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Biopolymers: An Introduction and Biomedical Applications

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ABSTRACT

Biopolymers are an important type of biomaterials that have many important applications in different fields of modern technology due to their important properties. One of these fields is the medical field, where biopolymers play a significant role due to their suitability for using in this field. This study reviews the academic work done in the literature on the analysis of different types of biopolymers such as chitosan, hyaluronic acid, collagen, alginates, silk fibroin, polyhydroxyalkanoates (PHA), poly(lactic-co-glycolic acid) (PLGA), gelatin, and polysaccharides including cellulose, starch, pectin, elastin, and keratin. Also, the most important medical properties and their biomedical applications are presented and explained. After reading this work, we will become familiar with different types of biopolymers, and it turns out that biopolymers have many unique biomedical properties such as non-toxicity, biodegradability, and biocompatibility. Based on these properties, biomaterials have many applications in medicine, including medical delivery, tissue engineering, healing wounds, and medical imaging devices.

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Introduction

Biomaterials are the basis for the development and improvement of biomedical technologies used both as medical treatments and in the manufacture of medical devices. The success rate and compatibility of biomaterials in the medical field depends on the presence of many unique and important properties including biocompatibility (the ability of materials to interact with living organisms without causing harm.) [1-7], biodegradability*(* the ability of living organss to break down complicated organic structures into their component parts [8], and non-toxicity (It is the ability of biomaterials to prevent damage to the medium in which they are implanted) [9-11]. Biopolymers are types of biomaterials that have many applications in the biomedical field due to the mentioned and many other important properties [12].

Biopolymers are organic materials that are produced naturally and come from living things like plants, animals, or microbes. Because they are biodegradable, non-toxic, and have a smaller carbon footprint than synthetic polymers, they are seen as more ecologically friendly options [13]. Biopolymers come in a variety of forms, each with special characteristics and uses. Examples that are often used include DNA, proteins, carbohydrates, and cellulose. These biopolymers may be used to create a variety of materials, including textiles, medical devices, packaging items, and adhesives. Biopolymers are used in a broad variety of applications. For instance, the medical industry uses biopolymers like collagen and chitosan for medication delivery and tissue engineering [14]. The materials that are used in medical treatment must be biocompatible to avoid any side effects in the patient's body. Most biopolymers are biomaterials that have high biocompatibility and therefore have important and well-known uses in medicine, both as implants and in the manufacture of medical devices. In addition to biocompatibility, biopolymers have many other unique properties such as bioactivity, long-term stability, biodegradation, non-toxicity, and so on. These behaviors make them desirable for applications in many fields, one of these fields is the biomedical field [15].

There are several works in the literature that have worked on the use of biopolymers in medicine, such as tissue engineering [16], drug delivery systems [17], wound healing [15, 18], bioactive coatings and implants, diagnostic tools, and controlled release systems.

This review provides a brief introduction to biopolymers, each type of biopolymer, and their important properties, especially medical, and finally, the most important medical applications of biopolymers are reviewed based on several important works done in the past on biopolymers in the medical field.

Biomaterials

The term "biomaterials" refers to materials that may be applied to the treatment of disease and that are compatible with living tissues [19-21]. They have particular features such as surface improvements, biocompatibility, and degradability. By offering scaffolds, encouraging tissue growth, and enhancing patient outcomes, biomaterials are essential in regenerative medicine, tissue engineering, and the creation of medical devices [22]. Also, biomaterials are either from nature or synthesized in the laboratory using metals and their alloys, polymers, ceramics, composite materials, and so on. These materials are utilized for medicinal purposes by affecting the entire or a portion of the living systems, therefore performing, augmenting, or replacing a natural function of human physiology. These materials are very complex and sensitive during their application, such as when employed for a heart valve, as hydroxyapatite coated hip implants, and so on [23]. Also, biopolymers have four main types (bioceramics, metallic biomaterials, biopolymers, and biocomposites), as each of them has its characteristics that contribute to the development of technology [23].

Biopolymers

Biopolymers are macromolecules that are found in nature and are often created by living systems such as micr oorganisms, plants, and animals [24]. In recent years, there has been an increasing trend towards using more natural polymers to manufacture various culinary and biomedical products [25]. It is worth noting that biopolymers have been used in a variety of industries, including textiles, cosmetics, medicines, and paper [26].

As previously stated, biopolymers are composed of repeated monomer units and are typically obtained from plants, animals, and microbes. In general, biopolymers' repeating units can be sugars, amino acids, or fermentative products such as aliphatic polyesters. These biopolymers may contain various functional groups such as hydroxyl, amino, amide, carboxyl, phosphate, and phenolic, which contribute to their diverse biological activity [27]. Biopolymers are often categorized into three groups: polysaccharides, proteins, and polynucleotides. Polysaccharides are typically composed of sugar moieties that are covalently bound together via glycosidic bonds [28]. Each glycosidic link causes the removal of one water molecule. Polysaccharides can be charged neutral (dextran, pullulan), polycationic (chitosan), or polyanionic (alginate) [29]. Polysaccharides can be homogeneous (having a single type of monomer, such as glycogen) or heterogeneous (containing many sugar units, such as xanthan gum and gellan gum) [30].

On the other hand, Proteins are polymers composed of amino acid moieties as their monomeric units. The amino acids are connected through amide bonds, which leads to the creation of a three-dimensional (3D) structure [31]. The polyamide chain represents the fundamental level in the protein structural hierarchy. The folding of the chain into secondary structures, such as alpha-helix and beta-pleated sheets, is facilitated by a range of molecular interactions, including hydrogen bonding, salt, and disulfide bridges, as well as hydrophobic and hydrophilic interactions. The interactions indicated above further compact the structure into tertiary structures. The creation of a quaternary structure is a result of interactions between various protein subunits [32]. Polynucleotides, such as DNA and RNA, are a class of biopolymers that consist of at least 13 nucleotide monomers or more [33]. Their biological purpose is separate and involves the storage, replication, and discernment of genetic information. The structural architecture of both nucleic acids consists of a phosphate group, sugar moiety, and four nitrogenous bases, with minor variations [34].

