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Evaluating Biopolymers as Sustainable Alternatives to Synthetic Polymers: Review

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Abstract

It is undeniable that human actions have an impact on the entire planet. One of the greatest challenges associated with environmental pollution concerns the nature of the materials we use. In contemporary times, polymers are used in almost every sector, including medicine, construction, aerospace, automotive, naval, food, electronics, and more. Biopolymers such as cellulose, starch, resin, pectin, and others offer us the opportunity to decrease the production of synthetic polymers. This research focuses on analyzing the properties of these natural materials, aiming to identify their capabilities as viable substitutes for synthetic polymers. By examining their physical, chemical, and mechanical characteristics, we seek to identify which biopolymers have the greatest potential to meet technical and environmental requirements. Furthermore, the potential of these biopolymers in areas such as medicine, construction, aerospace, and electronics is explored, outlining a more sustainable and resilient future for the materials industry. By understanding the viability and limitations of biopolymers, this study aims to provide valuable insights for the transition towards a more sustainable and ecologically responsible economy.

Keywords: Biopolymers, Synthetic Polymers, Eco-Friendly Alternatives, Sustainability.

Introduction

One of the challenges associated with the issue of environmental pollution concerns the nature of the materials we use. Among the materials utilized by humanity, polymers emerge as prominent elements, with plastics being the primary representative of this group (Law & Narayan, 2022). The term "polymers," derived from Greek, where "poli" means many and "mers" denotes repeatable units (Sperling, 2005), refers to large-scale molecules (macromolecules) composed of various repeatable units known as monomers. These monomers bond together through covalent bonds, forming larger molecules known as polymers.

In contemporary times, polymers are used in almost every sector, including medicine, construction, aerospace, automotive, naval, food, electronics (Ebewele, 2000), and more. They make up the plastic bags in supermarkets, the packaging of the food we purchase, and are present in the dyes of our clothes, residential buildings, and various other aspects of our daily lives (Andrady, & Neal, 2009).

In 2020, only 10% of the produced plastic was recycled, 14% was incinerated, while the remaining 76% ended up in landfills or was directly discarded into nature (Geyer, Jambeck, & Law, 2017), including oceans, forests, parks, among others. As plastics degrade, they transform into microplastics and plastic nanoparticles, infiltrating terrestrial, aquatic, and marine habitats, disrupting ecosystems, and threatening biodiversity (Geyer, et al., 2017; Galloway & Lewis, 2016).

Regarding their origin, polymers can be classified as natural and synthetic (Peacock, 2000). Synthetic polymers, like plastics, are predominantly derived from petroleum (Andrady, (2015), giving them specific physicochemical properties such as strength, durability, and lightweight. The economic viability of these polymers is notable due to their low production cost and applicability in virtually all areas, making them essential components of our lives (Peacock, 2000). Despite their exceptional characteristics for everyday use, the high resistance to natural degradation of synthetic polymers poses a threat to the environment and all living beings, compromising the future sustainability of the planet and subsequent generations (Geyer, 2020).

A biodegradable polymer is one that decomposes through the action of living organisms, such as fungi, algae, bacteria, among others (Tokiwa, Calabia, Ugwu, & Aiba, 2009; Emadian, Onay, & Demirel, 2017). The biodegradability of a material does not depend on its origin but rather on its chemical composition, the ease with which organisms can degrade the polymer (Kale et al., 2007). Therefore, there are petroleum-derived polymers, such as polybutylene adipate terephthalate (PBAT) or polycaprolactone (PCL) (Kale et al., 2007)), that are biodegradable, as well as non-degradable biopolymers, such as bio-polyethylene (Bio-PE) or bio-polyamides (Bio-PA) (Karamanlioglu, Preziosi, & Robson, 2017; Narancic, Cerrone, Beagan, & O'Connor, 2020).

This review will primarily focus on analyzing the properties biopolymers such as cellulose, starch, chitosan, and polylactic acid (PLA), examining their characteristics, origins, derivatives, and applications in the fields of food, plastic production, and biomedicine.

