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Applications of Biopolymers in Bioengineering: A Comprehensive Review

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Abstract

In contrast to the traditional use of petroleum-based polymers, biopolymers are primarily made of polymers derived from living organisms like plants and bacteria. These molecular chains can naturally degrade in the environment because they are made of repeating chemical units derived from sustainable sources. The growing usage of biomaterials is a sustainable solution to reduce dependency on non-renewable resources and alleviate environmental damage caused by synthetic materials. The ability of biopolymers to degrade naturally and to be non-toxic is essential for preserving a clean and secure environment. Biopolymers are now known to become more and more popular as a result of their unique qualities, which include non-toxicity, biodegradability, biocompatibility, and eco-friendliness. These characteristics are particularly useful in bioengineering domains such as agriculture, pharmaceuticals, biomedical, ecological, industrial, aqua treatment, and food packaging. A summary of the significance of biopolymers in creative and clever bioengineering applications is the goal of this review paper.

Keywords: Biopolymers, Biocompatibility, Biodegradation, Bioengineering.

Introduction

While polymers are substances made up of multiple molecules with a large molecular mass, monomers serve as basic building blocks. The formation of a polymer involves the repetition of monomer chains, which can occur naturally or be artificially produced (Subash *et al*., 2023). Biopolymers, inherent in living organisms, consist of monomeric components linked by covalent bonds and organized into elongated chain molecules, forming structures that are capable of undergoing biodegradation (Rajesh Banu *et al*., 2019). Primary sources of biopolymers include plants, trees, microbes, and various natural origins (Udayakumar *et al*., 2021). In contrast to the simpler and more arbitrary nature of synthetic polymers, biopolymers are intricate molecules characterized by well-defined three-dimensional structures as shown in **Figure 1**.

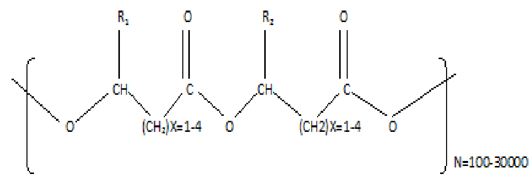

Figure 1. Biopolymer structure (Rai *et al*., 2021)

Using renewable resources allows for the creation of a large range of biopolymeric materials with distinct chemical and physical properties (Gusain *et al*., 2020). Many biopolymers, including lignin, starch, cellulose, and hemicelluloses, are found in nature. Biopolymers will be needed in large quantities for novel materials, but given their commitment to sustainable development, their cost-effectiveness needs to be improved (Wang *et al*., 2018). These polymers' qualities ought to be used in the creation of novel materials and goods that demonstrate their environmentally conscious use (Kar *et al*., 2022). As seen in **Figure 2**, recent research has focused on creating novel biodegradable polymers with strong mechanical and skeletal properties. Additionally, biopolymers derived from natural organisms are being produced in substantial quantities (Andreeßen & Steinbüchel, 2019).

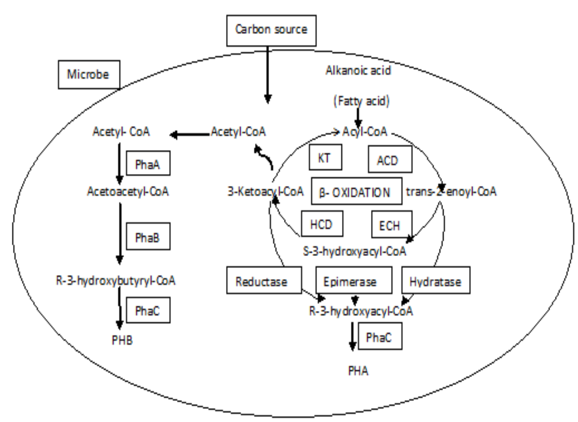

Figure 2. Biopolymer production in microorganisms (Gusain *et al*., 2020)