Due to the wide range of biopolymers with diverse chemical compositions, it is feasible to develop a variety of food and biomedical products that exhibit varying structural and physicochemical characteristics. This is feasible due to the existence of several functional groups on the polymeric chains of the biopolymer. The presence of functional groups in biopolymers facilitates their interaction with various components found in products [35]. However, biopolymeric materials have been found to have insufficient mechanical qualities, rendering them unsuitable for designing specialized products. To overcome this problem, numerous writers have suggested the utilization of cross-linkers, which are chemical agents with multiple functions and the capability to establish covalent bonds with the polymer chains. In addition, the use of the cross-linking procedure might lead to the creation of goods with diverse characteristics, as the chemical reaction can occur in distinct manners when the environmental parameters of the cross-linking reaction are altered [36].

Biomedical Properties of Biopolymers

Biopolymers have many important properties that make them applicable in many different fields, one of them is the biomedical properties that make them used in many important medical fields, such as tissue engineering, drug delivery, wound healing, and diagnostic tools. Some of the key biomedical properties are presented in Table 1.

Table 1. Biomedical properties of Biopolymers.

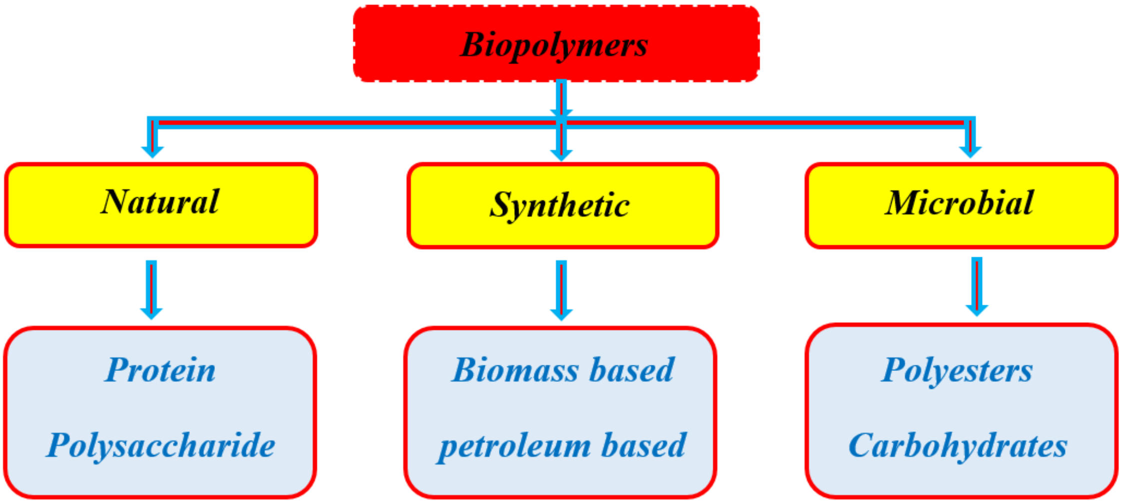
Properties of Biopolymers	Description
Biocompatibility	The ability to adapt to living systems without adverse effects is crucial for medical treatments like tissue engineering, drug delivery, and medical implants [6, 37-41].
Biodegradability	Natural degradation over time in the body is beneficial for applications like absorbable sutures and medication delivery systems requiring temporary support [42].
Non-toxicity	Safe for use in medical devices and drug delivery systems, without risk of negative side effects [9, 11, 43, 44].

Versatility	Existence in various forms such as proteins (collagen, gelatin) and polysaccharides (chitin, chitosan), enabling a wide range of medical uses [45].
Structural Support	Provision of support for tissue engineering scaffolds, aiding in cell development and differentiation into functional tissues [46].
Hemostasis	Ability to facilitate blood clotting, valuable in surgical supplies and wound dressings to reduce bleeding [47].
Bioadhesion	Capacity to cling to biological surfaces like mucosal membranes, useful for targeted drug delivery to specific parts of the body [48].
Antimicrobial	Inherent antibacterial properties, are beneficial in wound dressings and medical devices to prevent infections [48].
Immunogenicity Control	Ability to manage or lower immunogenicity through modifications, allowing use in various medicinal applications [49].
Regenerative Medicine	An essential role in providing scaffolds, growth factors, and other components for tissue regeneration and repair in regenerative medicine applications [50, 51].

Types of biopolymers

Biopolymers are complex macromolecules present in living organisms, consisting of repetitive monomer units. The three major types of biopolymers are shown in Table 2.

Table 2. Classification of biopolymers [52].



Natural biopolymers

Natural biopolymers, derived from natural sources, are extensively utilized in biomedical applications due to their desirable characteristics, including biocompatibility, biodegradability, high porosity, and the capacity for various chemical and physical modifications tailored for tissue regeneration [53-55]. Some natural biopolymers include collagen, fibrin, fibrinogen, platelet-rich plasma, alginate, gelatin, albumin, and hyaluronic acid. Biopolymers are frequently employed in the fabrication of biological scaffolds and have a higher propensity to promote cell development *[53]*. Natural biopolymers have significant promise for several applications in the biomedical industry, including dental, ophthalmology, wound healing, cosmetics, pharmaceuticals, medication delivery, food flavoring/preservatives, and waste-water treatment. These applications are relevant both now and in the future *[53]* .

