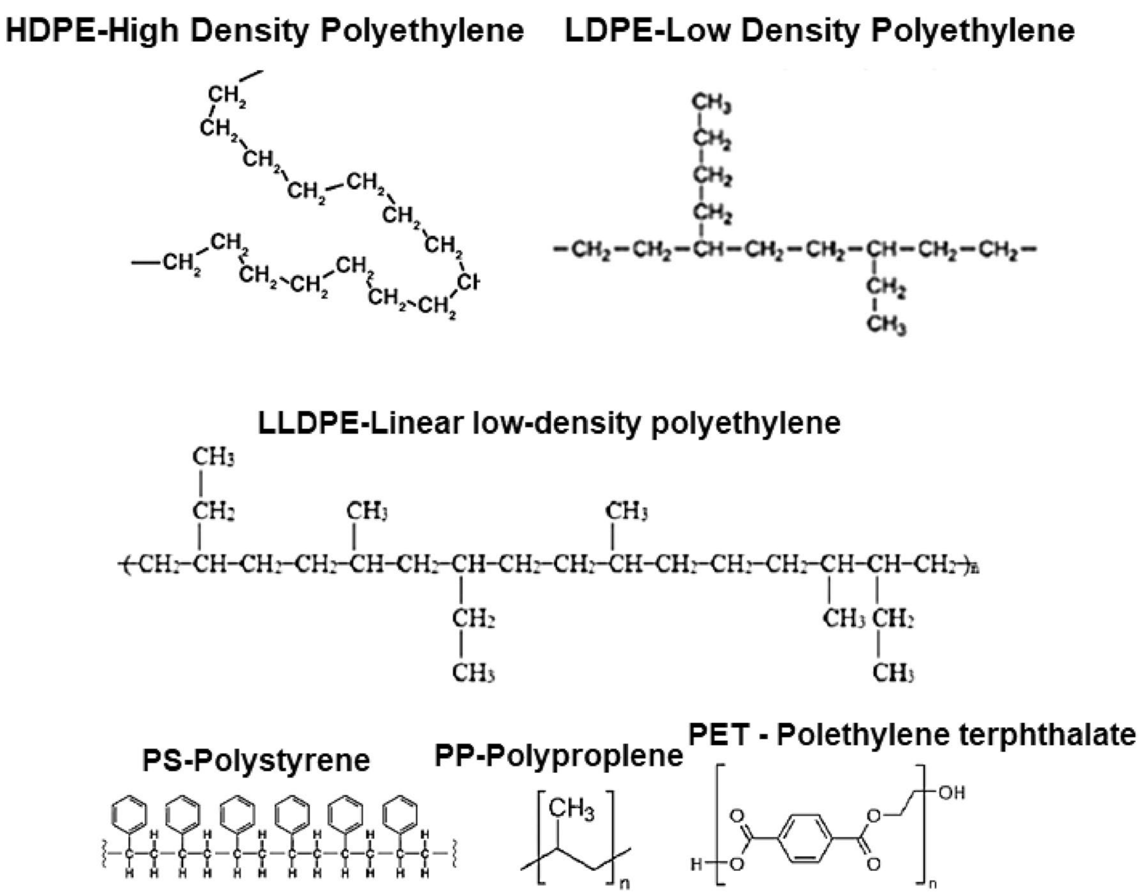


Fig. 2 Chemical structures of polymers

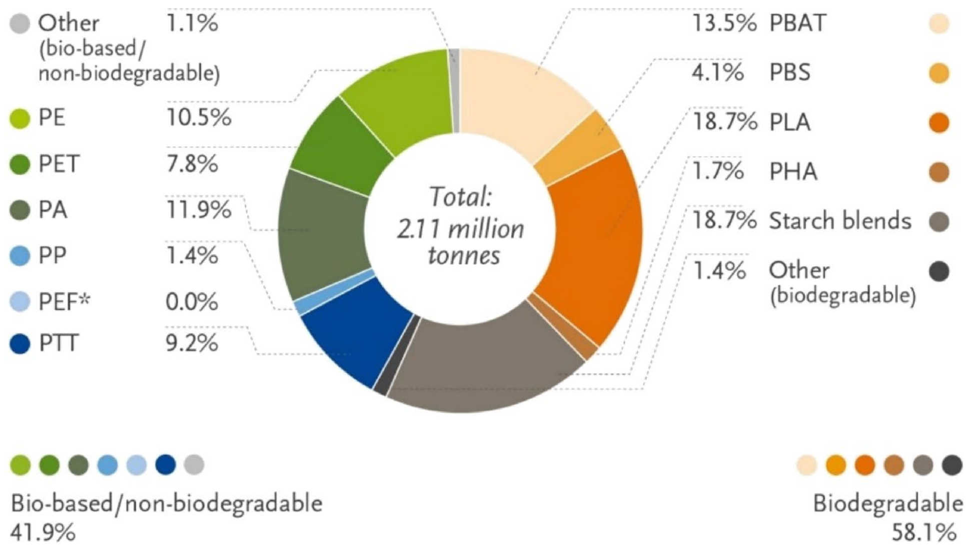


Fig. 3 Global production of bioplastic in 2020 [1]

Table 1 Scope of selected published reviews and book chapters on polymeric materials for food packaging

S. no.	Running title	Scope and main features	Year of publication	References
1	Safety and regulatory aspects	Guidelines for proper use of plastics for food packaging	2012	[6]
2	Bio-sourced polymers as alternatives to conventional food packaging materials	Opportunities, and challenges associated with biodegradable environment-friendly packaging	2021	[7]
3	An overview of biodegradable packaging	Highlights the characteristics of various biopolymers and their blends, comparison of properties between non-biodegradable and biopolymers	2021	[8]
4	Biobased materials for food packaging	Emphasis is placed on the categories of related biobased materials, their characteristics and advantages for food packaging, as well as the strategies used to improve their performances	2022	[9]
5	Food packaging in the circular economy	Recycling processes of commonly used food packaging materials and approaches to reduce chemical contamination	2018	[10]
6	Food packaging: Glass and plastic	Positive and negative aspects of glass and plastic packaging	2017	[11]
7	Biodegradable polymers for sustainable packaging	Current challenges associated with the barrier properties, processing and scalability of biodegradable polymers	2021	[12]
8	Bioplastics as food packaging materials	Weaknesses of bioplastics have been reviewed and analyzed to determine the potential of bioplastic composites	2021	[13]
9	Applications and Biodegradation of Polyhydroxyalkanoates and Poly(lactic acid) and its composites	Factors influencing biodegradation are outlined, information on various aspects of PHAs and PLA, and its composites for packaging application	2021	[14]
10	Mechanical Properties of Some Biodegradable Polymeric Composites	Tensile properties of polymers	2018	[15]
11	Impact on food quality and effect of innovative processing technologies	Insight into the connection between biobased packaging materials and innovative technologies such as high pressure, cold plasma, microwave, ultrasound, and ultraviolet light	2021	[16]

reports some relevant previously published reviews and book chapters and their major content on this issue. In this article, conventional plastics and biodegradable polymers as food packaging materials with their advantages and disadvantages have been discussed in detail.

Several publications have summarized the findings on Polymeric Materials for Food Packaging. Table 1 reports some relevant previously published reviews and book chapters and their major content.

2 Scope of the Review

Different aspects of Polymeric Materials for Food Packaging reported by different researchers are listed in Table. 1. In this review article latest contributions have been summarised.

3 Food Packaging Materials

Now it is difficult to imagine food without packaging. Food packaging protects the foods from physical, chemical and biological contaminations. At the same time, it enhances the life of food and preserves the quality. Number of packaging materials are being used but conventional petroleum-based polymers are the most commonly used packaging materials. This is because of easy accessibility and low cost of production. But the major problems with conventional plastics as a food packaging material is its non-degradable character. This creates environmental problem. Because of this, food packaging industry has paid lot of focus on biodegradable food packaging materials [17]. Number of attempts are now being made to create biopolymer-based biodegradable packaging films as a replacement for non-degradable plastics. This may solve to some extent the environmental problem [18]. Biodegradation, generally occurs by microorganisms [19]. Natural polymers are now preferred for making food packaging films because it can degrade within a reasonable time.

Number of biopolymers have been used for biodegradable packaging films. Normally they prevent oxidation of food for long period of time with high power to resist moisture, aroma, and transfer of solvents. Packaging materials made from biopolymers are normally used as wrappers for number of food items. Polysaccharide-based packaging materials have received maximum attention due to low cost, biodegradability and lot of availability. In addition, lipid-based and proteins are also used in the development of edible and biodegradable films. The biopolymer-based food additives not only enhance the shelf-life but also reduce the calories and enhance the texture and flavor of food items. The biobased materials are used in the preparation of films or coatings for their use in food packaging applications. The films are first formed and adhered to the surface of the product, while coatings are directly formed on the surface of the food products. Nevertheless, both films and coatings are comprised of rigid matrices and demonstrate certain physiological, biological, and other properties (Fig. 4) [20].

4 Requirement of Food Packaging Materials

Food packaging has become important to protect food from contamination, dust, spill, atmospheric conditions and for safe transportation. Now packaging is being developed based on the addition of antioxidant to improve the stability of oxidation-sensitive foodstuff. For this purpose, the use of natural antioxidants has been widely studied, particularly plant essential oils. Essential oils exhibit excellent antioxidant and antimicrobial properties. However, the utilization of essential oils as food preservatives is restricted due to stronger flavor. In order to overcome this problem, edible films are made with bioactive agents to induce desired functionality (Fig. 5) [21].

Active packaging controls the respiration of fruit and vegetables, lipid oxidation, loss of moisture and microbial activity [22]. It also preserves the nutritional value of food and decrease the wastage of food. According to report of Centres for disease Control and Prevention, more than 70 million people suffer from food related disease yearly [23]. It causes the economic burden and deaths. Four main groups of packaging materials are used for direct food contact: glass, metal, paper/cardboard (wood included) and a wide variety of plastics [24]. In current scenario this is shifting towards the development of sustainable packaging material which also get the preference in market. Nanotechnology can prolong and implement the basic packaging functions—containment, protection and preservation, marketing and communications (Fig. 6) [22].

Main differences between active and intelligent packaging materials are given in Fig. 7.

Fig. 4 Some features of biobased food packaging materials [20]

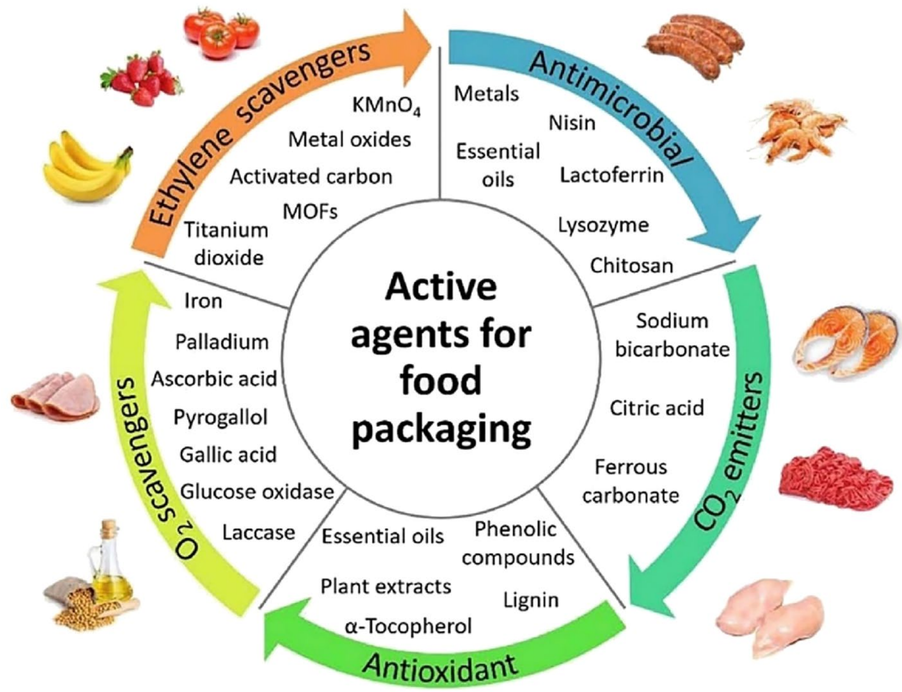


Fig. 5 Bioactive agents for smart food packaging applications [21]

Fig. 6 Function of packaging [22]

4.1 Packaging Functionality

Packaging functionality depends on type of material used for packaging (Table 2). The broad functions expected from packaging materials are protection, preservation, and presentation. The functionality is evaluated based on tensile strength, tear propagation resistance, penetration resistance, seal strength, gas transport properties, radiometric properties, water condensation behaviour etc. Most commonly, the biobased compostable materials are being used in packaging of food materials.

