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A Comprehensive Review of Biodegradable Polymers in Sustainable Packaging Applications

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Abstract

The widespread use of synthetic plastics poses significant environmental challenges due to their durability and dependence on non-renewable resources. Biodegradable plastics, derived from renewable biological sources, offer a sustainable alternative that can mitigate waste disposal issues and environmental pollution. This paper examines the factors influencing the suitability of bioplastics for various packaging applications and discusses emerging techniques to enhance their properties. Regarding packaging applications in particular, biodegradable plastics offer a viable substitute for conventional plastics. A class of plastics known as bioplastics is produced using renewable resources such as microorganisms, agricultural waste, or plants. They can be classified as Bio-based plastics derived from renewable biomass sources. They include polymers such as polylactic acid (PLA), polyhydroxyalkanoates (PHA), starch-based plastics, cellulose-based plastics, and protein-based plastics. ***Fossil-based plastics*** *are derived from fossil fuels like petroleum but can be biodegradable or compostable. They include certain types of biodegradable polyesters and polyolefins. Microorganisms have the ability to break down biodegradable plastics into biomass, carbon dioxide, and water under specific conditions. Examples include PLA, PHA, and certain starch-based plastics whereas* ***non-biodegradable bioplastics*** *do not readily decompose into natural elements. This group comprises non-biodegradable bio-based polymers like bio-based polyethylene terephthalate (PET) and bio-based polyethylene (PE). Each classification has its own set of advantages and limitations, depending on factors like cost, performance, and end-of-life disposal options. The choice of bioplastics depends on the specific application and environmental goals. The use of biodegradable plastics is growing in popularity as an environmentally preferable substitute for conventional plastics derived from petroleum. By addressing aspects like mechanical strength, barrier properties, and biodegradability, bioplastics can fulfill the varied needs of the packaging industry. Emerging techniques like nanocomposites, bioplastic blends, and surface modifications offer pathways to enhance the properties of bioplastics, making them viable for a broader range of applications. Ongoing research and development in this area will be essential for promoting the use of sustainable materials in packaging and diminishing the environmental effects of plastic waste.*

Keywords: Bioplastic, packaging, starch, cellulose, sustainability

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INTRODUCTION

Packaging encompasses product protection, security, and usability, ensuring safe handling and use. Common materials include wood, paper, glass, metals, plastics, and composites. Plastics are particularly prevalent due to their excellent properties such as nonpermeability, environmental inertness, durability, lightness, stability, and availability. However, these same properties contribute to their persistence in the environment, leading to solid waste accumulation if not properly recycled [1, 2]. Additives, plasticizers, and colorants in plastics contribute to significant environmental issues during disposal [1, 3]. Biodegradable and environmentally friendly, bioplastics made from renewable resources present a viable substitute for synthetic polymers [4].

Biopolymers is primarily produced from starch, proteins, cellulose, DNA, RNA, and peptides. The monomers for bioplastics include sugars, nucleotides, and amino acids. The creation of bio-based packaging materials involves complex, multi-stage processes in both design and manufacturing [5]. Ideal packaging materials should possess properties such as permeability to gases and vapors, effective sealing, resistance to chemicals, UV light, and transparency. Additionally, they should have strong mechanical properties, be machinable, cost-effective, and readily available It is critical to consider the bioplastic's shelf life and disposal options during the design stage [5–9].

Typically, products leave the production facility with three layers of packaging. The primary packaging is the layer that directly interfaces with the consumer. Secondary packaging groups individual units for transportation or multipacks, offering physical protection and facilitating easy handling during storage and distribution. It ensures safety against mechanical damage. Tertiary packaging, which includes pallets, trays, and cartons, is designed to protect products from mechanical damage and weather conditions during transit and storage [7, 8]. Environmental advantages like biodegradability, compostability, and the use of renewable raw materials are not sufficient on their own to establish a market for biopolymers. They should also be economically viable, suitable for their intended use, and ideally provide distinctive advantages during use.