Synthetic biopolymers

Synthetic biopolymers play a crucial role in biomedical applications due to their tailored properties and versatility. These polymers, derived from non-natural sources, are designed to serve as components in biomedical and pharmacological therapeutic systems. They are created from metabolite building blocks and are bioassimilable, making them suitable for time-limited therapeutic applications [56]. Polylactic acid (PLA) and polyhydroxyalkanoates (PHAs) are two synthetic biopolymers often used in biomedical applications. These biopolymers are produced by the use of microorganisms or genetically modified sources. Biopolymers has many benefits, including biocompatibility, repeatability, and stability, which make them very suitable for applications such as tissue engineering, medicine administration, and implants. 3D printing's potential in the biomedical field has expanded due to the discovery of synthetic biopolymers. Customised implants, scaffolds for tissue engineering, medication delivery systems, and organs-on-a-chip may be made using biopolymers as bio-inks in 3D printing. Enhancing biocompatibility, producing functional materials for diverse biomedical purposes, and establishing personalised drug delivery systems are all within the future scope of synthetic biopolymers in 3D printing. By providing accurate and tailored structures for improved patient outcomes and tissue integration, this advanced technology has the potential to revolutionise healthcare, regenerative surgery, and specific therapeutics [57].

Microbial biopolymers

Microbial biopolymers are made by living bacteria using enzymes to link various components like sugars, amino acids, lipids, and nucleic acids. Biological molecules or their constituent parts may be used as building blocks for various kinds of these materials. They have many potential uses since they are biodegradable, inexpensive, and renewable. [58]. A wide variety of medical, pharmaceutical, and biotechnological applications exist for microbial biopolymers. They are used in many different fields, including as medicine, biotechnology, cosmetics, food, absorbents, food additives, biosensors, and packaging. Because of their wide range of chemical and physical properties, bacterial biopolymers have many potential applications in medicine and industry, in addition to their important functions in pathogenicity. Their adaptability to different uses is due to the fact that their physicochemical qualities may be changed by chemical or enzymatic changes. Novel biopolymers with many uses in medicine, including as additives in food, cosmetics, and packaging materials, have been made possible by recent developments in the fields of synthetic biology and bioengineering [59].

Biopolymers and their medical applications

Biopolymers are divided into three primary classes based on the monomeric units utilized and the resulting structure of the biopolymer. Polynucleotides, such as RNA and DNA, are lengthy polymers consisting of 13 or more nucleotide monomers. Furthermore, polypeptides are concise chains of amino acids. Thirdly, polysaccharides are linear polymers formed by the bonding of carbohydrates. Materials composed of these molecules are categorized as pliable, elastic, and viscoelastic, and exhibit properties that lie between those of solids and liquids. Biopolymers are considered intelligent and flexible substances in living organisms due to their structures being continuously modified by enzymes during various stages of an organism's life cycle or in reaction to changes in the environment [60].

Biopolymers are a class of polymers that are derived from natural sources and are biodegradable, making them highly valuable for various biomedical applications. Their biocompatibility, versatility, and eco-friendliness have led to a wide range of uses in the field of biomedicine [61]. Here are the most common types of biopolymers and their medical applications:

Chitosan and Chitin

Chitosan is a naturally occurring polymer obtained by removing acetyl groups from chitin [62]. Chitin is a naturally occurring substance that is synthesized by organisms like mollusks and insects, which makes it readily available and cost-effective to acquire. Chitosan is a substance that is not harmful to living organisms, can be broken down naturally, and possesses the ability to kill bacteria and fungi [63]. Moreover, it possesses a favorable surface charge that facilitates the binding of negatively charged cargo such as DNA through electrostatic interactions. Chitosan can safeguard DNA from degradation by nucleases in gene therapy applications [64]. The properties of chitosan are primarily determined by its molecular weight and degree of acetylation, which significantly affect its many applications [65] Figure 1 shows the applications of chitosan in the medical field.

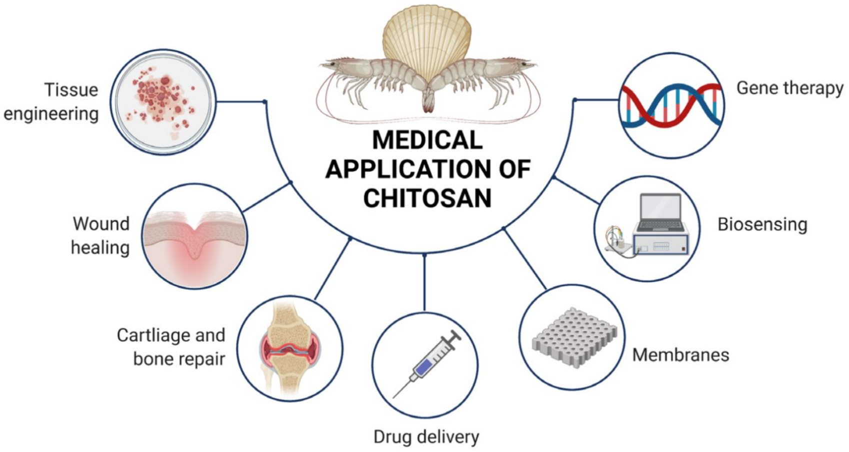


Figure 1. Medical applications of Chitosan [66].

Chitin was first discovered in 1811 by Braconnot and initially referred to as fungus due to its discovery in mushrooms. In 1823, Odier coined the term "chitin" for the substance found in the elytrum of the cock chafer beetle. He derived this name from the Greek word "chitos," which means coat. Chitin is a naturally-occurring polysaccharide that is commonly found in fungus, yeast, insects, and crustaceans. It serves as a structural component in these organisms, including their exoskeletons (Figure 2) [67]. It can be argued that specific forms of hydrogels and membranes can be used as drug delivery systems that are implanted as implants. This highlights the crucial applicability of chitin in this area [68].