4.2 Chemical Food Safety and Packaging

Chemical food safety is also a matter of concern [32]. It happens through migration of chemicals from packaging materials to food which causes illness in human being. The migration of chemicals to food through packaging materials is summarised in (Fig. 8). Papas et al. have reported the mass transfer of synthetic antioxidant between food matrix and food packaging materials [33]. Solvents used in printing on packaging materials also transfer in food by direct contact or evaporation, which change the organoleptic properties of food. The polystyrene milk container which are made up of styrene monomer may also lead toxicity. The styrene degrades in to respective oxide, causing mutagenic effect, irritation to skin, suppression of the activity of lungs, etc. [34].

4.3 Environmental Impact of Packaging

A large faction of Municipal solid waste is packaging waste. The common methods used for plastic waste management are land filling and incineration, which cause environmental pollution (Fig. 9). Recycling cost of packaging waste has become unbearable than the production cost, which is a serious concern for environment. Plastic materials used for

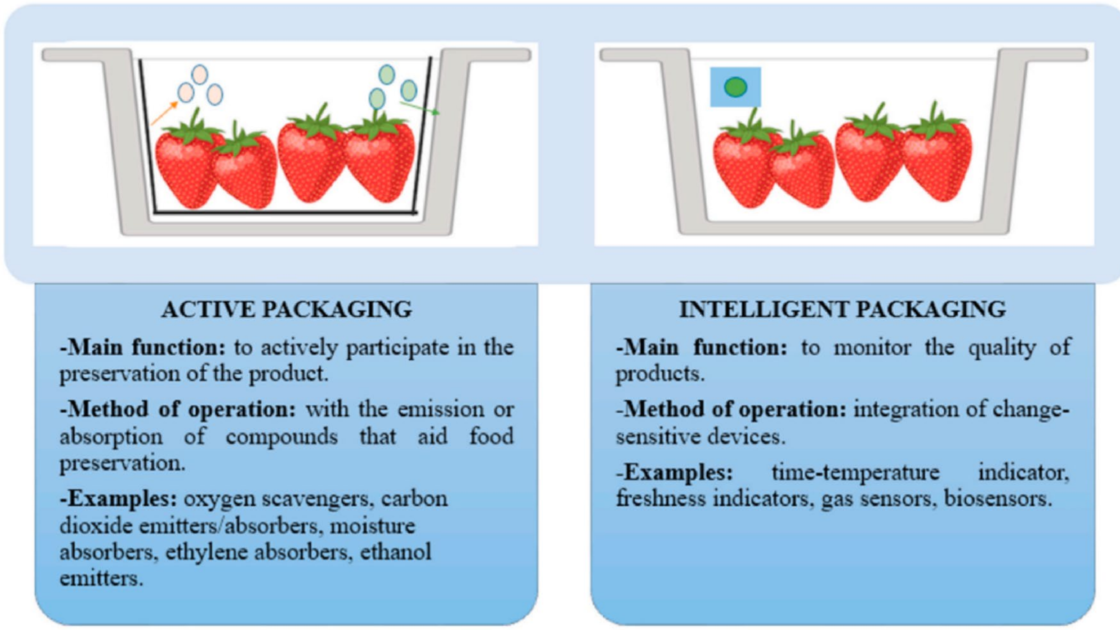


Fig. 7 Differences between active and intelligent food packaging materials [25]

Table 2 Packaging Materials and functionalities

S. no.	Packaging material	Functionality	References
1	Poly glycolic acid (PGA)	Barrier property	[26]
	Nanofiller blended biopolymer	Hydrophobicity and barrier protection	[27]
	Plastic films	Barrier property, sealing, printability	[28]
	Cellophane	Good mechanical property and elasticity	[22]
	PLA reinforced with cellulose nanowhiskers	Oxygen and water vapor barrier	[29]
	Chitosan reinforced with bacterial cellulose micro- and nanofibers	Mechanical, water vapor barrier, bacteriostatic, and bactericidal	[29]
2	Paper	Printability	[30]
3	Paper processed in biopolymer coating	Good barrier property	[31]
	Paper sheet containing polyaniline (PANI) and polystyrene (PS), in the presence of dispersed baggase pulp fibers	Antibacterial property	[22]
7	Inorganic nanoparticle	Antimicrobial	[22]
8	Organic nanoparticle	Good tensile strength, mechanical and barrier property, reduced cost, environmental friendly	[22]
9	Bio nanocomposite	Good mechanical, barrier and heat resistance property	[22]

food packaging remain undegraded for years, causing global warming, fossil resource scarcity etc. (Fig. 10). Most of the packaging plastic materials used in food industry are derived from fissile fuel. When packed food is thrown, the plastic is converted into microplastic and enter into the food chain and get bioaccumulated [35, 36].

4.4 Sustainability of Food Packaging

Food packaging material play a very important role in sustainable development [38]. It is very challenging area as number of factors are involved such as complexity of food products, transportation, consumer behaviour, marketing, spending trends, life cycle assessment, appropriateness of regulatory framework, etc. To bring the sustainability in food packaging, the biopolymer are being used in which biopolymers are mixed with biodegradable additives, which are easily biodegradable. Use of biopolymers for food packaging minimize the emission of greenhouse gases. Biopolymers are cheaper than fossil fuel-based polymers. Poly lactic acid (PLA), polycaprolactone (PCL), polyhydroxy butyrate (PHB) are commonly used biopolymers. Out of all

Fig. 8 Migration of contaminant from packaging material into food

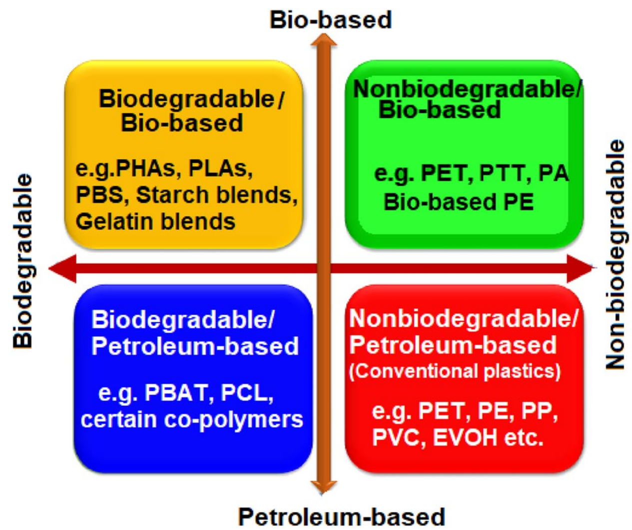


Fig. 11 Different types of polymers for food packaging [21]

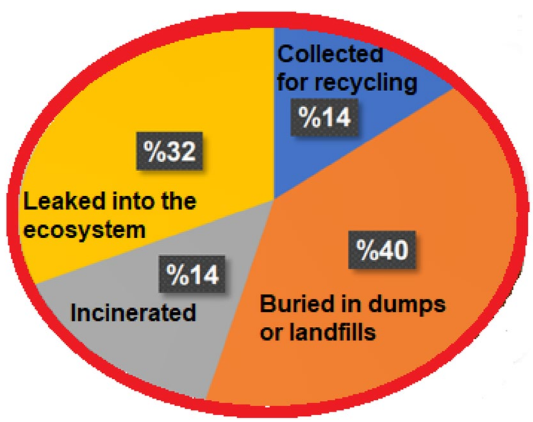


Fig. 9 Packaging waste management [35]

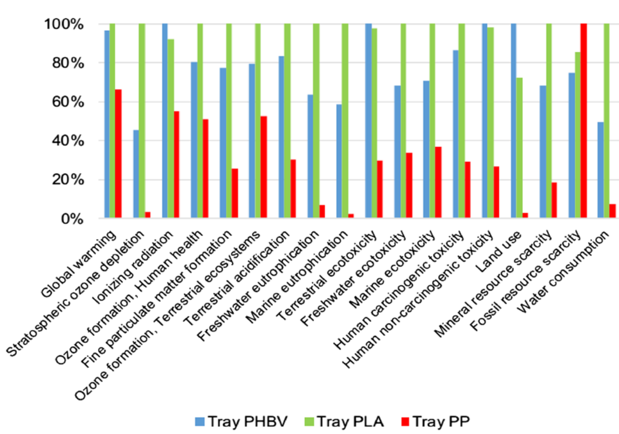


Fig. 10 Environmental impacts of packaging material [37]

biopolymers, PLA is comparable with petroleum-based plastics. Biodegradability of packing materials is also checked to develop sustainable packaging materials [39]. For sustainable packaging, it should be effective in terms of adding value to society, efficient throughout life cycle, recyclable and safe [40].

5 Polymer Packaging Materials

There are basically four types of polymer based packaging materials (Fig. 11) [21]

Petrochemical-based plastics caused more harm than good and therefore, bioplastics is considered to be a better alternative. Bioplastic is advantageous in many respects such as low carbon footprint, renewable resources, healthier rural economies and others. On the other hand, petrol-based plastics are non-biodegradable, non-renewable, and causing detrimental health issues due to release of harmful gases (Fig. 12) [40].

5.1 Petroleum based plastic materials

Petroleum based polymers are being widely used for food packaging. Although they are easy to process, possess good mechanical and barrier properties, but lack degradability and emission of greenhouse gases are major concern [41]. Polypropylene (PP), polyethylene (PE), polyurethane (PU), poly (ethylene terephthalate) (PET), polystyrene (PS), expanded polystyrene, polyamides (PA), and poly (vinyl chloride) (PVC) are commonly used petroleum-based polymers for food packaging [42].