Food packaging is essential in the food industry for the protection and preservation of various food types, and it is predominantly made from petroleum-derived plastics. Due to their excellent mechanical qualities, such as tear and tensile strength, effective barriers to gases and aroma compounds, heat sealability, and widespread availability at relatively low costs, plastics like polyvinyl chloride (PVC), polypropylene (PP), polyethylene terephthalate (PET), polyethylene (PE), polyamide (PA), and polystyrene (PS) are widely used [10]. The increased use of petroleum-based plastics poses significant environmental and health risks. These plastics contribute to ecological problems due to their nonbiodegradability, and they also impact the health of workers involved in cleaning or maintaining processing equipment [11].

Concerns about the overabundance of plastic in the environment have led to a shift in the development of "bioplastics," or packaging materials that improve performance while being simple to recycle and reuse.The European Bioplastics organization describes bioplastics as plastics that either originate from renewable resources (bio-based) or possess the ability to biodegrade and/or be composted. Vegetable oil, corn starch, potato starch, fibers from pineapple, jute, hemp, henequen leaves, banana stems, and even used plastic bottles and other containers can all be converted into bioplastics by the process of microorganisms [10, 12]. Biodegradable polymers are materials that can break down into carbon dioxide (CO_2), methane (CH_4), water (H_2O), and inorganic compounds under appropriate conditions of temperature, moisture, and oxygen, primarily through the enzymatic action of microorganisms [13]. Biodegradable packaging materials are those that decompose through the action of naturally occurring organisms like bacteria, yeast, or fungi. When composted, these materials can break down into fertilizer or humus [14, 10].

Although bioplastics are considered promising eco-friendly materials for food packaging, they face certain limitations, including inadequate mechanical and barrier properties as well as high production costs. However, these drawbacks can be mitigated. Blending two or more biopolymers can enhance their mechanical and barrier properties, and utilizing low-cost renewable resources like agricultural waste can help reduce production costs [15]. Various active components or additives such as antimicrobials, colorants, antioxidants, and nutrients can be incorporated into bioplastics to enhance their performance [16].

The exploration of recyclable and biodegradable plastics is a fascinating and rapidly developing field within packaging science. However, significant research is still needed to enhance their performance, including mechanical, thermal, and physical properties, to make them commercially viable. This progress is expected to be achievable in the coming years.

Classification of Bioplastics Biopolymers

Biopolymers are polymers derived from natural resources. They are renewable, biodegradable, and generally non-toxic. Biopolymers can be produced by biological systems such as plants (starch, cellulose, sugarcane), animals (chitosan from crustacean shells), and microorganisms (bacteria-produced polyhydroxyalkanoates) or chemically synthesized from biological starting materials like sugar, starch, oils, and natural fats [17–25].

Natural Polymers

Natural polymers are a diverse range of materials derived from animal, marine, and agricultural sources. These include polysaccharides like starch, cellulose, chitosan, and gums; proteins derived from plants (such as zein, gluten, and soy) and animals (including casein, collagen, and gelatin); as well as lipids, such as cross-linked triglycerides. These polymers are generally hydrophilic and crystalline, which creates challenges when processing them for moist food packaging. Nonetheless, their exceptional gas barrier properties make them suitable for use in food packaging [26].

Starch

Starch, derived from seeds, corn, wheat, rice, potatoes, sweet potatoes, and cassava, is the most abundant and commonly used renewable raw material. It is an easily biodegradable natural resource [27]. Starch is commonly utilized as a thermoplastic and serves as an alternative to polystyrene (PS). The material is plasticized by breaking down its structure with certain amounts of water or plasticizers such as glycerol and sorbitol, followed by extrusion. Its availability, affordability, and biodegradability make it a good fit for packaging applications. However, starch's poor moisture resistance and mechanical properties limit its use. To enhance these properties, starch is often blended with various biopolymers and additives [28].