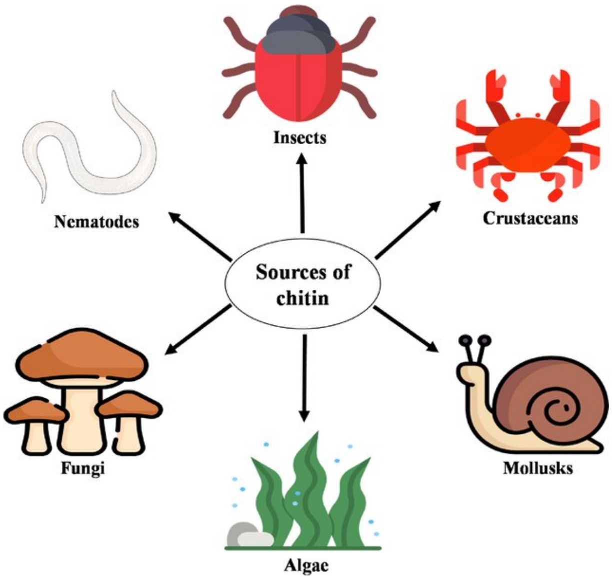


Figure 2. Natural sources of Chitin [69].

Hyaluronic acid

Hyaluronic acid (HA), also known as "hyaluronan," is a straight-chain polysaccharide. The structure consists of alternate repeating units of b-(1/4)-linked D-glucuronic acid and b-(1/3)-linked N-acetyl D-glucosamine [70]. It is classified as a member of the mammalian glycosaminoglycans family. HA, unlike the other members of the family, lacks sulfation and is a physically less complex polysaccharide that is not chemically bonded to a core protein [71]. It has a vital role in the composition of synovial fluid (SF). The molecular weight of HA falls between the range of 1.6 × 106 to 10.9 × 106 g/mol [72]. A number of animal tissues, including cockscombs, cartilage from the brain, and tissue joints, are potential sources of HA. It may also be made by mixing it with other bacteria, including Pseudomonas. When examining the structure, it is observed that the HA molecule consists of a significant amount of hydroxyl and carboxyl groups. When these groups are in an aqueous solution, they may form many hydrogen bonds, both inside and between molecules. [73].

Hydrophilicity and rheological behavior are two of hyaluronic acid's unique properties that have made it useful in biological applications. [74]. Hydrogels made from HA can function as scaffold materials that mimic the natural tissue conditions and offer a 3D elastic and compressive network for the grown cells [75]. Xie et al. conducted a study where they created ethosomes containing hyaluronic acid (HA-ES) with the intention of employing them as a carrier for transdermal medication administration. They used rhodamine-B (RB) as the model drug in their experiment [76]. Figure 3 summarizes the medical applications of Hyaluronic Acid.

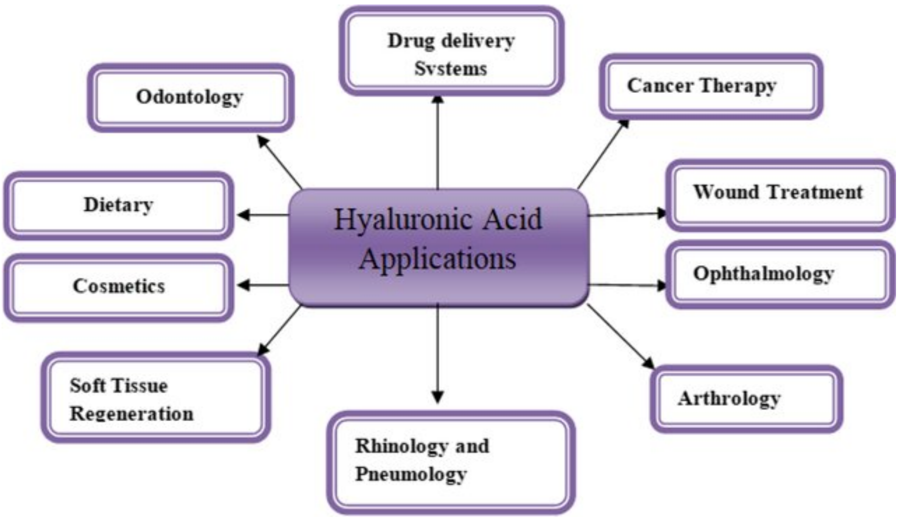


Figure 3. Biomedical applications of HA [77].

Collagen

Collagen, the most prevalent protein in the animal kingdom [78], is located in the extracellular matrix. This protein undergoes cross-linking to create a framework, resulting in a material that is extremely compatible with living organisms, capable of breaking down naturally over time and composed of organic compounds. Collagen is often subjected to cross-linking or combined with other substances, such as different types of polymers, to improve its mechanical characteristics [79], The structure of Collagen is shown in Figure 4. Collagen has certain limits, such as challenges in regulating the rate of release and breakdown. Collagen has been employed in several applications such as medication delivery, tissue engineering, injectables, and wound dressings [80]. Dong et al. [81] recently conducted a review on the applications of collagen.

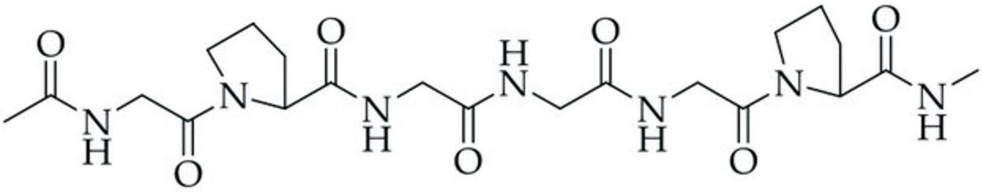


Figure 4. Chemical structure of Collagen [82].