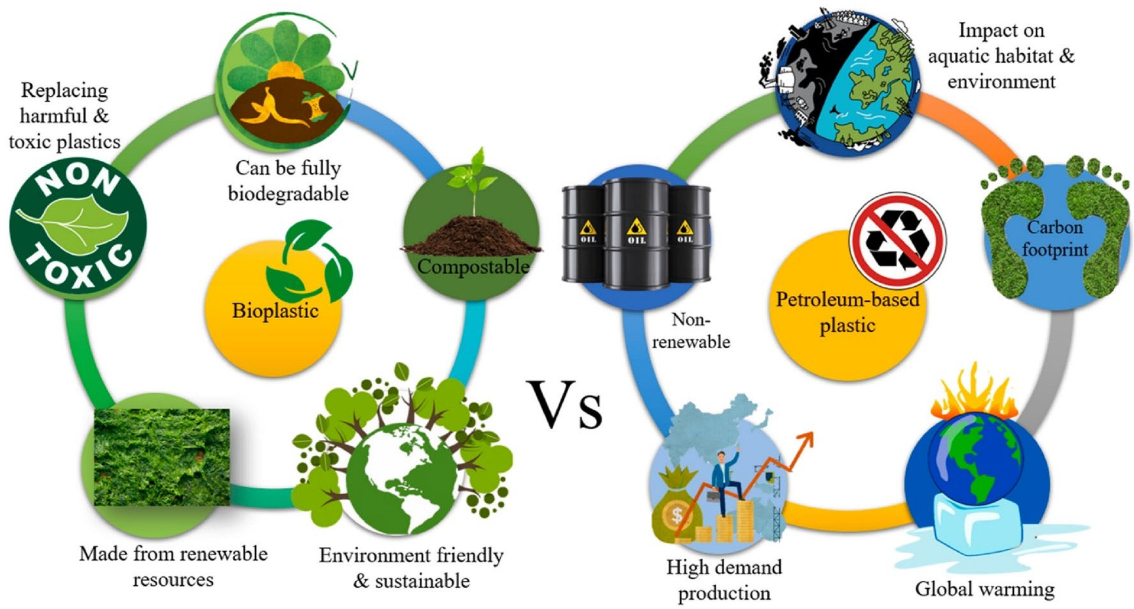


Fig. 12 Comparison between bioplastic and petroleum-based plastic [40]

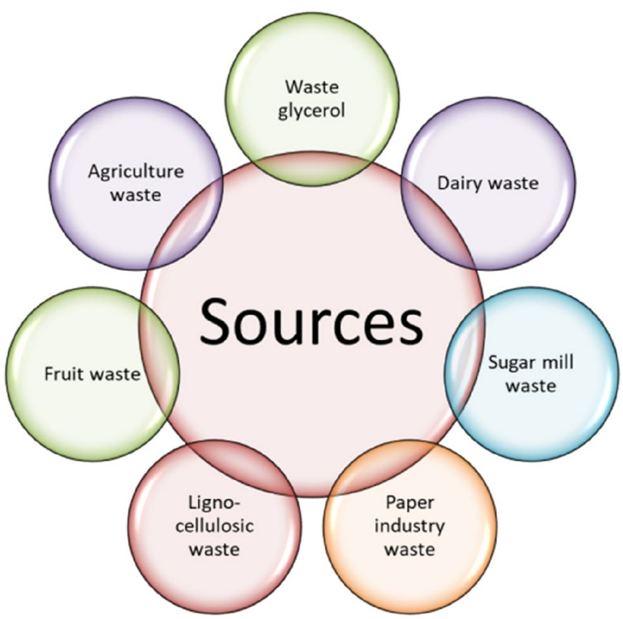


Fig. 13 Sources of substrate for biopolymer production

5.2 Biobased Packaging Material

Biobased polymers are the polymers which are produced by living (micro)organisms like plants or microbes through metabolic engineering processes and are originated from renewable resources like wood, polysaccharides, food waste, agriculture waste or lignocelluloses (Fig. 13) [43]. These polymers are biodegradable, biocompatible and ideal for food contacts. Based on the method of synthesis, biobased polymers are divided into three groups: Microbially Originated.

Polymers, Wood Based Polymers and Protein Based Polymers. These are discussed below.

Biobased packaging materials such as cellulose and chitin can be converted in nanoform, where their utility as food packaging material, in the form of film or coating has been improved. Coating of Nanofibrilated cellulose (NFC) on bio high-density polyethylene (HDPE) improved the grease resistance and decrease the oxygen permeability [44]. Although nanocellulose is inert for intelligent packing but it gives excellent support to intelligent materials used in food packaging. The intelligent agent which are reported by various researchers with biobased nanomaterials (Table. 3) can also work as freshness sensor, antibacterial and antioxidant agents, etc.

5.2.1 Microbially Originated Polymers

Microbially originated polymers are synthesized by fermentation process. Various renewable biomasses are used as substrate for fermentation in the presence of enzymatic catalyst [53]. Biopolymers such as xanthan, dextrans, pullulan, glucans, gellan, alginate, cellulose, cyanophycin, poly (gamma-glutamic acid), levan, hyaluronic acid, cellulose, organic acids, oligosaccharides, polysaccharides, and polyhydroxyalkanoates can all be biosynthesised by microorganisms [54].

Table 3 Active/intelligent agent blended biobased material and their applications

S. no.	Biobased nanomaterials	Active/intelligent agent	Application	References
1	Nanocellulose	Flavonoid silymarin	Effective antioxidant properties	[45]
2	Nanocellulose	Ferulic acid and derivatives	Antioxidant and bactericidal effects	[46]
3	Bacterial nano cellulose	Sulfobetaine methacrylate	Sensors to monitor food humidity, bactericidal against *Staphylococcus aureus* and *E. coli*	[47]
4	Nanofibrilated cellulose (NFC)	Tannins	Antioxidant property	[48]
5	Cellulose Nanocrystal (CNC)	Wheat gluten incorporating TiO_2 nanoparticles	Antimicrobial activity against *S. aureus*, *E. coli*, *Saccharomyces cervisiae*	[49]
6	AgNP/BNC-PVA	Ag NPs	Antimicrobial activity against *E.coli*	[50]
7	Bacterial Nanocellulose	Methyl red	Freshness indicator for broiler chicken	[51]
8	Sugarcane bagasse nanocellulose hydrogel	Zn^{2+} cross-linking	Colourimetric freshness indicator	[52]

5.2.2 Polyhydroxyalkanotes (PHA)

PHA is produced within the bacterial cell via fermentation and first introduced by Beijerinck and colleagues. Polyhydroxybutyrate(PHB), polyhydroxyvalerate(PHV), polyhydroxyhexanoate (PHH) and polyhydroxyoctanoate(PHO) are widely used PHA, among which PHB is the most popular in terms of durability and acceptability due to its similarity with conventional plastics [54]. In the presence of high carbon and limited oxygen, sulphur, nitrogen and phosphorus, PHB is synthesized as energy storage by gram negative bacteria *Alcaligenes eutrophus.* It accounts for 70–80% of cellular dry weight, depending on source of carbon and microbial colony [55].

The renewable resources for PHA synthesis are food waste materials like fats, domestic waste, frying oil, crude glycerol, and starch, fructose, maltose, xylose etc., or n-alkanes or n-alcohol and gases. PHA polymers are synthesized by linking large number of monomers and it provides the best biodegradability and properties similar to conventional plastics [56]. Due to high biodegradability, it is best suited for short term food packaging. PHA also possess biocompatibility with human tissues and so, acceptable as medical implant devices like nails, screws, or bone plates. Depending on the carbon atoms, as repeating unit, PHAs are classified in three groups: Short chain length PHAs(sCL-PHAs) which contain 4 to 6 carbon atoms, medium chain length PHAs(mCL-PHAs), which contain more than six carbons, and long chain length (lCL-PHAs), with more than 14 carbon atoms [54].

PHAs synthesis takes place by providing excess carbon and limiting nitrogen sources in substrate [57]. In the limited quantity of oxygen and nutrients, the bacterial cell are not able to divide and grow, and bacterial metabolites synthesize hydroxyalkyl-CoA(HA-CoA). HA-CoA in the presence of enzyme PHA synthase, PHA polyester is synthesized by polymerization. The acetyl-CoA which acts as intermediate in all PHA polymer synthesis, are produced from cellular metabolic pathways like krebs cycle, de novo synthesis of fatty acids and glycolysis cycles. The metabolic conversion from acetyl CoA to PHA depends on the amount of nutrient in medium. In high nutrients availability, acetyl CoA diverted to krebs cycle, provide energy for cell growth and inhibit 3-ketothiolase (PhaA) synthesis and thus blocks PHA synthesis. However, in unbalanced nutrient supply, Coenzyme A directly diverted to 3-ketothiolase production and results in PHA accumulation in bacterial cell [58] (Fig. 14).

PHA is recovered from bacterial cell by cell lysis, followed by purification and precipitation. Various methods like solvent extraction, enzyme digestion or chemical are used for PHA recovery. However, solvent extraction is most promising method due to high purity (94–98%). Although enzymatic method may also provide high purity (approximately 90%) but less acceptable due to high cost involved.

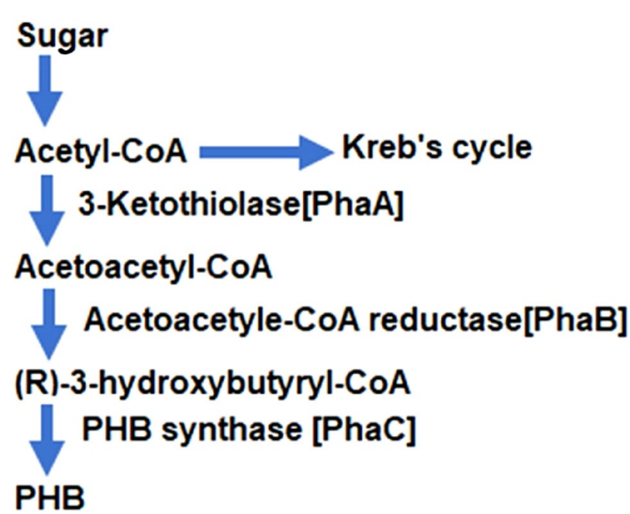


Fig. 14 Flow chart of PHB synthesis

5.2.3 Polylactic Acid (PLA)

PLAs are made from aliphatic monomers either by starch fermentation or lactic acid monomers via chemical synthesis. Fermentation can be carried out on any carbohydrate rich products like wheat, corn, sugarcane, kitchen waste etc. The synthesis of PLA involves the production of Lactic acid followed by lactide monomers and then polymerization [59].

The popularity of PLA as food packaging is increasing since last decade among industrialist due to optimum mechanical strength, nontoxicity, biodegradability, and renewability. During production, it leaves low waste, emit less carbon and consume less energy. The poor heat resistance capacity makes it limited usage in food containers. However, number of researches have been conducted in recent years to improve heat resistance and reduce cost. Heat resistance can be improved by blending PLA with cellulose [60]. In addition to this, other polymers and different range of fillers has also been incorporated to improve end product performance and reduce cost. Furthermore, the addition of nanofillers like talc, silica, and nanoadditives are used to improve its physical and chemical properties. However, inclusion of nanomaterial may lead to high cost which can be reduced by inclusion of raw materials.

The antimicrobial ability of PLA has been investigated in recent years. PLA surface coatings made by incorporation of silver nanoparticles, sophorolipid, cellulose nanocrystals, lysozyme exhibit preventive effects against *Escherichia coli*, S*almonella* spp., *Staphylococcus aureus, Listeria monocytogenes, Micrococcus lysodeikticus* and increase the shelf life of perishable fruits [61].

5.2.4 Exopolysaccharides (EPS)

Exopolysaccharides are long chain polysaccharides produced from bacterial fermentation. The substrate used for bacterial fermentation can be a carbohydrate rich food waste, coconut water, potato peel, dairy waste, sugar cane molasses, sugar cane juice etc. Lactic acid bacteria have been used since decades for improving functional properties of foods in terms of prebiotics and probiotics. However, with advancement and increasing awareness about safe food consumption, lactic acid bacteria are used to produce exopolyscaccharides to improve food texture and safe packaging. Other than gram positive and gram-negative bacteria, Exopolysachharides are also synthesized by yeast, fungi and blue green algae [62]. Exopolysaccharides are secreted outside the bacterial cell during growth and recovered by separation and purification. Based on the number of sugar monomers, Exoplosaccharides are divided into two groups: Homopolysachharides, which consist of one type of sugar monomer like α D glucans, β D glucans, Fructans, galactans or fructans and Hetropolysacharides, which consist of different type of sugar monomers as structural unit. Other than the sugar monomers, the structural unit also contains other derivatives like DNA, amino sugars, lipids, pyruvates, succinates, glucuronic acid, etc. [63].

Exopolysaccharides (EPS) produced from LAB possess good structural integrity and smooth and shiny surface that facilitate the formulation of edible coating/film for food products. Moreover, despite of low productivity from LAB, exopolymers are integrated with other nanocomposites to provide, antioxidants and antimicrobial properties [64]. The barrier properties for moisture prevention can be improved by adding fillers like glucose, glycerol or oleic acids. Edible film formulation by incorporation of EPS with starch like corn starch, cassava starch showed good mechanical and chemical properties. Composite EPS film prepared by incorporation of sodium carboxymethylcellulose (CMC) with Lactic acid Bacteria (*Lactobacillus plantarum*), demonstrate improved antioxidant activity and reduced moisture absorption capacity [65, 66]. Among all the EPS, Kafiran is gaining attention due to its antimicrobial activity and biodegradability.