Cellulose

Cellulose, the most abundant natural polymer, is obtained through the delignification of wood pulp or cotton linters. Its hydrophilic and crystalline nature, along with poor mechanical properties in its raw form, makes it challenging to use in packaging. Consequently, cellulose is treated with chemicals such as NaOH, H2SO4, and CS2 to produce cellophane, which boasts excellent mechanical characteristics [29]. Cellulose derivatives are created by modifying cellulose in its solvated state through esterification or etherification of the hydroxyl groups. These derivatives, such as hydroxypropyl cellulose, hydroxypropyl methylcellulose, carboxymethyl cellulose, and methyl cellulose, are used to produce films or edible coatings [29]. One method to enhance the moisture barrier of cellulose ether matrices is by incorporating hydrophobic compounds, such as fatty acids, to develop a composite film [30].

Chitin

After cellulose, chitosan, also referred to as chitin, is the second most prevalent polysaccharide in the natural world. It is naturally present in the fungal and yeast cell walls as well as the exoskeletons of arthropods. Commercial production involves chemical extraction from prawn and crab waste. Chitosan is produced by the deacetylation of chitin, with its properties influenced by factors such as alkali concentration, incubation time, the ratio of chitin to alkali, temperature, and the source of chitin [31]. Chitosan can form films without additives and demonstrates good permeability to carbon dioxide and oxygen, along with excellent mechanical and antimicrobial properties. These characteristics aid in minimizing oxidation and offer benefits in prolonging the shelf life and preserving the quality of food products [32].

Proteins

Proteins, composed of amino acids, can be sourced from plants (such as wheat gluten, corn, zein, and soy protein) and animals (including casein, whey, keratin, and gelatin). Their unique side chains make them valuable for modifying the characteristics of packaging materials. Due to their renewable nature, biodegradability, and excellent gas barrier properties, proteins and protein-based materials are widely used in various industrial applications. However, like starch-based polymers, their hydrophilic nature poses challenges, necessitating blending with other polymers or chemical or microbiological modifications [29].

Casein, a protein extracted from milk, undergoes a transformation when combined with appropriate plasticizers at temperatures ranging between 80 to 100 degrees Celsius, resulting in materials exhibiting a spectrum of mechanical characteristics, from rigid and fragile to pliable and durable. These films crafted from casein possess an opaque quality. Despite its comparably elevated cost, it finds application in bottle labeling due to its exceptional adhesive attributes.

Gluten-based plastics showcase a notable sheen and demonstrate effective resistance to moisture in specific environments. While they do not dissolve in water, they do absorb some when submerged. Presently, investigations into leveraging gluten for edible films, adhesives, or thermoplastic purposes are underway, prompted by its economical production and widespread availability [33].

Soy proteins are accessible in various forms like soy flour, soy concentrate, and soy isolate for commercial use. Soy protein isolate (SPI) holds potential for crafting edible and environmentally friendly packaging films. However, films derived from SPI tend to be overly brittle, restricting their performance. To enhance their quality, the addition of a plasticizer like glycerol is necessary through modification processes [34].

Keratin, sourced economically from waste materials like hair, nails, and feathers, stands as the most cost-effective protein option. However, it’s processing presents challenges owing to its intricate structure and notably high cysteine group content [35]. Conversely, whey proteins, which are byproducts of the cheese industry, find extensive use in the creation of edible films and coatings.

Films are frequently enhanced with lipid components such as vegetable oils, fatty acids, natural waxes, and resins to increase their hydrophobicity and moisture barrier capabilities.

Synthetic Polymers

These bioplastics are manufactured through traditional chemical synthesis using biobased monomers. Among them, polylactic acid (PLA) stands out as one of the most widely accessible and utilized options in commercial settings.

Polylatic Acid (PLA)

PLA, considered one of the most promising biodegradable polyesters, is derived from renewable sources such as corn, sugar beets, and potato starch, making it an eco-friendly alternative for commercial applications to replace materials like high density polyethylene (HDPE), low density polyethylene (LDPE), polystyrene (PS), and polyethylene terephthalate (PET). The process involves turning corn or other carbohydrates into dextrose, which is then fermented to produce lactic acid. Next, lactic acid monomers are directly polycondensed to create PLA pellets, or they can be polymerized by ring-opening of lactide. This transparent material offers a wide range of processing options, including injection molding, extrusion (both cast film and blow molding), and thermoforming [36].