Alginates

Alginates are water-soluble polymers that are extracted from dark-colored seaweeds and exist as hydrocolloids. Due to its ability to break down naturally, compatibility with living organisms, lack of antigenic response, and maximum capacity for chelation (Figure 5). it is frequently used in biomedical contexts for various purposes such as tissue engineering, drug delivery, and treatment of gastric reflux [83]. Alginate is utilized as a scaffold or conduit for tissue stabilization and regeneration. Macrocystis porifera and Ascophyllum nodosum are two primary sources of alginates. Alginate hydrogels can be formed by either chemical or physical crosslinking of the polymer chains, primarily through ionic crosslinking with multivalent cations. These gels can include a water substance exceeding 95% and can undergo heat treatment without disintegrating [84]. Alginate is used for texturizing organic products, forming gels, removing proteins, extending the shelf life of potatoes, immobilizing banana enzymes, making minced fish patties, and meat products, water retention, stabilizing ice cream, and dispersing substances. Alginate exhibits a strong affinity and binding capacity towards metal particles, making it an effective adsorbent for heavy metals. Moreover, these devices are employed for the transportation of fungicides, insecticides, and other similar substances, while adhering to safe agricultural methods. The U.S. Food and Drug Administration (FDA) recognizes it as a polymer with many applications in recovery treatments and food supplements [85].

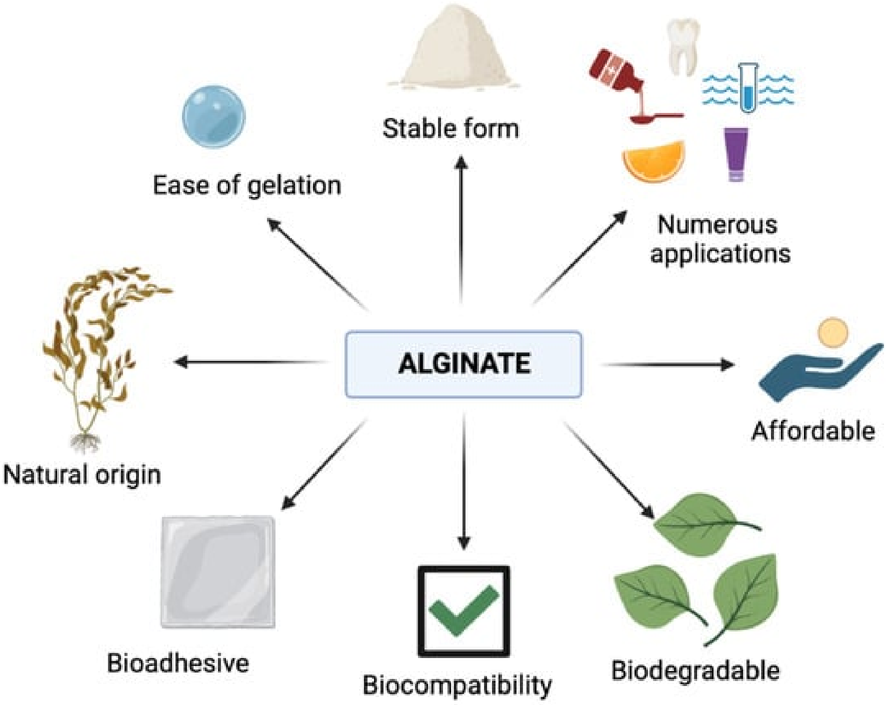


Figure 5. Biomedical properties of alginates [86].

Silk Fibroin

Silk is a protein biopolymer that is produced by certain insects and arachnids, such as silkworms, spiders, mites, scorpions, and some flies [87, 88]. The silk fiber consists of polymer chains that are aligned in parallel to its axis, which gives rise to robust and non-stretchable fibers. This unique property has made silk fibers suitable for surgical sutures in previous times [89]. Silk has recently been used in the development of scaffolds for bone tissue engineering [90]. Silk, being a readily manipulable biopolymer, enables the fabrication of various shapes and structures for silk-based biomaterials. This characteristic has implications for their degradability and applicability in medical micro-devices. Silk-based scaffolds are appropriate for addressing a wide range of bone restoration and regeneration goals in the field of Applied Sciences [89].

Polyhydroxyalkanoate (PHA)

Polyhydroxyalkanoate is produced by microbes under limited growth conditions. Ralstonia eutropha, a commonly studied bacterium, is extensively utilized for the manufacture of PHA [91]. The polymer poly (3-hydroxybutyrate) (PHB), often known as PHA, was initially discovered in Bacillus megaterium by the French scientist Lemoigne in 1926 [92]. PHA is a type of linear thermoplastic polymer that falls under the category of bio-based bioplastics. These intracellular carbon and energy reserves can be created by many bacteria. PHA is a thermoplastic polyester composed of hydroxyl acid (HA) monomers that are linked together by an ester bond as shown in Figure 6.

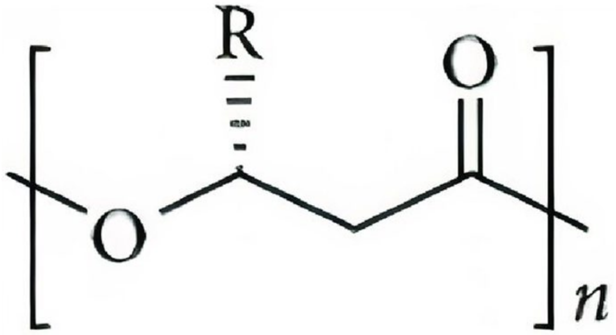
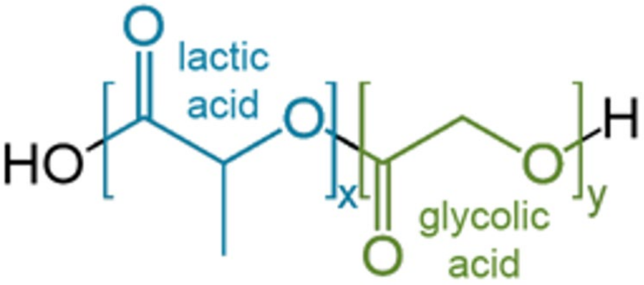


Figure 6. Chemical structure of Polyhydroxyalkanoate [93].