5.3 Wood Based Polymers

Wood based polymers are predominantly derived from lignocelluloses polysaccharides. Lignocelluloses contain 40–50% cellulose, 25–30% hemicellulose and 20–25% lignin (Fig. 15). Other than the packaging material, wood fibbers are used for non-woven products, paper products, and various panel boards [67].

5.3.1 Cellulose and Hemicellulose

The nanoscale dimensions of cellulose nanoparticles allow scientists and technologists to use the cellulose most efficiently due to its strong, entangled nanoporous network. Various methods have been employed to incorporate different materials with cellulose nanoparticles to achieve multifunctional properties, such as the ability to enhance mechanical or barrier properties, enhance coloring, and improve dyeing [67]. The incorporation of chitin, with cellulose nanocrystals, give strong percolating network, homogenous surface and fillers for best tensile strength [68]. Nanocomposite films prepared from nanocellulose and alginate polymers, showed good tensile strength but high concentrations of cellulose nanomaterials, decrease the transparency of the film [69]. A blended film prepared from sugarcane bagasse extracted carboxymethyl cellulose (CMC), with getalin, agar and glycerol, exhibit, low water vapor permeability and high biodegradability [70]. Figure 16 represents the flow for development of CMC blended bioplastics.

Hemicellulose, is a sugar polymer, and second largest constituent of wood. It consists of glucose and several small

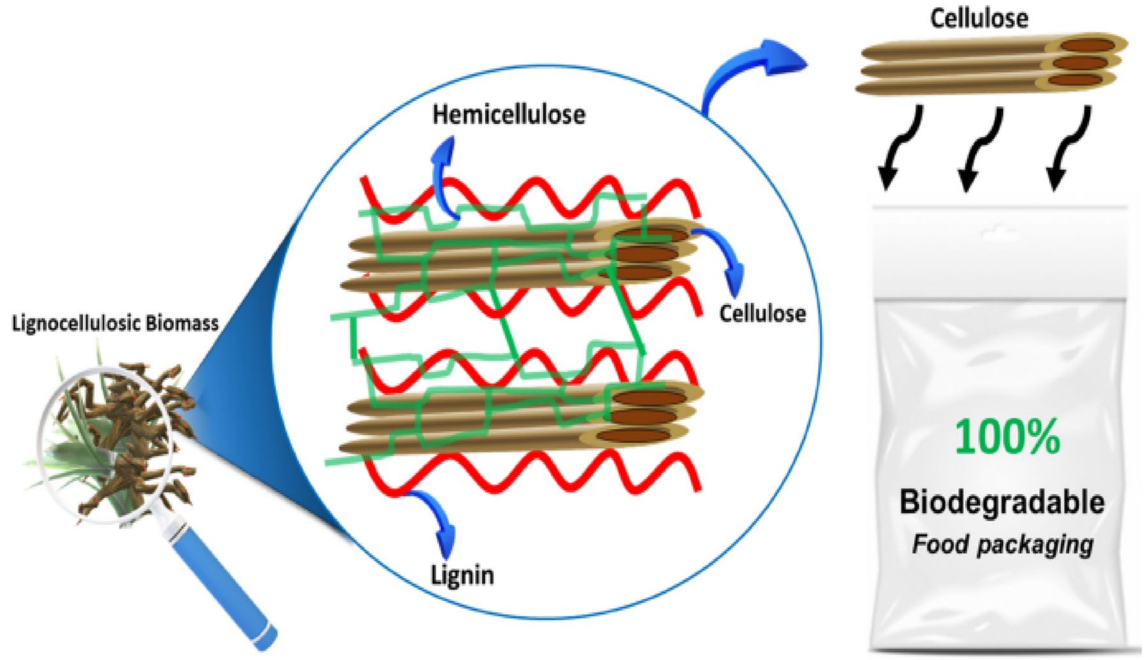


Fig. 15 Structural composition of lignocelluloses biomass

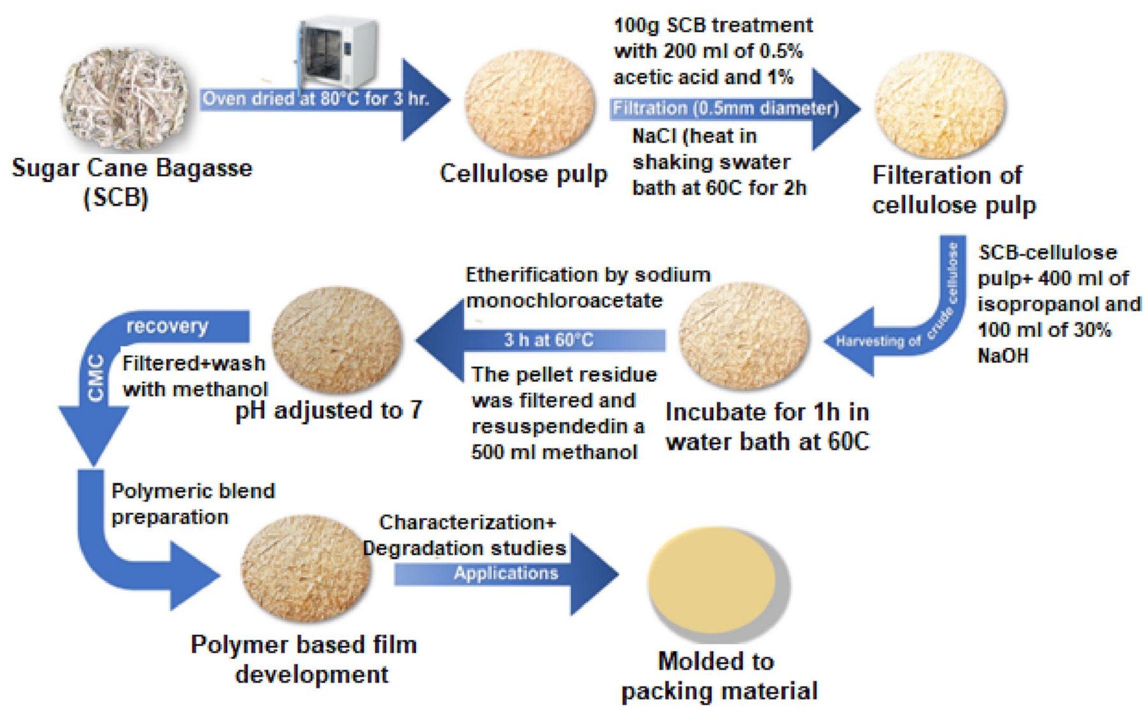


Fig. 16 Flow of development of CMC bioplastics

sugar molecules, synthesized via photosynthesis in plant cell. They account for 25–30% of wood dry weight. Hemicellulose is considered a potentially more environment friendly alternative to plastics for packaging material. Extraction of hemicelluloses from plant cell is carried out by various methods like, steam explosion, hot water extraction, acid extraction or alkali extraction. However, highest yield (84%) was reported with two step alkali extraction-delignification method. Other than food packaging, hemicellulose is widely used for film production due to its low molecular weight and functional hydroxyl group. The film is generally prepared by casting and drying method [71]. Figure 17 represents a common process of film formation from hemicelluloses solution.

Food packaging materials must have acceptable mechanical properties, a good barrier and flexibility. Due to their branched and amorphous structures, unmodified hemicellulose films do not show good mechanical properties. In addition to this, the presence of hydroxyl group makes it more susceptible for moisture absorption. To improve the mechanical and barrier properties, hemicelluloses film requires physical and chemical modifications [72]. The addition of plasticizer like sorbitol, glycerin in composite film(hemicelluloses-chitosan) represents improved barrier property, elongation at break but reduced tensile strength. However, on the down side, addition of plasticizer, results in increased moisture absorption due to hydrophilic nature of plasticizer. To prevent water absorption and improved hydrophobic nature, etherification with galactoglucomannan (GGM) with butyl glycidyl ether indicates improved thermal and mechanical property [73].

5.3.2 Chitosan/Chitin

Chitin is also an abundant biopolymer on earth after cellulose. It mainly originates from the exoskeleton of marine invertebrates and insects or the cell wall of some fungi. Chitosan is a cationic biopolymer, which can be produced by deacetylation of chitin. Chitosan has amino and hydroxyl group in its structure, which enabled the antimicrobial activities against gram-positive and gram-negative bacteria. Chitosan films showed good antimicrobial and antioxidant activities for food packaging. The crustacean shell waste generated from sea industry is used to produce chitin, further converted into chitosan through deacylation process [74]. The presence of the amino group in chitosan helps in the interaction with bacterial cell wall, which cause leakage of cell fluid and ultimately bacterial cell death [75]. It also forms cellophane kind layer on food surface which prevents the microbial attack. In addition, chitosan layer hinders gas exchange, make the oxygen unavailable for aerobic microbes [74]. Quaternized chitosan decrease the microbial metabolism by chelating with essential trace metals required for microbial metabolic machinery [76]. Chitosan promote the chitinase enzyme formation which degrade the fungal cell wall [77]. Due to vast properties chitosan can be used as packaging film or in the form of coating.

Blending of chitosan with bio proteins improve moisture barrier property, compatibility, thermal stability [74]. Lysozyme blended chitosan film packing improves the freshness and shell strength [78]. Chitosan is an amazing raw material for making intelligent packaging film. Carrot anthocyanin mixed cellulose-chitosan film has been reported to check the freshness of dairy products. After 48 h of storage at 20 °C, a color change from blue to purplish-pink can be observed [79].

5.3.3 Lignins

Every year, approximately 80 million tons of lignin is used in paper making industry, from which 2% is only utilized by

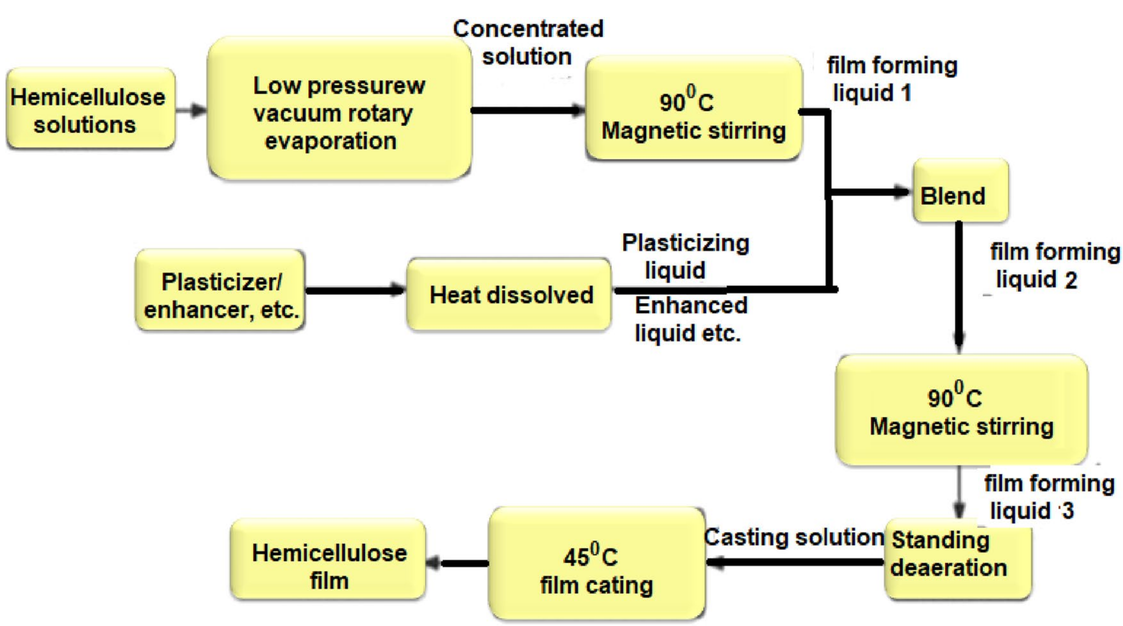


Fig. 17 Flow chart of hemicelluloses film formation

industries for processing and 98% are wasted in fuel. Technical lignin is obtained by delignification methods from which, kraft lignin and lignosulfones accounts for 90% of technical lignin produced by paper industry [80]. In the synthesis of phenol–formaldehyde (PF) resins, lignin can replace phenolic compounds. In addition to this, the phenols in the petrochemical-based PF resins can be replaced by lignin as a biodegradable material. Presence of hydroxyl group, and hydrophilic nature, lignin polymers are used in combination with starch, amino acids, polylactic acids for improved mechanical and reduced moisture absorption features. A packaging film prepared with lignin (as reinforcement material) with starch (extracted from sago palm) showed improved barrier property and seal strength [81]. Other than reinforcement material, lignin can also be used as stabilizer, and plasticizer, with cellulose, PLA, PHB polymers for production of biodegradable and biocompatible bioplastics [82].