Cellulose

Cellulose emerges as the most abundant natural polymer in nature, playing a crucial role in the structural integrity of the cell walls of higher plants (Klemm, Heublein, Fink, & Bohn, 2005). Furthermore, its presence extends to various organisms, including bacteria, algae, fungi, and, more peculiarly, in some animals such as tunicates (Habibi, Lucia, & Rojas, 2010). Cellulose is an organic chemical compound with the formula $(C6H10O5)n$ (Klemm, Philipp, Heinze, Heinze, & Wagenknecht, 1998), discovered by the French chemist Anselme Peygen (Bharimalla, Deshmukh, Patil & Vigneshwaran, 2015). This polysaccharide consists of a linear chain, composed of several hundred to over ten thousand units of D-glucose β(1→4), called cellobiose (Klemm, et al., 1998; Saitoh, Ohno, & Matsuo, 2013; Sjöström, 1993). These linear glucose chains aggregate to form robust microfibrils.

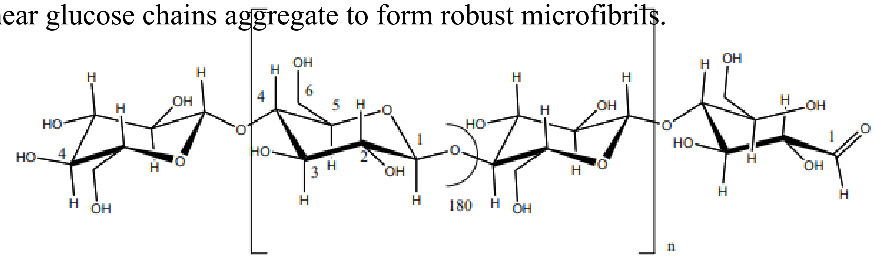

Figure 1. Schematic representation of cellulose chemical structure.

Several properties of cellulose are intrinsically linked to its degree of polymerization, which varies according to the source of extraction of the cellulose material. The abundant presence of hydroxyl groups gives cellulose an extensive network of hydrogen bonds between its individual chains (Heinze, & Liebert, 2001). The extraction of cellulose involves the processing of various fibers (Saitoh, et al., 2013), and due to hydrogen bonds, cellulose manifests insolubility in water and many solvents (Lynd, Weimer, Van Zyl, & Pretorius, 2002).

Despite its limited solubility, cellulose is susceptible to chemical modifications that enable its application in various sectors (Heinze, & Liebert, 2001). Additionally, cellulose can be used to produce derivatives (cellulosic) with specific characteristics and properties adjusted to the demands of a particular application area (Siracusa, Rocculi, Romani, & Rosa, 2008). The process for obtaining pure cellulose involves treating the fibers with sodium chloride and concentrated acids at high temperatures (Heinze, & Liebert, 2001; Saitoh, et al., 2013).

Cellulose derivatives are obtained through chemical processes, such as the cellulose acetate production method (Lynd et al., 2002), or through an enzymatic process known as cellulolysis (Siracusa, Rocculi, Romani, & Rosa, 2008), in which cellulose is depolymerized and converted into glucose ((Heinze, & Liebert, 2001). The resulting glucose can be transformed into a variety of products, such as ethane, sorbitol, and levulinic acid (LevA), serving as a basis for the production of biopolymers (Saitoh, et al., 2013). These derivatives undergo different processes to originate various polymers, including polyethylene, polyoxyethylene, polyvinyl chloride, polystyrene, polypropylene, polyurethanes, polyamides, polymeric hydrogels, cellulose acetate (Lynd, 2002), among others. These polymers are widely used in food packaging (Granström, 2009) and the production of bioplastics (Lynd, 2002), exhibiting characteristics and properties analogous to petroleum-derived plastics (Wohlert, 2021).