Polyhydroxyalkanoate is assimilated by a diverse range of microorganisms, including gram-positive bacteria, cyanobacteria, anaerobic bacteria, photosynthetic microbes, and archaea. These materials are biocompatible, completely biodegradable, have excellent processability, are non-toxic, and exhibit significant auxiliary variety [85]. In addition, it has been shown that PHAs had antibacterial effects against pathogens, such as S. aureus. The use of Chlorhexidine (CHX), an effective antifungal agent combined with PHB/PEO fibres, resulted in a 99-100% reduction in E. coli and S. aureus. PHAs also have antimicrobial properties in the gastrointestinal tracts of mammoths, tigers, and prawns [85, 94].

Poly (lactic-co-glycolic acid) (PLGA)

Polylactic-co-glycolic acid polymers are anionic copolymers composed of glycolic acid and lactic acid (Figure 7). PLGA is frequently employed in biomaterials due to its biodegradability, biocompatibility, and ability to safeguard cargo from degradation [95]. The molecular weights of PLGA typically range from 10000 to 20000 g/mol, although it is possible to generate higher molecular weights [96]. By adjusting the ratio of lactic acid to glycolic acid, it is possible to modify characteristics such as circulation time and breakdown rate. PLGA, which is FDA-approved, has undergone significant research and has been found to have several applications. It has been modified to be used as a biomaterial for delivery and tissue engineering purposes [97]. Xu et al., Danhier et al., and Mir et al. have conducted comprehensive reviews on PLGA and its uses [98-100].



X and y represent the number of times each unit repeats

Figure 7. Schematic diagram of the structure of PLGA [101].

Gelatin

Gelatin is a heteropolysaccharide found in the cell walls of plants. Gelatin consists of a complex arrangement of carbohydrates that can be found in important cell walls and is particularly abundant in non-woody plants. Gelatins are commercially derived from citrus strips or apple pomace, which are residual biomass generated by juice manufacturing facilities. Gelatin is believed to primarily consist of D-galacturonic acid (GalA) units, which are connected in chains through á-(1-4) glycosidic linkage [85]. Furthermore, several studies have demonstrated the potential application of algae for the production of biofuels [102-104]. It has extensive usage as a gelling agent, employed to solidify desirable components, and as a stabilizer in pharmaceutical products [105].

Polysaccharides (Cellulose and Starch)

Cellulose is a naturally occurring polysaccharide made up of glucose monomers that are connected linearly through b-(1 / 4) bonds. It serves as a primary component of the cell walls in algae, bacteria, green plants, and vegetables [106]. It is the most prevalent polymer found in nature and is widely recognized for its exceptional strength, fibrous structure, and inability to dissolve in water [107]. Cellulose is a polymer that contains a significant amount of hydroxyl groups due to the three reactive hydroxyl groups per anhydroglucose unit in its polymeric structure [108]. The hydrophilic characteristic of cellulose molecules is mostly attributed to the functional and reactive hydroxyl groups [109]. Cellulose's insolubility in water is due to the presence of numerous inter- and intramolecular hydrogen bonds, which contribute to its crystalline structure [110]. Different processes, including oxidation, etherification, esterification, and micronization, can be employed to create various forms of modified celluloses. Cellulose derivatives such as hydroxypropyl cellulose (HPC), microcrystalline cellulose (MCC), silicified microcrystalline cellulose (SMCC), hydroxyethyl cellulose (HEC), sodium carboxymethylcellulose (SCMC), ethyl cellulose (EC), methylcellulose (MC), and oxycellulose (OC) have been widely utilized in the food and biomedical sectors [111]. These cellulose derivatives, also known as cellulosic, can be modified by the required industrial applications [112].

Plants produce and accumulate starch within their tissues as a way of storing energy. Typically, it is deposited as minute granules or cells that have dimensions ranging from 1 to 100 µm. Starch is the second most plentiful carbohydrate obtained from plants, behind cellulose, and serves as a significant raw resource [113, 114]. Starch is the primary carbohydrate found in plants and serves as a stored source of nourishment during periods of development, hibernation, and germination. As a biodegradable polymer with distinct chemical properties, it holds significant potential as a versatile and renewable resource for a wide range of material applications in both food and non-food sectors. Extensive research has been conducted on the content and characteristics of starches that are accessible for commercial use. The characteristics of each starch are highly influenced by the plant from which it is derived [115].

There are several valuable biomedical applications due to its biocompatibility, biodegradability, and versatility. A notable use of modified starches is in drug delivery systems, where they can be utilized as carriers to progressively encapsulate and release pharmaceutical substances, hence improving their stability and bioavailability [116]. Starch-based hydrogels possess exceptional water absorption characteristics, rendering them appropriate for applications such as wound dressings and tissue engineering scaffolds. Furthermore, researchers have investigated the use of starch-based materials in diagnostic platforms, such as biosensors and imaging agents, because of their convenient functionalization and ability to interact with biological molecules [117].

3.2.10. Pectin

Pectin is a group of complex polysaccharides found in the cell walls of actively growing and dividing plant cells. It is also seen in the area where cells meet within secondary cell walls, such as in the xylem and fiber cells in woody tissue. Pectin plays a vital role in the initial growth and ripening of fruit. It is often a secondary product of the food and fruit processing industry and is thus easily available. [118]. A linear polysaccharide composed of D-galacturonic acid units connected by α-1,4 links makes up the majority of it. On occasion, however, sections with a lot of branches break up its mostly linear pattern. Because it is safe, non-toxic, easily produced, and widely available, pectin finds employment in many different contexts. Because of its gelling, thickening, stabilizing, and emulsifying qualities, it is also widely used in the food industry. [119]. Because of its capacity to form hydrogels, pectin finds widespread use in food that are both wet and thick. The gelling properties of pectin have made it a popular ingredient in many foods, including jams, fruit juices, candies, dairy products, and jellies. The application of this substance as a stabilising agent in colloidal dispersions is diverse, encompassing emulsions, antioxidant-fortified meals, acidified milk drinks, and high-protein fruit drinks [120].