6 Protein Based Polymers

6.1 Gelatin and Collagen

Gelatin is an odorless protein, comprised of random polypeptide chain and extracted from collagen via partial hydrolysis. The high functional properties of gelatin make it a valuable biopolymer in the food industry. Based on its processing method, it can be divided into two: (1) type A: with an isoelectric point of pH 8–9, obtained from collagen treated with acids; and (2) type B: with an isoelectric point of pH 4–5, obtained from collagen treated with alkali, which converts asparagine and glutamine residues into their acids, resulting in a higher viscosity. Gelatin obtained from pig skin are referred to as type A and gelatin obtained from bones and beef skin are referred to as type B [81]. Due to the high moisture absorption tendency, several improvements are required to modify the hydrophilic nature of film prepared from gelatin. The addition of natural extracts, via crosslinking modification, demonstrated improved gel strengthening in comparison to pure gelatin film [82]. Addition of ferulic acid by dry casting prevents humid absorption for almost 15 days without damage. Other biopolymers like chitosan, zinc oxide nanoparticles, tea polyphenols with gelatin in varying amounts are used to enhance antimicrobial and antioxidant's ability [83].

6.2 Soy Protein

The good adhesiveness, fiber binding, and great texture formation capability of the soy-based film make it the area of interest for many researchers. These films are prepared from soy protein isolates, which contain 90% protein [84]. Soy protein isolates are precipitated from various soy sources such as soy milk, soy flour, or crude soybean. Films prepared from different sources exhibit different molecular weights and thus different mechanical and functional properties. The mechanical and physical characteristics of the soy-based film can be improved by adding some substances [85]. Qianqian et al. [86] added stearic acid by conjugation technique and found 35.4% reduction in water vapor permeability and up to 75% reduction in water absorption capacity. Adding cysteine in solution, improves the tensile strength of soy film by making disulfide bonds. Other than soy proteins, globulin proteins, pea proteins, Zein protein, are also used for food packaging [86].

6.3 Casein and Whey Proteins

Casein and whey both are obtained from milk after cheese production. In aqueous solutions, casein can make film due to intermolecular hydrogen, and electrostatic bonds. However, the films are moisture sensitive due to their hydrophilic nature. The physical and chemical properties can be improved by adding genipin, wax, polysaccharides, lipids, and glutaraldehyde via crosslinking, to reduce moisture absorption and increase shelf life [87]. Whey-based food packaging is prepared from whey protein concentrate (WPC) and whey protein isolates (WPI) and both are rich sources of sulfur-containing amino acids like methionine, and cysteine. Heating whey protein isolate solution for denaturation at 80–100 °C for few min. leads plasticized films formation. At alkaline pH 6.6, heating solution at 75 °C for 30 min. provide more uniformity in WPC film. Thus, the tensile strength, elasticity and uniformity in film can also be improved by giving UV treatment in alkaline pH (7 to 9). The hydrophilic nature of film can be prevented by addition of lipids like waxes, plant oils, or fatty acids [88].

7 Biodegradable Plastics as Food Packaging

Biodegradable plastics comprised of only 1% of production annually. Biodegradable plastics are environment friendly and decompose in environment by fragmentation process [89] (Fig. 18).

The degradation of plastics is affected by the raw ingredients used, chemical characteristics, and design of the finished product, as well as the climatic conditions such as location and temperature under which the product is expected to biodegrade. Henceforth, few characteristics can be used to determine the biodegradability of packaging material as discussed below:

i. The biodegradable product should contain at least 50% organic mass, for making it biodegradable upto 90% within 6 months.

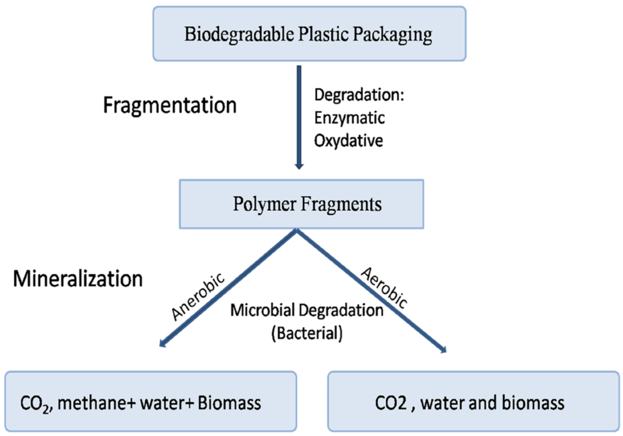


Fig. 18 Stages of Biodegradation

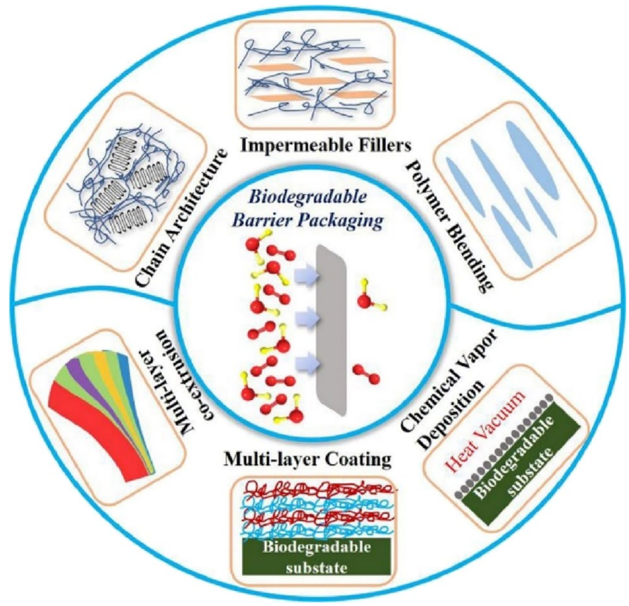


Fig. 19 Approaches for high barrier biodegradable packaging

ii. Biodegradable plastics should not contain heavy metal, beyond the health limits.

iii. The rate of biodegradation can be determined by production of CO_2 or mineralization of matter. Although some fermented food and beverages liberate CO_2 during storage and excess of CO_2 may decrease the shelf life. To determine the CO_2 permeability from biodegradable packaging Carbon Di Oxide Transmission Rate (CO_2TR) is used. It allows the amount of CO_2 permeable inside and outside of the packaging material [90].

iv. The oxygen permeability can be determined by Oxygen Transmission Rate (OTR). Oxygen Permeability Coefficient (OPC) is expressed in Units of kg mm^{-2} s^{-1} Pa^{-1} while OTR is expressed in cc-mil. A low value of OPC, indicates low oxygen permeability which increases the shelf life of food product [91].

v. Moisture content in the environment has a direct impact on the pace of physical or chemical degradation. The Water Vapor Transmission Rate (WVTR) is widely used method to calculate water permeability. It is expressed in kg mm^{-2} Pa^{-1}

vi. Apart from this, the structural and operational approaches (film forming, injection molding, blow molding, or sheet extrusion) used for a particular polymer determine its mechanical properties. Since most of the food items are stored at low temperature, the biodegradable plastics must possess a strong tensile strength. Addition of nanoparticles like PLA and PCL increases the tensile strength [92].

vii. Additions of biosurfactants like polysaccharide-lipid complex, lipoproteins, phospholipids, etc., will provide even surface and enhance biodegradability of the package. Biosurfactants are produced from microorganisms either extracellular or intracellular. It contains functional groups, which provide more stability under high temperature and pH [93].

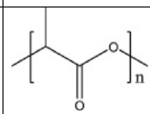
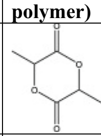
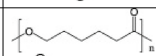
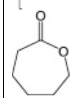
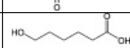
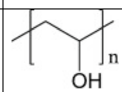
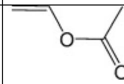
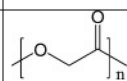
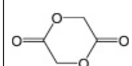
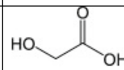
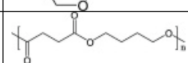
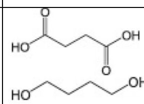
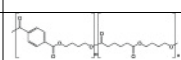
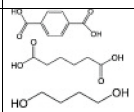
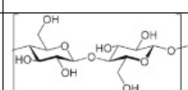
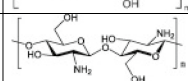
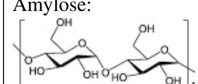
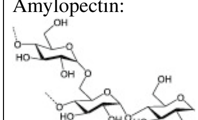
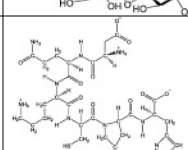
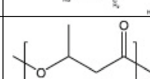
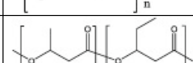
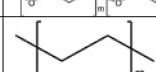
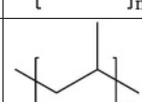
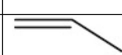
viii. Addition of additives like agricultural waste, colorants, nanocomposites, dialdehyde starch and silica [94], cellulose nanofibers [95], edible oils, natural rubber, soy protein will improve biodegradability. Addition of biodegradable additive convert degradation of plastic to biodegradable by attracting microorganism and increase the rate of degradation.

Chemical structures of biodegradable polymers and the corresponding monomers (for synthetic polymers) are given in Table 4 [1].

7.1 Barrier Properties of Biodegradable Food Packaging Materials

Continuous efforts are being made to develop biodegradable plastics with the emphasis on the improvements of mechanical and/or transport properties. The packaging materials should have good barrier character to oxygen and water vapor, transparency and good mechanical performance. The penetrant's diffusion and solubility in polymers are primarily determined from the nature of penetrate, processing methods used to fabricate membranes, structure and morphology of polymers. The barrier of biodegradable polymers can be improved via improvements in crystallization/orientation, chain configuration, polymer blending, multi-layer coextrusion; nanotechnology and coating (Fig. 19) [12].

Table 4 Polymer and monomer structure of common biodegradable polymers [1]

Biodegradable Polymers	Polymer Structures	Monomer Structures (for synthetic polymer)	Tensile strength (MPa)	WVTR (38 °C), 90% RH ($g/m^2/day$)	Elongation at break (%)
PLA			44	27–50	30.7
PCL	 		16	20–25	250–300
PVA			1.5–4	2000	200–800
PGA	 		13	10	40
PBS			40	2200–2300	150
PBAT			12–30	130	500
Cellulose/ Bacterial Cellulose			13–59	4.6–9	4–10
Chitosan			38–77	0.5–1.3	17–76
Starch	Amylose:  Amylopectin: 		4.8–8.5	7.8–9	35–100
Gelatin			17	290	20
PHB			25	1.16	5
PHBV			40	10	2.3
PE		$H_2C{=}CH_2$	10–30	4–23	213–745
PP			40–50	9.3–11	100

7.2 Classification Biodegradable Plastics

Biodegradable plastics are classified into two groups (Fig. 20):

1. Biobased Biodegradable Plastics
2. Fossil Based Biodegradable Plastics

7.3 Applications of Biodegradable Plastics in Food Packaging

The application of biodegradable plastics had been attempted from last few decades as biodegradable waste bags, mulch films, wound sutures, biodegradable staples or pins, etc. Furthermore, for storing perishable food items, these biodegradable plastics not only provide an attractive packaging but also increase the shelf life. The commonly used food grade biodegradable packaging is, net coverings for fruits, egg trays, rigid beverage bottles, etc.