Table 1. Cellulose derivatives, production methods and applications

Derived from cellulose	Obtaining method	Application	References
Ethanol	Ethanol is obtained through the fermentation process of glucose, under the influence of zymase, an enzyme responsible for catalyzing the reaction that converts glucose into ethanol.	Ethanol undergoes a dehydration process in the presence of a catalyst, leading to its conversion into ethylene. This ethylene is subsequently utilized in the synthesis of polymers such as polyethylene, polyethylene oxide, and polyvinyl chloride. These polymers are then employed in the production of bioplastics.	22
Cellulose acetate	Cellulose acetate is synthesized through the use of acetic anhydride, toluene as a solvent, and sulfuric acid as a catalyst.	Cellulose acetate emerges as a promising polymeric matrix for the synthesis of ecofriendly, sustainable, and recyclable bio-based composites derived from renewable sources. In the field of biomaterials, cellulose acetate finds application as membranes for various biomedical purposes.	18,22
Hydroxyethyl cellulose	Hydroxyethyl cellulose is obtained through the treatment of cellulose with sodium hydroxide, followed by a reaction with ethylene oxide, resulting in the introduction of hydroxyethyl groups to form a hydroxyethyl ether.	This substance finds utility across diverse industrial and pharmaceutical contexts, exhibiting versatility in its applications. Its efficacy is notably demonstrated in the polymerization processes of Polyvinyl Acetate (PVAC) and acrylic latices for Polyvinyl Chloride (PVC).	26

Starch

Starch stands out as one of the most abundantly synthesized polysaccharides by plants, playing a crucial role as an energy reservoir (Buléon, Colonna, Planchot, & Ball, 1998; Muneer, Nadeem, Arif, & Zaheer, 2021). Major sources of starch include cassava, potatoes, corn, rice, wheat, Jackfruit seeds, and Plantain peels (Tester, Karkalas, & Qi, 2004; Muneer, 2021). Recognized as one of the predominant carbohydrates in our diet, starch, in its purestate, appears as a white, odorless, and tasteless powder (Muneer, Nadeem, Arif, & Zaheer, 2021). Starch is a crystalline homopolymer (Kaur, Singh, McCarthy, & Singh, 2007), composed of two distinct polysaccharides: amylose, a linear chain polysaccharide of D-glucose with α-D(1, 4')-glucan linkages, and amylopectin, sharing the main structure of amylose but with numerous branching points linked in α (1→4) glycosidicand α (1→6) (Pérez & Bertoft, 2010).

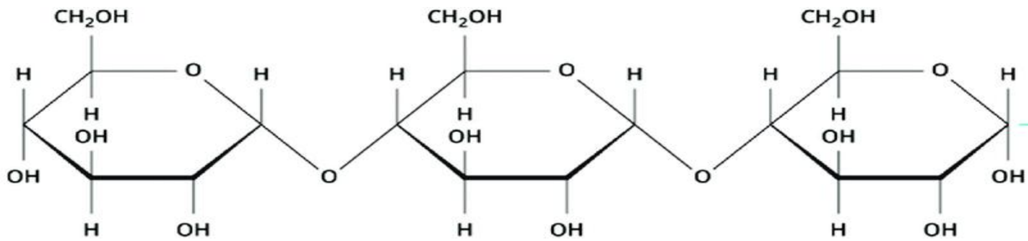

Figure 2. Schematic representation of starch chemical structure.

Native starch exhibits insolubility in water below its gelatinization temperature (Kennedy, & Panesar, 2005), containing approximately 15-30% amylose and 70–85% amylopectin (Muneer, Nadeem, Arif, & Zaheer, 2021). The predominantly linear nature of amylose imparts elasticity to bioplastics, while the more branched form of amylopectin provides increased tensile strength and enhanced elongation properties (Wurzburg, 1986).

The use of starch in bioplastics production, including thermoplastics (Avérous, 2004), significantly contributes to the development of more sustainable and environmentally friendly materials (Swati, 2014). Bioplastics derived from starch are not only degradable in soil and water but can also be used to manufacture biocompatible, non-toxic, biodegradable, rigid, and elastic plastic films [(Muneer, Nadeem, Arif, & Zaheer, 2021; Kaur, Singh & Singh, 2005). Celina et al. (2005) conducted research on the physical characteristics of biodegradable films produced from modified cassava starch.

The chemical structure of starch can be modified through chemical, enzymatic, physical, or combined methods, resulting in products with distinct characteristics and properties compared to native starch (Celina et al. 2005). Due to these modifications, starch finds broad applications in the industry for the production of more economical and environmentally favorable plastic materials, blends, and composites (Kabir, Kaur, Lee, Kim, & Kwon, 2020).