3.2.11. Elastin

Elastin-based materials are highly appealing for use in tissue engineering due to their exceptional characteristics. This protein exhibits long-term stability, flexibility, self-assembly, and biological activity, making it a structural protein. Elastin is a protein that imparts elasticity to organs and tissues. It is primarily found in organs such as elastic ligaments, blood vessels, skin, and lungs, where elasticity is of utmost importance [121]. The incorporation of elastin into biomaterials is crucial in areas of the body where elasticity is noted, such as the skin and blood vessels. Therefore, it is commonly employed for the regeneration of soft tissue [122]. Elastin-like polypeptides (ELPs) enhance the stability and biocompatibility of polymeric structures. Due to their adjustable characteristics, they serve as very effective drug-delivery vehicles and have the ability to specifically target the brain [123]. Figure 8 illustrates the primary uses of ELPs.

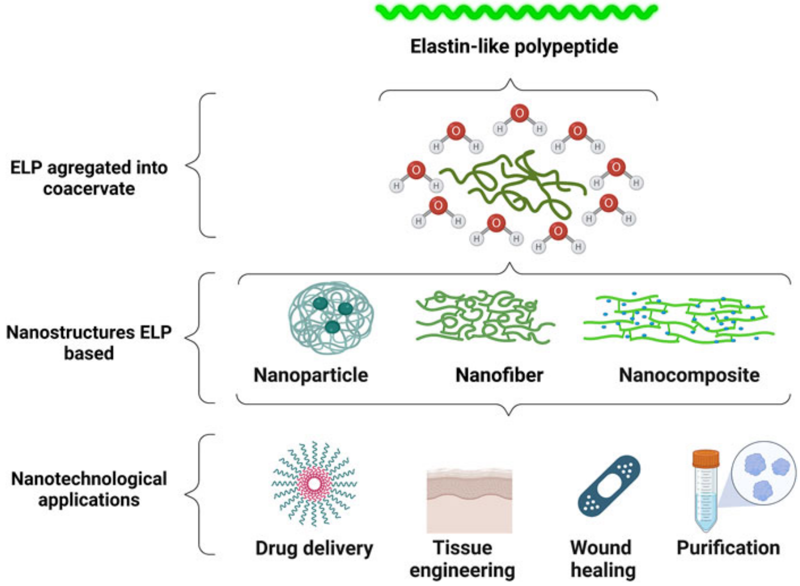


Figure 8. The main applications of Elastin-like polypeptides (ELPs) [124].

3.2.12. Keratin

Keratin is a polypeptide protein composed of several amino acids. It contains disulfide-cysteine amino acid linkages, which form both intermolecular and intramolecular bonds with both non-polar and polar acids [125]. A recent investigation indicated that hydrogels made from keratin-based materials had the ability to induce neurogenesis and promote tissue regeneration in mice with peripheral nerve injuries [16]. Keratin, a protein, has demonstrated great potential as a material for use in the biomedical field, particularly in the regeneration of soft and neural tissues. This is due to its impressive effectiveness and performance in biological functions. The bioscaffolds and substrates derived from keratin have a high capacity for optimizing biocompatibility, biodegradability, and non-immunogenicity [16].

Keratin possesses biological qualities and a multifunctional structure of amino acids that enable it to enhance cell proliferation and adhesion. This makes it suitable for use in soft tissue engineering, as it can be easily processed and changed [126]. Because of its biological functioning, which encourages the invasion and proliferation of Schwann cells, the biomaterial is the first of its type to be effectively used in neural tissue engineering [127]. Figure 9 illustrates the origins and uses of keratin.

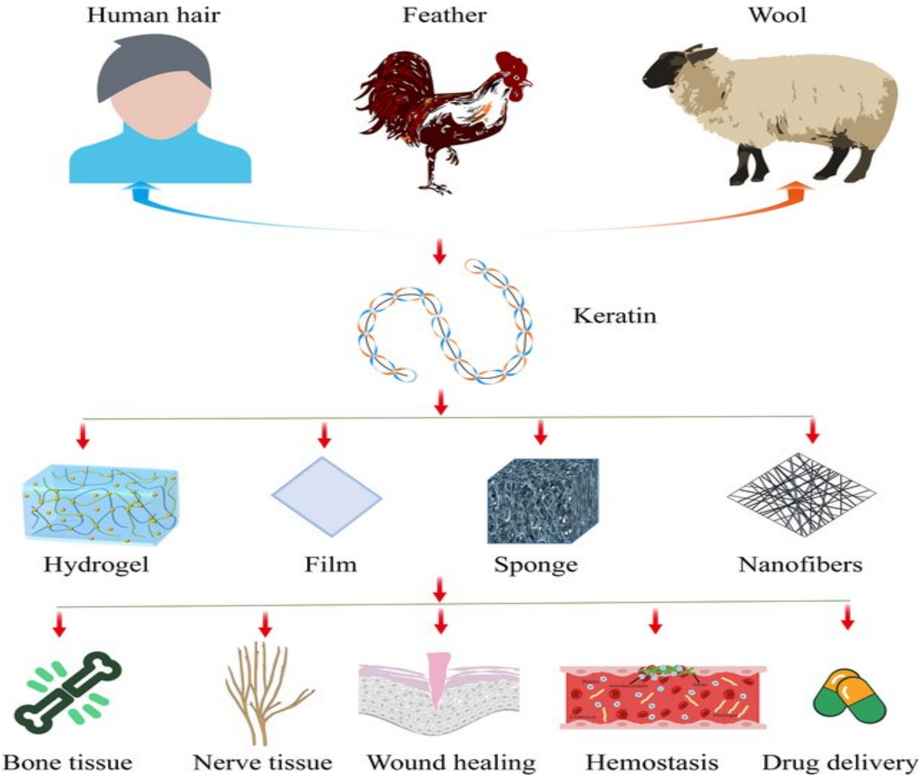


Figure 9. Keratin source and its biomedical applications [128].