In the food processing and packaging industry, different biodegradable polymers offer different applications. The qualities of a material can be improved by combining two polymers. The biodegradable trays produced by combining cassava starch with sugarcane bagasse along with other polysaccharides like cornhusk, orange bagasse, showed more resistance and rigidity than EPA trays [96]. In the same way, blend of PHA/PHB showed an excellent quality for food packaging [97]. The combination of PHA/ZnO, poly (3-hydroxybutyrate-*co*-3-hydroxyvalerate) with wood fibre (PHBV/wood fibre) possesses improved tensile strength, elasticity, and form a thin film, which is suitable to pack junk food and wrap meals [98]. Furthermore, the blend of cellulose and alginate, form an excellent film used in food packaging industry.

7.3.1 Films

As in recent times demand for biodegradable polymers are increasing for resolving many of the environmental problems, one of the major causes of environmental issues are excessive use of non-degradable synthetic materials [99]. Thus, for replacing plastics (PE) as packaging material biodegradable films are widely used. These are formed by adding additives during manufacturing process. Usually, enzymes are used as additives and helps in breakdown of plastic material. These biodegradable films have following desirable properties which make them better than PE films [100]:

- It allows controlled respiration.
- Acts as good barrier.
- Helps in maintaining structural integrity
- It helps in preventing and reducing microbiological spoilage.

For the production of biodegradable films not all types of biodegradable materials are used, there are three major categories viz:

1) Starch-based polymers,
2) Polyhydroxybutyrate (PHB) polymers
3) Polylactides (PLA)

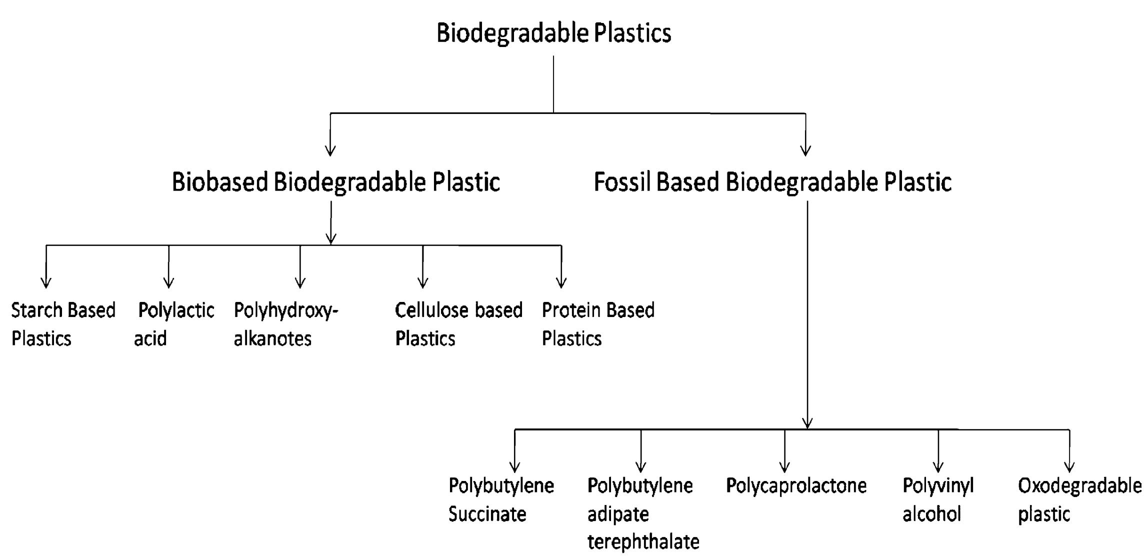


Fig. 20 Classification of biodegradable plastics

7.3.2 Starch-Based Polymers

Starch is one of the most commonly used materials in the production of biodegradable films. To use films based on starch in food packaging as well as in food coating, this was the first identified option [101]. Starch based films can act as high oxygen barriers and are very effective as an edible coating for foods with higher respiratory rates, such as fruits and vegetables. The membrane has a potential to prevent respiration and slow down oxidative process [102, 103]. Starch-based films are hydrophilic and therefore have poor moisture resistance, so in this case they are also considered to have excellent properties if the coating needs to be washed off after application. In addition, cheap edible starch-based films are usually tasteless, colourless and odourless. Strawberries are coated with thickened glycerol corn starch solution, which maintains significant firmness, clarity and colour including the loss of weight. High AM (Antimicrobial) starch coating (66% AM) provides greater efficiency than 24% AM starch coating [104]. The starches also play a crucial role in fruit quality in addition to the amylose content. It has been reported that coating with another starch low in AM can maintain fruit quality. The antibacterial agents such as essential oils (EOs) are added to starch coatings in controlling pathogens and extending the shelf life of minimally processed fruits and vegetables [105].

To develop bioactive starch food packaging materials, bottom-up approach has been used to develop bioactive starch food packaging materials based on Phyto synthesized metallic nanoparticles (Fig. 21) [106].

Starch satisfies many of the criteria for a suitable selection as a material for packaging. It is biodegradable, cheap, renewable, easy to process, and safe for consumption. Another key feature is that it is compatible with a wide range of other biopolymers.

The most commonly used methods for producing starch-based films are extrusion and casting. Starch shows shape memory characteristics. Shape-memory materials are advanced biopolymeric materials which undergo a phase transition between an initial temporary phase (leading to temporary shape) and a permanent phase (leading to permanent shape), when exposed to a specific stimulus such as temperature, humidity, pH, etc. [105].

Current research in the field of starch-based films is oriented in the following directions: improving the green production technology; applying the GC principles by making the packaging material active or responsive; increasing the mechanical properties, namely the tensile strength (TS) and elongation at break (Eb) [107]. TS expresses the ability of a material to withstand forces that tear it apart; Eb measures flexibility and stretchability (extensibility) prior to failure.

8 Polyhydroxy Butyrate (PHB) Polymers

Family belonging to poly(hydroxyalcanoates) (PHAs) polymers have received a lot of interest in the food packaging sector. These are synthesized biologically from a wide range of microorganisms using controlled bacterial fermentation (75 different genera). However, Gram-negative bacteria have been the most commonly used microbes (some of its examples are *Alcaligenes*, *Azobacter*, *Bacillus* and *Pseudomonas*). Some of the gram-positive bacteria are also used for the synthesis are *Rhodococcus*, *Nocardia* and *Streptomyces* [108]. In fact, in the presence of an abundant source of carbon (e.g., glucose or sucrose) or lipids (e.g., vegetable oil or glycerine) and a smaller number of macro-elements (such as phosphorus, nitrogen, trace elements, or oxygen), bacteria can accumulate up to 60–80% of their weight in the form of PHA to prevent starvation.

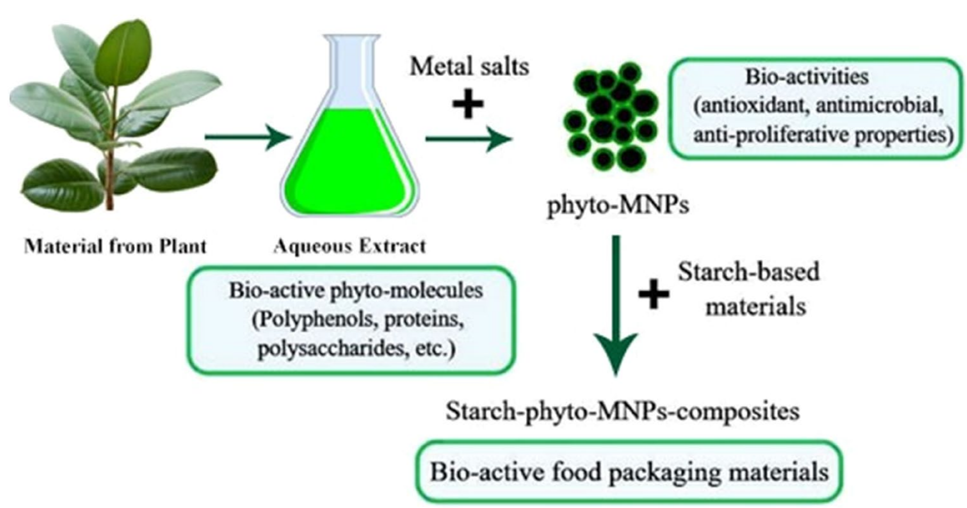


Fig. 21 Schematic representation of "green" bottom-up approach to develop bioactive starch food packaging materials based on Phyto synthesized metallic nanoparticles (Phyto-MNPs) [106]

Alcaligenes eutrophus is gram-negative bacteria and is mostly used in the production of PHA as it can be easily grown, its biochemistry and physiology can also lead to synthesis of PHA and cell can also accumulate 80% of the cell weight in the dry form [109].

Properties regarding PHAs are:

- Isotactic
- Semicrystalline
- High molecular weight thermoplastic polymer
- Insoluble in water
- Good resistance to UV rays
- Biodegradability

One of the most common forms of PHAs is poly(hydroxybutyrate) (PHB), the simplest form of PHA, has crystallinity providing good gas barrier performance and has lot of utility in food packaging applications [110]. The biggest disadvantage of PHB for the plastic processing sector is its low resistance to heat deterioration. It has a melting temperature of roughly 160–190 °C, which is near to the degradation temperature [111]. PHB's application in the food packaging sector has been limited, due to its high cost and brittleness. However, a biodegradable toughened PHB composite with superior mechanical properties can be developed (Fig. 22) which can overcome the shortcomings and open up new possibilities for food packaging and other industrial applications [111].

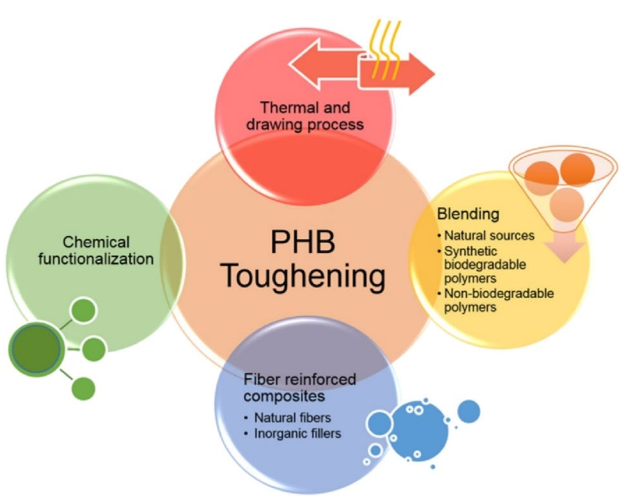


Fig. 22 Different PHB modification approaches [96]

9 Polylactic Acid (PLA)

PLA is biodegradable aliphatic polyester produced using the maturation of sustainable assets like corn, cassava, potato, and sugarcane [112]. PLA offers superior properties to other aliphatic polyesters, including high mechanical strength, dimensional stability, biodegradability, biocompatibility, bio absorption ability, transparency, energy savings, low toxicity, and easy processing [111]. Thus, PLA has gained a significant attention in preparation of films and coatings for food packaging. A number of studies have recognised the potential for PLA to be used as antimicrobial packaging [113].