Due to its properties, starch is often blended with other polymers, such as PVA (Polyvinyl Alcohol), PLA (Polylactic Acid) (Kabir et al., 2020; Sajilata, Singhal, & Kulkarni, 2006), among others, to enhance characteristics such as thermal stability, ductility, mechanical strength, gelatinization, and various others (Kabir et al., 2020; Tharanathan, 2005; Xie, Liu, & Cui, 2006). Starch-derived biopolymers and their combinations have the potential to replace polymers derived from fossil fuels. The starch/polyhydroxybutyrate (PHB) blend could be an alternative to polypropylene (PP) (Kabir et al., 2020; Pérez, & Bertoft, 2010) in the manufacturing of caps, pens, toys, food containers, cosmetics, and food packaging, among other uses. Meanwhile, the starch/Polybutylene succinate (PBS) combination exhibits properties similar to low-density polyethylene (LDPE) and can be applied in the production of films intended for the food industry for food packaging (Kabir et al., 2020; Pérez, & Bertoft, 2010; Chung, Liu, Lee, & Wei, 2011).

Table 2. Starch blends and their characteristics

Blends	Characteristics	References
PVA (Polyvinyl alcohol)	The starch/PVA blend is employed in the production of biodegradable biofilms with low oxygen permeability, preventing oxidation reactions and inhibiting microbial growth. The starch/PVA blend serves as a viable alternative to petroleum-based packaging due to its suitable mechanical properties and water resistance.	36,37
PLA (Polylactic acid)	Despite its outstanding properties, PLA (Polylactic Acid) incurs high production costs and exhibits low impact resistance, thereby constraining its widespread application. A more cost-effective alternative lies in the starch/PLA blend, which not only boasts economic advantages but also embodies non-toxicity and biodegradability, among other commendable qualities. This blend stands out as an ideal candidate for deployment in the production of bioplastics.	39, 41, 43
PBS (Polybutylene succinate)	The addition of starch to PBS as a filler enhances flexibility and accelerates the biodegradation time, while also expanding its applications in washable packaging and hygiene products.	38, 42

Chitosan

Chitosan is one of the biopolymers that most captivates the interest of academics and researchers worldwide, as well as its enormous potential attracting the attention of various sectors (Crini, 2019). Chitosan is a linear-chain polysaccharide obtained through the deacetylation of chitin via an alkalinization process at high temperatures (Firzanah, Akmal, Ahmad, Ahmad, & Noorasikin. 2023). Chitin is one of the most abundant polymers globally and the most prevalent in the marine environment, serving as the primary structural component found in the exoskeletons of arthropods such as crustaceans and insects, as well as in the cell walls of fungi (Jiménez-Gómez & Cecilia, 2020).

In terms of its composition, chitosan consists of (β1→4) linked residues of N-acetyl-2-amino-2-deoxy-D-glucose (glucosamine, GlcN) and 2-amino-2-deoxy-D-glucose (N-acetyl-glucosamine, GlcNAc) residues (Crini, 2019). The amino group in chitosan has a pKb value of approximately 6.5, leading to significant protonation in neutral solutions, which increases with rising acidity (decreasing pH) and the %DA-value. This characteristic renders chitosan water-soluble and a bioadhesive that readily binds to negatively charged surfaces, such as mucosal membranes. Additionally, chitosan can effectively interact with other surfaces via hydrophobic interactions and/or cation-π interactions (with chitosan acting as a cation source) in aqueous solutions (Sharkawy, Barreiro, & Rodrigues, 2020).

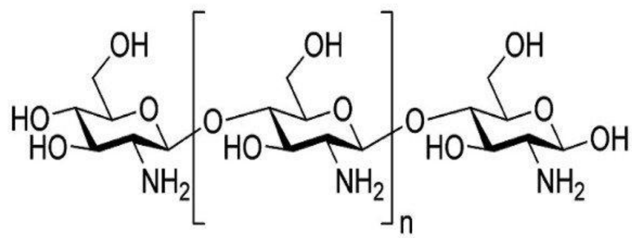

Figure 3. Schematic representation of chitosan chemical structure.

Chitosan is a biopolymer with significant medical applications, playing a crucial role in cell growth and tissue engineering. Due to its properties such as antibacterial activity, biocompatibility, and biodegradability, this biopolymer is utilized not only in medicine but also across various other industries. It can be employed in different forms according to the specificity of the final product, including gels, films, membranes, scaffolds, and others (Crini, 2019; Guo, 2024; Pellá, 2018).