Some microorganisms and enzymes with unique degradable properties help biopolymers degrade more quickly. Biopolymers, which have atoms of nitrogen and oxygen in their skeleton, break down into CO_2, water, biomass, humid water, and other elements of nature (Elgarahy *et al*., 2023). Biodegradable polymers find

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extensive applications in bioengineering, such as in wound dressings, drug delivery systems, tissue engineering, and various other fields (Accinelli *et al*., 2015). Because of their special qualities—like their helical structure, stiffness, charge-free chains, and strong resistance to cold and salt—biopolymers are excellent thickening and stabilizing agents, especially in harsh pool environments.

Applications

Water Treatment

Researchers have presented novel techniques for purifying water, investigating methods for reusing water while emphasizing ecologically sustainable methods of treatment (Al Sharabati *et al*., 2021). By leveraging the unique characteristics of biopolymers, the use of natural polymers in membrane synthesis, production, and manufacturing presents an attractive and ideal approach to the development of completely biodegradable membrane materials (Awasthi *et al*., 2022). Through an adsorption-desorption method, researchers have recently used orange peel-activated carbon to remove herbicides containing chlorophenoxyacetic acid from water. It was demonstrated that this bio-derived activated carbon from water greatly absorbed herbicides including chlorophenoxyacetic acid (Awasthi *et al*., 2022). Membrane customization requires the employment of biopolymers, while cellulose polymers—which are abundant in polysaccharides—are extensively employed in a variety of water-related applications. Because cellulose is modified, membranes made of bacterial cellulose (BC), carboxymethyl cellulose (CMC), and cellulose nanofibrils (CNF) have different functions (Bishop *et al*., 2021). Membranes constructed from carboxymethyl cellulose (CMC), cellulose nanofibrils (CNF), and bacterial cellulose (BC) exhibit diverse functionalities owing to modifications in cellulose (Bernat *et al*., 2021). The efficacy of these modified membranes in eliminating anthraquinone and azo dyes from wastewater underscores the potential of biopolymer-based solutions in propelling the advancement of water treatment technologies (Brodin *et al*., 2017).

Tissue Engineering

Several intriguing properties of chitosan include its non-cytotoxicity, enhanced adsorption capacity, superior biodegradability, remarkable biocompatibility, and gel-forming ability. It also exhibits improved biological properties, including antifungal, antibacterial, and antitumor properties (Camacho-Muñoz *et al*., 2020). Because chitosan in hydrogel form has strong properties for cell adhesion, cell survival, cell interaction, and neurite outgrowth promotion, it is widely used in tissue engineering (Dilkes-Hoffman *et al*., 2019). Biological activity, self-assembly, elasticity, and long-term stability characterize elastin, a structural protein (Emadian *et al*., 2017). Elasticin is a protein that is known to give organs and tissues their elasticity. It is mostly present in organs like blood vessels, skin, lungs, and elastic ligaments that need to be flexible (Anjana *et al*., 2020). The addition of elastin to biomaterials becomes extremely important, especially in areas where the skin and blood vessels noticeable elastic effect is essential. Because of these advantages, elastin is frequently used in soft tissue regeneration, utilizing its special qualities for practical uses (García-Depraect *et al*., 2022).

Drug Delivery

Excellent qualities include functionality, water solubility, non-toxicity, biodegradability, and biocompatibility in biopolymers and their derivatives (Gil-Castell *et al*., 2016). Furthermore, through the controlled release of drugs, these biopolymers have the ability to lower the toxicity of medications. Collagen, the most prevalent protein in the animal kingdom, features a recurring sequence of glycine, proline, and hydroxyproline, adopting a triple helix structure (Hong & Chen, 2017). Due to its remarkable biocompatibility, collagen is utilized in drug delivery applications as coatings, films, and microparticles (Karamanlioglu *et al*., 2017).