PLA production is a multistep and complicated procedure. This technique necessitates stringent variables control (temperature, pressure, and pH), catalyst is also used, and extensive polymerization timeframes [114]. PLA can be made using a variety of polymerization techniques, including polymer condensation, ring opening polymerization, and direct approaches (azeotopic dehydration and enzymatic polymerization). Direct polymerization and ring opening polymerization are the most commonly utilised manufacturing processes nowadays [115]. PLA has number of properties useful for use in food packaging, including direct handling applications, with a safety rating of "usually safe" (GRAS) [116]. Thermoformed and/or extruded PLA packages have recently been intended to address the needs of common applications such as cups, overwrap, blister packages, and food and beverage containers.

10 Containers

Controlled environment is essential to protect the quality of the food products. Thermo formed containers or the trays can be utilised for packing of salads, fruits and vegetables. The polymers are melt extruded to produce sheets, which are then heated to temperatures above Tg and Tm to form a specified shape. The majority of biodegradable polymer trays are brittle and water resistant. The structural qualities of the tray do not change when it is frozen. Mangoes, melons, and other tropical fruits were stored in trays manufactured from orientated PLA. Fruits packed in PET trays had the same shelf life as fruits packed in PET trays [117].

11 Foamed

Starch-based foams are used to apply for loose fill. Loose-fill moulding, foam extrusion, expandable bead moulding, and extrusion transfer moulding are some of the techniques used to make foamed items [118]. Food packaging can be made from a variety of foamed goods based on starch, such as trays, clamshells, and so on. However, direct food contact coatings are necessary. Paraffin and other polymers are recommended on PLA and starch coatings. The adhesion of the foamed product to the coating is crucial. Novamont developed in the USA is starch-based foam used in a variety of packaging applications [8]. Green Cell™ foam developed by Landaal Packaging systems is a sustainable alternative to PP foam. In moist soil, it decomposes completely within 4 weeks [119].

12 Active Agents for Food Packaging

Active packaging is a system in which the product, package, and environment interact positively in order to improve the shelf life or to achieve desired characteristics. It has also been characterised in the form of food packaging that modifies nature of the packaging material in order to improve shelf life or facilitate safety or sensory attributes as retaining the packaged food's quality. Active ingredients and products need to extend shelf life or maintain or improve the condition of packaged foods, "according to Regulations 1935/2004/EC and 450/2009/EC" [120].

The purpose of active packaging is to enhance preservation of food and shelf life through the usage of lots of techniques together with temperature control, oxygen removal, moisture control, and the addition of chemical compounds together with salt, sugar, carbon dioxide, in addition to herbal acids, or an aggregate of those for efficient packaging [121]. With advances in active packaging, many foods preservation benefits have been discovered, such as slowing down oxidation in muscle foods, controlling the rate of respiration in horticultural products, microbial growth and moisture migration in dry products. In addition, active packaging uses coatings, micro-perforation, laminates, spray coefficients, or polymer blends to selectively adjust to alter the air concentration of gaseous components within the packaging.

13 Antimicrobial Packaging

One of the most common causes of food spoilage is the growth of pathogenic and/or spoilage microorganisms, antibacterial compounds are among the most studied active ingredients in packaging foods. Antimicrobials are one of the most widely available groups of active substances, such as emission sachets and absorbent pads. Most antimicrobial-active encapsulation systems are formed from silver, silver zeolite, glucose oxidase, triclosan, chlorine dioxide, ethanol vapor emissions, natamycin, sulfur and allyl isothiocyanate as active compounds. Some of the examples of antimicrobial agents are silver, copper, gold and platinum. [122, 123]

13.1 Packaging with Carbon Dioxide Emitters

Carbon dioxide (CO_2) is a gas molecule that is soluble in water and the lipid phase of food, forming carbonic acid and acidifying the food product in the process. Carbon dioxide's antimicrobial characteristics are well-known in the food sector, and it is widely used in preservation of the quality and extension of shelf life. CO_2 acts in a complicated way. It includes interactions such as altering of the bacterial cell membrane, inhibition of bacterial enzymes, and changes in cytoplasmic pH. The combined effect causes the lag phase to be extended, inhibiting the growth of many spoilage microorganisms [124].

Commonly used CO_2 emission technologies include two active ingredients: baking soda ($NaHCO_3$) and organic acids. Citric acid is often the acid of choice for such CO_2 emission systems. CO_2 emitters can also be composed of several different combinations of active substances. For example, the combination of ascorbic acid and iron carbonate produces CO_2 and consumes O_2 in a 1:1 ratio [125].

13.2 Antioxidant Agents

Antioxidants have also received considerable interest due to their ability to improve the stability of foods that are sensitive to oxidation [126]. Oxidative decomposition is the main reason for food spoilage after microbial growth. Oxidative reactions can lead to:

1) oxidation of fatty acids which deteriorate food nutritional quality
2) production of off-flavours and odours
3) pigment degradation leads to change in colour.

Antioxidant activity is known to be imparted to active packaging systems by a variety of synthetic and natural antioxidant chemicals. As a result, a careful selection should be made, taking into account dietary features as well as health and safety concerns. Synthetic antioxidants such as butylated hydroxytoluene (BHT), butylated hydroxyanisole (BHA), and tert-butylhydroquinone (TBHQ), which are now suspected to be possibly hazardous to human health, are being phased out. Edible films and active film coatings based on cellulose derivatives, chitosan, alginate, galactomannans, gelatin, are some examples of natural antioxidants for lipid food [127].

14 Biosensor in Food Packaging

Unlike chemical sensors, only a small variety of biosensors have been created for use in intelligent packaging. Sensors for the direct detection of bacteria, which require contact with the food products (or the fluids from food), as well as the sensors for detecting volatile chemicals generated during deteriorating food products, are among them [128]. The most widely recognized biosensors which are considered for smart food packaging are discussed below:

14.1 Fluorescent and Microfluidics Biosensors

Bioluminescent or fluorescent dyes are immobilised with the solid polymer matrix in a fluorescence-based biosensor. The biosensor device consists of a coloured polymer coating embedded in a thin film. The luminous sensor sensing coating works in the presence of molecular oxygen emitted from the package's headspace using a simple diffusion technique that washes out light in a flexible approach. The oxygen concentration is calculated by using calibration curve as how it effects different luminescence parameters [129]. This reversible technique uses a fluorescence-based oxygen sensor that does not consume dyes or oxygen in the photochemical reactions involved and does not produce any by-products. Additionally, when fluorescence-based biosensors come into touch with food pathogens, it can create a variety of colours. Furthermore, these biosensors could function as an electronic nose or tongue, reducing pathogen detection time from hours to days. The benefits of the microfluidic sensors are their small size in systems, which allow them to detect small substances in large volumes over time [130].

14.2 Biosensors Based on Electrochemical

These biosensors based on electrochemical; in recent times are gaining importance for assessing quality of food according to their functions. Depending on the biological recognition process, there are two types of electrochemical biosensors: Affinity-based biosensors and biocatalytic sensors. Redox enzymes, the tissue slices or the entire cells serve as identification materials in biocatalytic biosensors, allowing them to identify target biomolecules [131]. Antibodies, antibody fragments, and aptamers are used as recognition elements in affinity-based sensors.

Biocatalytic biosensor devices provide a number of advantages, including a simple shape and ease of use, small size, low cost, and often no additional equipment. These qualities make them easy to adopt with the packaging materials [132]. Furthermore, these biosensors are exceptionally particular and specific to the target substrate, also no pretreatment or separation processes are required.

Electrochemical biosensors have following advantages:

(1) lower detection limit,
(2) sensor approach is very simple
(3) reduced background signal.