PLA is emerging as a progressive choice for environmentally friendly food packaging due to studies showing its superior performance compared to synthetic plastics [37]. It is offered in a range of formats such as films, thermoformed cups and trays, containers, and coatings designed for paper and paperboards.

Microbial Polymers

This category comprises polymers synthesized through microbial fermentation of polysaccharides, representing a recent and innovative field with significant industrial potential. Included in this group are polymers like polyhydroxyalkanoates (PHA), PHB, and microbial polysaccharides such as pullulan, curdlan, and xanthan.

Polyhydroxyalkanoates

Polyhydroxyalkanoates (PHAs) are biodegradable, thermoplastic, biocompatible, and thermally stable, with a melting temperature of approximately 180°C. These polymers are extracted using solvents like methylene chloride, propylene chloride, or chloroform. They are naturally produced by bacteria fermenting plant-based feedstocks like sugars or lipids. PHAs, either in isolation or in conjunction with starch or synthetic plastics, yield exceptional packaging films [38]. Among over 100 PHA composites, PHB stands out as the most prevalent type, resulting from the polymerization of 3-hydroxybutyrate monomers, possessing properties akin to PP but with increased stiffness and brittleness. It degrades in both aerobic and anaerobic environments, producing CO2 and H2O. Additionally, PHB is optically active, water-insoluble, and demonstrates outstanding gas barrier properties [39]. PHAs show potential as substitutes for numerous traditional polymers because of their comparable chemical and physical attributes. They also offer printability, flavor and odor barrier capabilities, heat sealability, resistance to grease and oil, temperature stability, and ease of dyeing, thereby enhancing their applicability in the food industry [40].

The application of various microbial polysaccharides, such as xanthan, pullulan, curdlan, and others, as packaging films represents an innovative concept requiring biotechnological methods.

Pullulan, generated by the yeast-like fungus Aureobasidium pullulans from sugar-containing substrates, is a linear, water-soluble exopolysaccharide (EPS). It is used in packaging for a variety of products, such as food, medications, and cosmetics. Films made from pullulan are edible, uniform, transparent, printable, heat-sealable, flexible, and possess excellent oxygen barrier propertiesAdditionally, they are naturally biodegradable, non-toxic, tasteless, and odorless. Pullulan membranes also exhibit inhibitory effects on fungal growth, making them particularly suitable for food applications [41].

Curdlan, a bacterial polysaccharide derived from Agrobacterium biobar and Agrobacterium tumefaciens, serves primarily as a gelling agent in the food industry, yet its considerable potential in packaging film development remains largely untapped.

In contrast, Xanthan is derived through aerobic fermentation of Xanthomonas campestris, where sucrose or glucose serves as its main carbon source. It possesses high viscosity, water solubility, and non-toxic properties. Despite these attributes, limited information exists regarding its potential in the packaging sector, possibly due to the associated high production costs. Nevertheless, studies have shown promising results, such as reduced weight loss and respiration in acerola fruit when coated with xanthan, thereby preserving color and extending shelf life [42].

Biodegradation Process

Biodegradation refers to the breakdown, disintegration, or loss of mechanical properties in packaging materials facilitated by microorganisms. This process typically involves hydrolysis followed by oxidation. The rate at which biodegradation occurs depends on factors like temperature (typically between 50 to 70°C), humidity levels, and the type and amount of microorganisms present. In industrial composting, bioplastics are transformed into water, CO_2, and biomass within approximately 6-12 weeks [10]. Biodegradation can occur aerobically or anaerobically, resulting in the formation of compost or sludge in the former case, and methane and hydrogen (biogas) in the latter.

Natural biopolymers like starch and cellulose are hydrophilic and prone to swelling, unlike polyolefins commonly used in mainstream packaging materials, which are hydrophobic and exhibit high resistance to hydrolysis, peroxidation, and biodegradation. Prooxidants are typically incorporated into polyolefins to initiate oxobiodegradation. Although oxobiodegradation follows a similar mechanism to natural biodegradation, the latter requires immediate mineralization. Additionally, oxobiodegradation at room temperature progresses much slower compared to hydrobiodegradation.