Agriculture

Effective controlled-release fungicide and herbicide formulations have been made by commercializing a number of naturally occurring biopolymers with active pesticide groups. When gum biopolymers are paired with one or more fungicides, they serve a specific purpose in protecting seeds from fungal diseases (Mallampati *et al*., 2016). Both chitin and CS, occurring naturally, showcase the ability to control plant diseases in agriculture. They have been shown to have antifungal, antiviral, antibacterial, and antiparasitic effects. They're also employed in the chelation of nutrients and minerals. This action strengthens plant defense mechanisms and helps keep diseases from gaining access to these vital elements (Rai *et al*., 2021).

Food Industry

Polyhydroxyalkanoates (PHAs) have demonstrated great promise as fossil-derived polymer substitutes in the bioeconomy, and they could substantially swap out polyolefins in packaging applications (Asgher *et al*., 2020). Their advantageous physical properties and biocompatibility are the reason for this. For products that need a lot of moisture, cellulose acetate works well even though it doesn't have the best gas and moisture barrier qualities for food packaging (Herbes *et al*., 2018). This reduces fogging and promotes breathability. As per current research, polyethylene (PE) and polypropylene (PP) packaging foils show significant promise as active packaging materials with antioxidant and antibacterial properties in the food industry when coated with chitosan (CS) and polyphenol colloidal formulations (Wu *et al*., 2021).

Environment

Because of their various applications, environmentally friendly production methods, and biodegradability, biopolymers provide viable alternatives to non-renewable materials (Raza *et al*., 2018). The adverse impacts of synthetic polymers on the ecosystem highlight the significance of sourcing materials from renewable sources that decompose swiftly in the environment to alleviate the consequences of their extensive usage and avert additional environmental harm (Sajid *et al*., 2022). Biopolymers, which include proteins, polysaccharides, and lipids, have been studied as renewable raw materials that could replace petroleum-based, non-biodegradable plastics. In recent years, their demand has significantly increased (Scaffaro *et al*., 2018).

Biomedical

Biopolymers are widely used in medicine for a variety of purposes, including tissue guidance, controlled drug delivery, cellular proliferation, suturing, covering, fixing, adhesion, isolation, and guidance (Mikula *et al*., 2021). Sutures made of poly-(L-lactic acid), poly-(glycolic acid), and their copolymers are frequently used because of their exceptional flexibility and reliable knot toughness (Shruti & Kutralam-Muniasamy, 2019). The delivery of medication frequently involves the use of poly (ortho ester) and poly-hydroxy groups. When building artificial blood arteries, polyurethanes—which have qualities like pliability, hardness, and resistance to wear and tear—are crucial components. Polyester amides are essential for tissue engineering, hydrogel formation, and drug delivery (Thakur *et al*., 2018). Their applications span various medical products, including surgical masks, gloves, gowns, towels, sanitary napkins, diapers, surgical headgear, shielded panties, antimicrobial textiles for surgical curtains, and wipes (Yáñez *et al*., 2022).

Conclusion

Growing industrial interest in biopolymers and the production of eco-friendly products from them has been observed in recent years. Biopolymers are biodegradable, lightweight, easily fabricated, non-toxic, environmentally sustainable, and exhibit high skeletal behavior, which increases mechanical strength and stiffness. It is possible to modify these materials to satisfy different performance standards. The characteristics of hybrid biopolymer-based materials are influenced by a wide range of variables, such as surface area, particle size, specific temperature, environmental impact, and chemical composition. A detailed analysis reveals that biopolymers are widely accepted in a variety of industries, including tissue engineering, drug control, agriculture, pharmaceuticals, biomedicine, bioengineering, and the food sector. The versatility of biopolymers allows for a multitude of uses. Future research on biopolymer-based products may replace non-biodegradable, conventional materials that are detrimental to the environment. With these bioproducts' improved functionality and durability, new markets might open up. Finding the viability and effectiveness of biopolymers will require ongoing research into performance and life-cycle assessment.

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