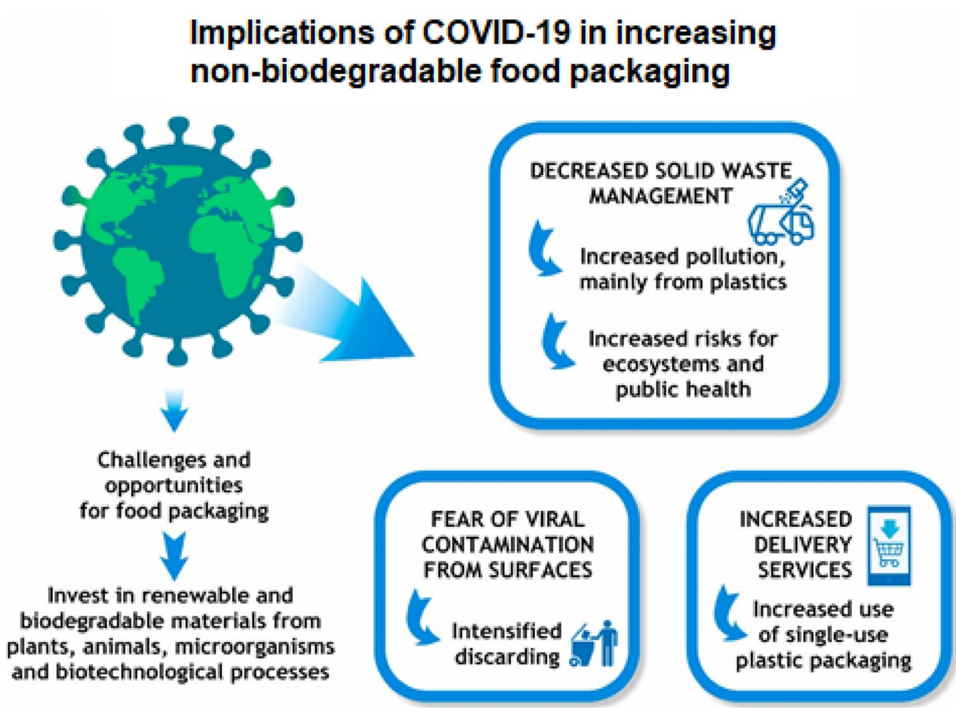


Fig. 23 Increase in non-biodegradable food packaging and COVID-19 crisis

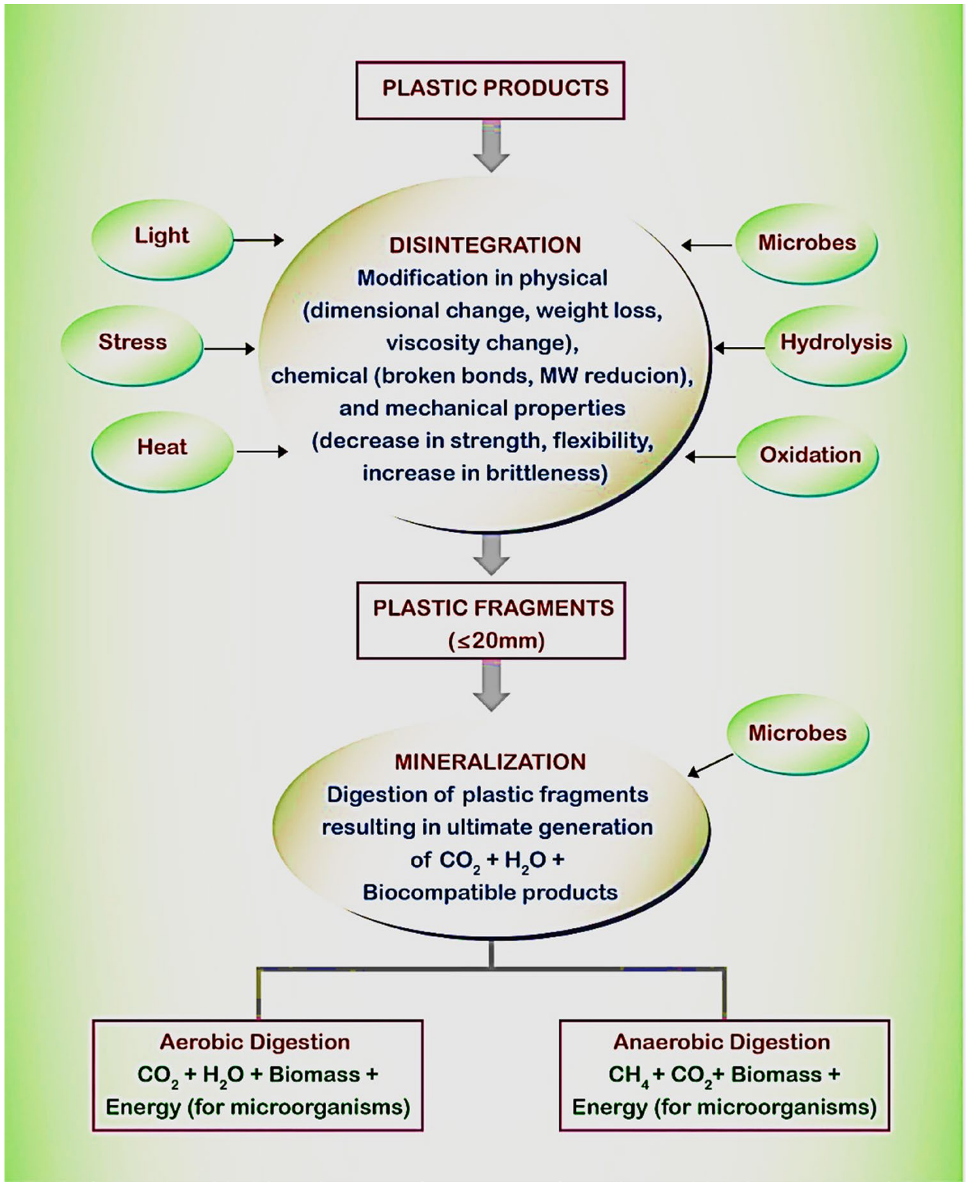


Fig. 24 Schematic representation of plastic degradation

A biosensor based on single-walled carbon nanotube (SWCNT)—for the food microbes has been reported in the literature as one of the most prevalent electrochemical biosensors for foods [133, 134]. A biosensor based on diamine oxidase (DAO) has been utilised to measure amines in the packed food in the atmosphere, and a DNA-based biosensor is used to detect probable carcinogens in food samples [135].

14.3 Gas Sensors

The gas sensors are beneficial for detecting the leakage of gas in packaging and determining the qualities of food. These sensors can also detect the presence of spoiling gases, which includes basic oxygen, carbon dioxide and nitrogen compounds, all of them are emitted when the food spoils [121].

Furthermore, it is also used to detect pesticides such as carbamates in vegetables and fruits, and may be a fast, sensitive alternative to testing the rancidity of meat products. It consists of three parts: the sensing electrode, the counter electrode and the reference electrode. A small layer of electrode separates the counter electrode from the working electrode, and reference electrode is utilised to keep the working electrode at a consistent voltage.

The gas sensor concept has been demonstrated to encounter CO_2 compounds inside food containers. These sensors outperform traditional sensing technologies because they may be used in hazardous environments and are unique to

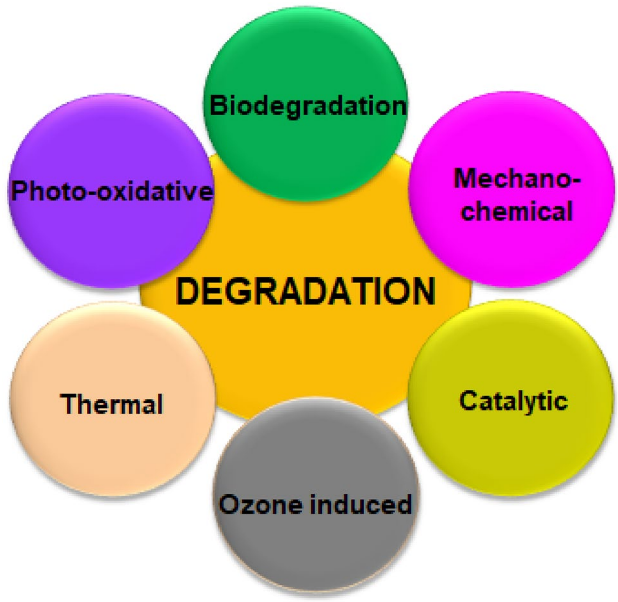


Fig. 25 Factors affecting degradation of polymers

target the gas molecules. They are also unaffected by electromagnetic interferences. There is different type of biosensors in food packaging.

15 Impact of Food Packaging During COVID-19

Consumers behaviour during COVID pandemic particularly in respect of food and its packaging changed. Most of the people started online purchasing for home delivery. Due to this food packaging materials (mostly non-biodegradable or non-renewable) increased considerably. This created lot of problems in plastic waste management. The main causes and outcomes of the increased use of single-use non-biodegradable packaging during COVID-19, are given in Fig. 23 [136].

16 Degradation/Biodegradation of Polymeric Food Packaging Materials

Food packaging is very important in food industry because it protects the food contamination. It also maintains the quality and safety of food products. Conventional plastic packaging's do not degrade easily and pollute the environment. Natural polymers and their derivatives can be used to produce biodegradable packaging materials. The biodegradable polymers degrade easily and protect the environment. In addition to chemical and physical methods, microbes play important role to degrade the polymers. Biodeterioration influences plastic's surfaces and modifies physical, chemical, and mechanical properties. Structure and composition of polymers control chemical and structural changes. Overall process of degradation is shown in Fig. 24 [137].

Degradation and biodegradation in general depend on number of factors as shown in Figs. 25 and 26 [138]

One simple example of degradation may be taken as hydrolysis of Polylactic acid (PLA) to explain the mechanism of an abiotic chemical degradation. The degradation in basic and acidic medium follows different mechanisms (Fig. 27) [139].

Fig. 26 Factors affecting biodegradation

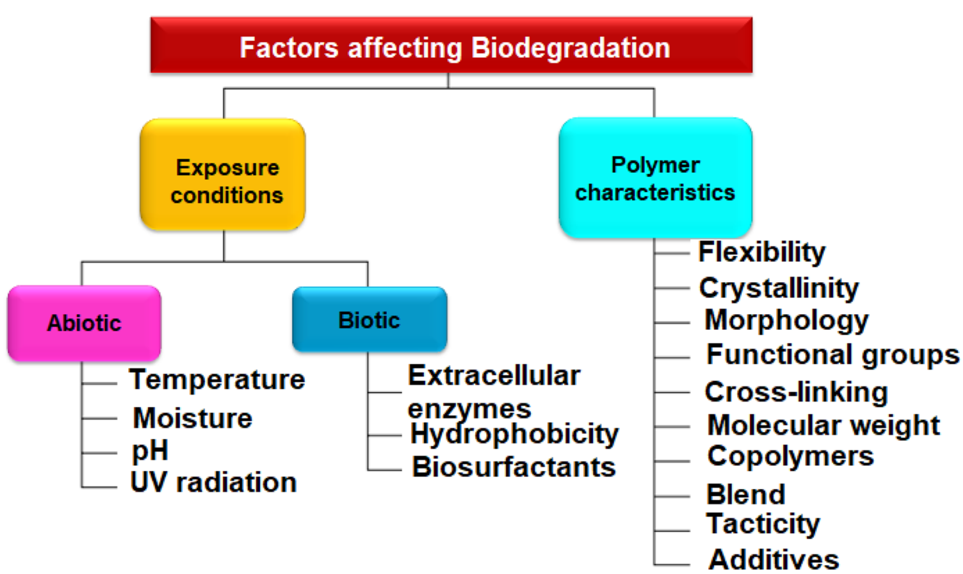
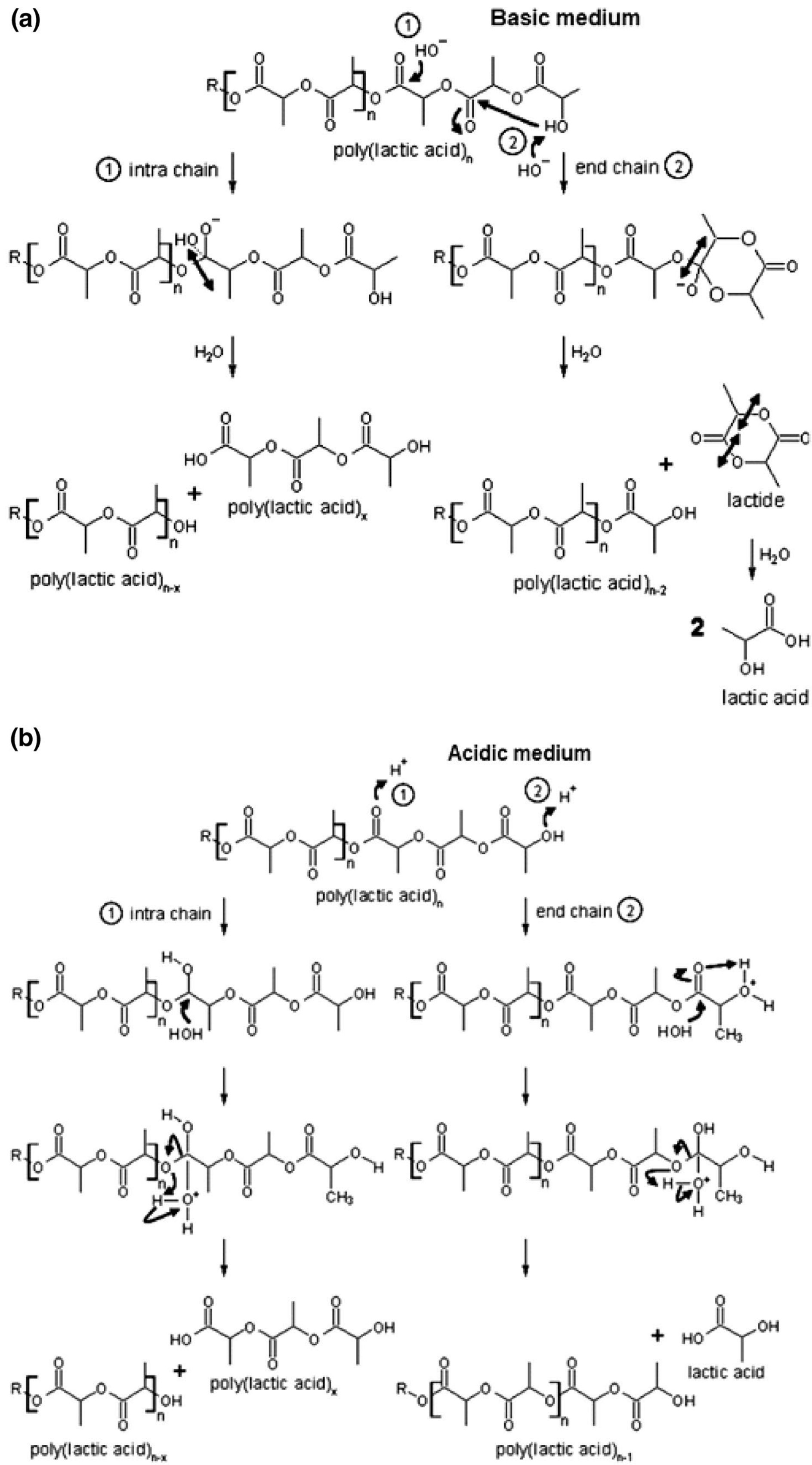


Fig. 27 Degradation of PLA by hydrolysis



17 Conclusions

During the last decades, polymers as food packaging materials are being used extensively. In food industry, packaging is very important for food protections. Food packaging has different functions and it is also related to food wastages. Out of different food packaging, plastic is the most preferred item. However, with different type of problems associated with plastics waste, attempts are being made for alternative bio-sourced plastics. Bio-sourced plastic is very advantageous in food packaging industry. Different aspects of polymer with special reference to biodegradable plastics have been discussed in detail. Reference of plastics as food packaging material during COVID-19 is also made. Increasing fundamental research in the use of biodegradable polymers in food packaging and effort to protect the environment, requires deep understanding and there are lot of challenges for commercialization, which are to be tackled.

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