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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 owing to their durability and dependence on nonrenewable resources. Biodegradable plastics derived from renewable biological sources offer a sustainable alternative that can mitigate waste disposal issues and environmental pollution. This study 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 are viable substitutes 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 that are derived from renewable biomass sources. These 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 such as petroleum, but can be biodegradable or compostable. These include certain types of biodegradable polyesters and polyolefins. Under specific conditions, microorganisms can break down biodegradable plastics into biomass, carbon dioxide, and water. Examples include PLA, PHA, and certain starch-based plastics, whereas* ***nonbiodegradable bioplastics*** *do not readily decompose into natural elements. This group comprises non-biodegradable bio-based polymers, such as bio-based polyethylene terephthalate (PET) and bio-based polyethylene (PE). Each classification has its own set of advantages and limitations depending on factors such as cost, performance, and end-of-life disposal options. The choice of bioplastics depends on their specific applications and environmental goals. The use of biodegradable plastics is growing in popularity as environmentally preferable substitutes for conventional plastics derived from petroleum. Bioplastics can fulfil the varied needs of the packaging industry by addressing aspects such as mechanical strength, barrier properties, and biodegradability. Emerging techniques, such as 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 is essential for promoting the use of sustainable materials in packaging and diminishing the environmental effects of plastic waste.*

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INTRODUCTION

Packaging encompasses product protection, security, and usability and ensures safe handling and use. The common materials used include wood, paper, glass, metals, plastics, and composites. Plastics are particularly prevalent owing to their excellent properties such as nonpermeability, environmental inertness, durability, lightness, stability, and availability. However, these properties contribute to their persistence in the environment, leading to solid waste accumulation if not properly recycled [1, 2]. The additives, plasticizers, and

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colorants in plastics contribute to significant environmental issues during disposal [1, 3]. Biodegradable and environmentally friendly bioplastics made from renewable resources are viable substitutes for synthetic polymers [4].

Biopolymers are primarily produced from starches, proteins, cellulose, DNA, RNA, and peptides. Monomers used in bioplastics include sugars, nucleotides, and amino acids. The fabrication of bio-based packaging materials involves complex multistage 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 shelf life and disposal options for bioplastics during the design stage [5–9].

Typically, products leave production facilities that have three packaging layers. Primary packaging is a layer that interfaces directly with consumers. Secondary packaging groups individual units for transportation or multipacks, offering physical protection and facilitating the ease of handling during storage and distribution. This 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, such as biodegradability, compostability, and the use of renewable raw materials, are not sufficient on their own to establish a biopolymer market. They should also be economically viable, suitable for their intended use, and ideally provide distinct advantages.

Food packaging is essential in the food industry for the protection and preservation of various food types, and is predominantly made from petroleum-derived plastics. Owing to their excellent mechanical properties, such as tear and tensile strength, effective barriers to gases and aroma compounds, heat sealability, and widespread availability at relatively low costs, plastics such as 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 owing to their non-biodegradability, and also affect 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, pineapple fibers, jute, hemp, henequen leaves, banana stems, and even plastic bottles can be converted into bioplastics by microorganisms [10, 12]. Biodegradable polymers can be broken 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 decompose through the action of naturally occurring organisms such as bacteria, yeast, and fungi. When composted, these materials can break down into fertilizers 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 and high production costs. However, these drawbacks could be overcome. Blending two or more biopolymers can enhance their mechanical and barrier properties, and utilizing low-cost renewable resources such as 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 in the packaging science. However, significant research is still required to enhance their performance, including the mechanical, thermal, and physical properties, to make them commercially viable. This progress is expected to be possible in the future.

Classification of Bioplastics Biopolymers

Biopolymers are polymers that are derived from natural sources. 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 such as sugar, starch, oils, and natural fats [17–25].

Natural Polymers

Natural polymers are diverse materials that are derived from animal, marine, and agricultural sources. These include polysaccharides such as starch, cellulose, chitosan, and gums; proteins derived from plants (such as zein, gluten, and soy) and animals (including casein, collagen, and gelatin); and lipids, such as cross-linked triglycerides. These polymers are generally hydrophilic and crystalline, which creates challenges when they are processed 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. Their availability, affordability, and biodegradability make them suitable for packaging applications. However, poor moisture resistance and mechanical properties of starch 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 delignification of wood pulp and cotton linters. Its hydrophilic and crystalline nature, along with its poor mechanical properties in its raw form, make it challenging to use in packaging. Consequently, cellulose is treated with chemicals such as NaOH, H2SO4, and CS2 to produce cellophane, which exhibits excellent mechanical characteristics [29]. Cellulose derivatives are created by modifying cellulose in its solvated state through esterification or the etherification of hydroxyl groups. These derivatives, such as hydroxypropyl cellulose, hydroxypropyl methylcellulose, carboxymethyl cellulose, and methyl cellulose, are used to produce films and edible coatings [29]. One method to enhance the moisture barrier of cellulose ether matrices is to incorporate hydrophobic compounds such as fatty acids to develop a composite film [30].

Chitin

Chitosan, also known as chitin, is the second most prevalent polysaccharide in nature. It is naturally present in fungal and yeast cell walls as well as in the exoskeletons of arthropods. Commercial production involves the chemical extraction of prawn and crab waste. Chitosan is produced by the deacetylation of chitin, and its properties are influenced by factors such as alkali concentration, incubation time, chitin-to-alkali ratio, temperature, and chitin source [31]. Chitosan can form films without additives and demonstrates good permeability to carbon dioxide and oxygen as well as 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 (e.g., wheat gluten, corn, zein, and soy protein) and animals (e.g., casein, whey, keratin, and gelatin). Their unique side chains make them valuable in modifying the characteristics of packaging materials. Owing to their renewable nature, biodegradability, and excellent gas-barrier properties, proteins and protein-based materials are widely used in various industrial applications. However, the hydrophilic nature of starch-based polymers poses challenges, necessitating blending with other polymers or chemical or microbiological modifications [29].