Discussion and Conclusion

In light of the objectives aimed at reducing the impact of human activities on the environment through more sustainable practices, biopolymers, alongside renewable energy sources, represent the optimal pathway toward achieving a more balanced coexistence with our environment. Due to their inherent characteristics, biopolymers offer the best option for decreasing the reliance on synthetic polymers, which contribute to pollution in oceans, flora, and the planet as a whole. Their attributes, such as biocompatibility, render them widely applicable in the production of implants and other medical applications (Law, & Narayan, 2021).

Regarding the food industry, biopolymers can be directly incorporated into human or animal diets. Certain biopolymers, like chitosan, are utilized as food additives and as processing co-adjuvants (Ali, Sharma, Salama, Ling, & Li, 2022). Chitosan's ability to bind with fats provides health benefits, making it a popular choice among nutritionists for obesity management. Moreover, studies indicate that dietary fiber from chitosan possesses hypocholesterolemic activity, capable of reducing cholesterol and low-density lipoproteins. In the food sector, biopolymers also hold significant potential for food packaging materials (Law, & Narayan, 2021; Ali, 2022). Biopolymers such as cellulose and chitosan serve as excellent raw materials for food packaging due to their analogous properties to conventional plastics, along with their antibacterial and biodegradable characteristics (Baranwal, 2022).

In the pharmaceutical industry, where interest has been steadily increasing, biopolymers find diverse applications, including implants and medications. Biopolymers like PLA, silk, and chitosan are regarded as the future of implants (Baranwal, 2022; Rebelo, Fernandes & Fangueiro, 2017). PLA, with properties similar to certain synthetic polymers such as polypropylene, can be utilized in the creation of implants (Bergström & Hayman, 2015; Khouri, 2024). Additionally, it can serve as a stent for the dilation of intravascular vessels (Zong, 2022). Being a biocompatible material, it prevents foreign body reactions and can be biodegraded by the human body without leaving any exogenous material, thereby eliminating the need for a second surgery to remove the stent. Promising results have emerged from studies worldwide, such as that of Tami et al. (2000), who developed biodegradable stents based on PLA. Other researches also indicate that PLA-based materials can be employed in the production of vascular prostheses, thereby restoring blood flow (Tyler, Gullotti, Mangraviti, Utsuki, & Brem, 2016; DeStefano, Khan, & Tabada, 2020).

Other polymers, including chitosan, are gaining attention for their potential in drug delivery and the production of antibacterial medications, particularly for bacteria resistant to other types of drugs (Tao, 2021). In addition to their antibacterial properties, chitosan exhibits anti-inflammatory and antioxidant characteristics (Abd El-Hack, et al., 2020; Petrovici, Anghel, Dinu, & Spiridon, 2023), making it crucial for developing medications to combat certain degenerative diseases such as Alzheimer's and Parkinson's. Chitosan can also be utilized in implants for ligaments, bones, cartilage, and more. Meng et al., (2009) utilized a coating of chitosan and heparin to promote the acceleration of reendothelialization and the healing process following coronary stent implementation in a porcine iliac artery. The results demonstrated that the coating could enhance endothelial cell compatibility and hemocompatibility on the stent surface.

Beyond the pharmaceutical, biomedical and food industries, biopolymers are emerging as primary substitutes for petroleum-derived polymers (Kumar, 2024). The use of biopolymers for producing biodegradable polymers has potential applications in the textile, aviation, decoration, automotive, electronics sectors, and for producing bags and plastic bottles, as exemplified by cellulose acetate (Palencia, 2021), which is used for manufacturing biodegradable plastic bags. In addition to cellulose acetate, lignocellulosic fibers can be utilized in plastic material production. Another option is thermoplastic starch (TPS) (Raj, Chandrasekhar, Naresh & Kim, 2022), which, due to its characteristics, can be employed in protective packaging materials, including biodegradable packing peanuts and cushioning materials that can replace polystyrene and other non-biodegradable options. PLA fibers are widely used in the textile industry due to their properties akin to conventional polymers like polyester, as well as their biodegradable nature. PLA fibers are used to produce various types of clothing (Fattahi, Khoddami, & Avinc, 2020; Yang, 2021), and their lightweight nature and ability to allow greater air circulation make them suitable for casual and sportswear.

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