During oxobiodegradation, carboxylic acid (–COOH) undergoes conversion into alcohol, aldehyde, and ketone molecules, which are susceptible to degradation through low-molecular-weight compounds generated during peroxidation, initiated by light or heat. This process is primarily responsible for the loss of mechanical properties in hydrocarbon polymers. Subsequently, bioassimilation occurs through fungal enzymes or bacteria, leading to the production of CO2 and biomass, ultimately resulting in humus formation.

Synthetic polymers typically contain antioxidants and stabilizers to inhibit polymer oxidation during biodegradation, thereby extending material shelf life and enhancing performance [43].

Bioplastics Derived from Non-edible Sources

In a world where food is a scarce resource, it is possible to produce bioplastics from non-edible materials. Items like orange peels, pomegranate peels, banana peels, and potato peels are utilized in bioplastic production. Recently, bioplastic films made from polysaccharide residue feedstock have become highly sought after. Lignocellulosic feedstocks, which include cellulose, hemicellulose, starch, and pectin, are particularly valuable for this purpose.

Pomegranate Peel

It is a rich source of bioactive compounds, containing lignin (5.7%), hemicellulose (10.8%), cellulose (26.2%), and pectin (27%) [43]. When subjected to acid hydrolysis, the polysaccharides in the peel are converted into monosaccharides, breaking down into their cellulose, hemicellulose, and lignin components. These components are then utilized to develop bioplastics [44].

Orange Peel

The peel contains carbohydrates that can be utilized for producing biomolecules. Improper disposal of unprocessed peels leads to various environmental issues [44]. Thus, it is advisable to collect this waste and convert it into bioplastics.

Advantages and Disadvantages of Bioplastic

Plastic is a major environmental pollutant used daily [45]. To reduce this pollution, we should transition to bioplastics instead of petrochemical-based products. This switch can address many environmental problems [46]. Bioplastics are distinguished by their eco-friendly, compostable, biodegradable, and energy-efficient properties [47].

The future of biodegradable plastics is highly promising. Some of the advantages of bioplastics include:

- Reduced carbon footprint [48, 47, and 49].
- Energy efficiency [48, 47, 49].
- Partially derived from natural feedstock [48, 47, and 50].
- Environmental safety [51].

However, the use of bioplastics can present several challenges. Some of the disadvantages include:

- High cost [50, 52].
- Brittleness [53, 54].
- Thermal instability [48, 54].
- Various recycling difficulties [50].

Applications

Bioplastics are utilized as packaging materials for products with both short shelf lives, such as vegetables and fresh fruits, and long shelf lives, such as potato chips and pasta [54]. The applications of bioplastics vary based on the materials from which they are made:

- *Cellulose:* Used in packaging, disposable household items, and electronic devices [55, 56, 57, 58].
- *Starch:* Employed in food packaging, agricultural foils, textiles, and construction [57, 59 58, 60].
- *PLA:* Applied in films and food packaging [61, 62].
- *PHA:* Used primarily for food packaging [47, 63, 61].

CONCLUSION

This review has discussed the classification, sources, life cycle, advantages, disadvantages, and applications of bioplastics. Using renewable resources to produce bioplastics instead of petrochemical-based plastics offers significant environmental and ecological benefits. Petrochemical plastics have numerous drawbacks, including environmental pollution, toxic gas emissions during manufacturing and recycling, and potential health risks like cancer from consuming food stored in plastic containers. Bioplastics, on the other hand, are sustainable, renewable, and biodegradable. As a result, it is imperative to support and finance bioplastics research and development.

Due to technological advancements, changing consumer demands, and governmental regulations, the sustainable packaging industry is always changing. Companies adopting sustainable packaging practices contribute to environmental conservation, enhance their brand reputation, and meet modern consumer expectations. Future research and development in materials science, supply chain logistics, and consumer behavior will further advance the effectiveness and adoption of sustainable packaging solutions.

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