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

Gluten-based plastics show notable sheen and effective resistance to moisture in specific environments. Although they do not dissolve in water, they absorb some water 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) has the potential to be used to produce edible and environmentally friendly packaging films. However, SPI films tend to be excessively brittle, restricting their performance. To enhance their quality, the addition of a plasticizer such as glycerol is necessary through modification [34].

Keratin, sourced economically from waste materials, such as hair, nails, and feathers, is the most cost-effective protein option. However, its processing presents challenges owing to its intricate structure and high cysteine group content [35]. Conversely, whey proteins, which are byproducts of the cheese industry, are extensively used in the production 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

Bioplastics are manufactured via traditional chemical synthesis using bio-based monomers. Polylactic acid (PLA) is one of the most widely accessible and utilized options in commercial settings.

Polylactic Acid (PLA)

PLA is considered one of the most promising biodegradable polyesters and is derived from renewable sources such as corn, sugar beets, and potato starch, making it an eco-friendly alternative for commercial applications and replacing materials such as high-density polyethylene (HDPE), low-density polyethylene (LDPE), polystyrene (PS), and polyethylene terephthalate (PET). This process involves converting 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 polymerized by the 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 because of 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 paperboard.

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 were extracted using solvents, such as methylene chloride, propylene chloride, and chloroform. They are naturally produced by bacteria-fermenting plant-based feedstocks such as 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 is the most prevalent type, resulting from the polymerization of 3-hydroxybutyrate monomers, possessing properties similar to PP but with increased stiffness and brittleness. It degrades in both aerobic and anaerobic environments, and produces CO2 and H2O. Additionally, PHB is optically active, water-insoluble, and has outstanding gas barrier properties [39]. PHAs are potential 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, and curdlan, as packaging films represents an innovative concept that requires biotechnological methods.

Pullulan, generated from sugar-containing substrates by the yeast-like fungus *Aureobasidium pullulans*, is a linear water-soluble exopolysaccharide (EPS). It is used in packaging for a variety of products such as food, medications, and cosmetics. Pullulan films are edible, uniform, transparent, printable, heat-sealable, flexible, and possess excellent oxygen barrier properties. In addition, 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; however, its considerable potential for packaging film development remains largely untapped.

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

Biodegradation Process

Biodegradation refers to the breakdown, disintegration, or loss of the mechanical properties of packaging materials facilitated by microorganisms. This process typically involves hydrolysis followed by oxidation. The rate at which biodegradation occurs depends on factors such as temperature (typically between 50 °C and 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, such as starch and cellulose, are hydrophilic and prone to swelling, unlike the polyolefins commonly used in mainstream packaging materials, which are hydrophobic and exhibit high resistance to hydrolysis, peroxidation, and biodegradation. Prooxidants are typically incorporated in polyolefins to initiate oxobiodegradation. Although oxobiodegradation follows a mechanism similar to that of natural biodegradation, the latter requires immediate mineralization. Additionally, oxobiodegradation at room temperature progresses much more slowly than hydrobiodegradation.

During oxobiodegradation, carboxylic acid (–COOH) undergoes conversion into alcohol, aldehyde, and ketone molecules, which are susceptible to degradation by low-molecular-weight compounds generated during peroxidation initiated by light or heat. This process is primarily responsible for the loss of the mechanical properties of 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 that inhibit polymer oxidation during biodegradation, thereby extending the shelf life of the material and enhancing its performance [43].

Bioplastics Derived from Non-edible Sources

Bioplastics can be produced from non-edible materials in a world where food is scarce. Items such as oranges, pomegranates, bananas, and potato peels are utilized in bioplastic production. Recently, there has been a high demand for bioplastic films made from polysaccharide residue feedstock. Lignocellulosic feedstock, including cellulose, hemicellulose, starch, and pectin, is particularly valuable for this purpose.

Pomegranate Peel

It is a rich source of bioactive compounds, including 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, which are broken down into cellulose, hemicellulose, and lignin components. These components have been subsequently utilized to develop bioplastics [44].

Orange Peel

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

Advantages and Disadvantages of Bioplastic

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

Therefore, the future of biodegradable plastics is highly promising. Some of the advantages of bioplastics include the following.

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

However, the use of bioplastics presents several challenges. Some of the disadvantages include the following.

- 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 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 depending on the materials from which they are produced.

- *Cellulose is* 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 to films and food packaging [61, 62, 63, 64].
- *PHA:* Used primarily for food packaging [47, 65, 63, 64, 61].

CONCLUSION

This review discusses the classification, sources, lifecycles, advantages, disadvantages, and applications of bioplastics. The use of 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 such as cancer, from consuming food stored in plastic containers. On the other hand, bioplastics are sustainable, renewable, and biodegradable. Therefore, it is imperative to support and finance the research and development of bioplastics.

The sustainable packaging industry is constantly changing owing to technological advancements, changing consumer demands, and governmental regulations. Companies that adopt 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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Author’s Contribution Statement

All authors contributed equally to the study conception and design. Neetu Saharan conducted material preparation, data collection, and analysis. The initial draft of the manuscript was authored by Prof. Neeraj Wadhwa. All authors reviewed and approved the final version of the manuscript.

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