3.2.13. Fibrin

One biopolymer that plays an important role in blood clotting is fibrin. In its fibrous state, it has remarkable biomechanical qualities such as perfect viscosity and elastic and stiffness as well as resistance to breaking and the capacity to stretch [129]. Human-derived fibrinogen and thrombin, the active ingredients in fibrin-based products like fibrin sealants, improve coagulation factors and promote blood clotting. The wide range of biological applications of fibrin, including drug delivery, tissue engineering, implant fabrication, and hemostasis, has led to its comprehensive investigation [130]. Frameworks for cartilage tissue engineering have been developed using fibrin-based hydrogels, which promote cell proliferation in labs and encourage the growth of cartilage-like tissue [131]. Moreover, hydrogels based on fibrin have been used to wound healing to promote the development of new tissue and speed up the healing process [129].

3.2.14. Agarose

Agarose is a biopolymer that is made from seaweed. Because of its unique properties, it is widely used in medicinal fields. Also, aAgarose is a polysaccharide that is safe, recyclable, and has a strong ability to gel [132]. A common use is in the production of hydrogels, which are complex structures made of linked polymers with the capacity to hold large amounts of water. Because of their promising applications in regenerative medicine, drug delivery, and tissue engineering, hydrogels have been the subject of much research. In order to facilitate tissue regeneration, agarose hydrogels have been used to encase many cell types, including skeletal muscle cells, osteochondral muscle cells, and stem cells[133]. To enhance their biocompatibility and mechanical properties, Agarose has been collaborating with other biopolymers, such collagen, to create hybrid hydrogels. Furthermore, hydrogels containing agarose have been created to promote the regeneration of skeletal tissues, particularly bone and cartilage [134]. Figure 10 illustrates the chemical composition and several medical uses of Agarose.

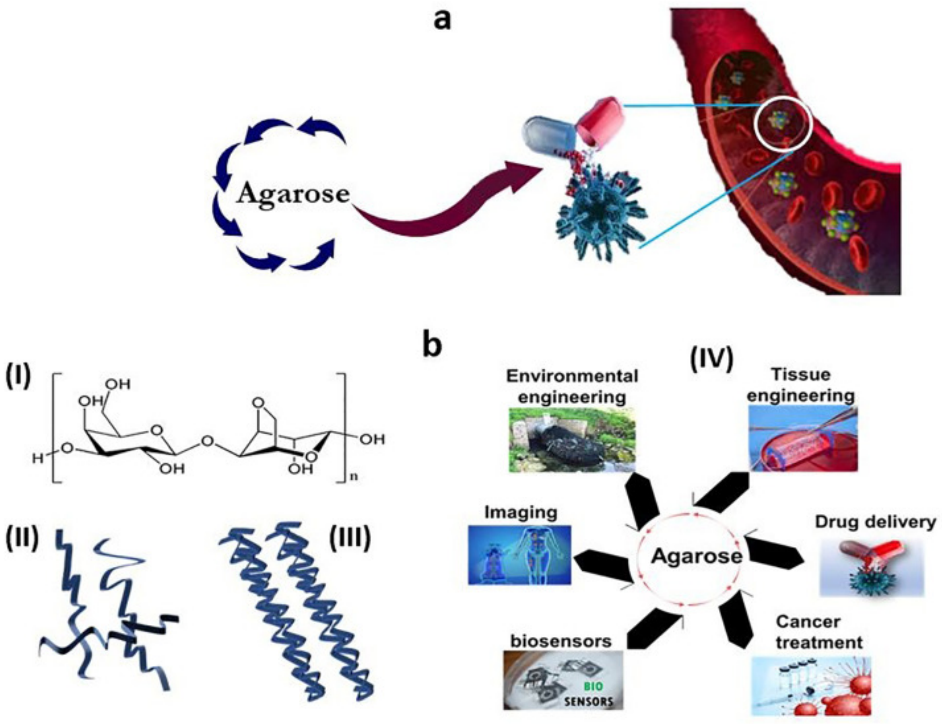


Figure 10. Chemical Structure and Medical Applications of Agarose [135].

3.2.15. Carrageenan

Carrageenan is an organic compound obtained from red seaweeds. It is used in food products as emulsifiers, stabilizers, and agents for thickening and gelling [136]. Recent studies have shown that carrageenans have bioactive qualities that may modulate the immune system, fight viruses, bacteria, and coagulation, and even prevent cancer. Because of these characteristics, carrageenans have great potential in the biomedical industry. Tissue engineering, drug delivery, and wound healing are just a few of the biomedical applications of carrageenan-based hydrogels. They have also found utility in the extraction of metals, medicines, dyes, and other water-based contaminants [137]. Because of its nontoxicity, compatibility with living things, and natural degradation capability, carrageenans have found usage in drug delivery systems. They have found their way into a wide variety of pharmaceutical products, including film, hydrogels, microparticles, nanoparticles, inhalable systems, pellets, tablets, suppositories, films, fast-dissolving inserts, beads, and pellet [138].

3.2.16. Fibronectin

Biopolymer fibronectin has several applications in the biomedical field, particularly in the fields of bone regeneration, cardiac repair, and wound healing. The extracellular matrix (ECM) of different organs contains a glycoprotein, which is necessary for cell adhesion, migration, and proliferation [139]. To improve cell adhesion and proliferation, hydrogels based on fibronectin have shown promise as a tissue engineering tool. As an example, fibronectin-coated surfaces have been used to improve cell adhesion and proliferation in tissue culture plates. Also, hydrogels based on fibronectin have been used for heart repair, encapsulation of fibroblasts and kidneys, and skeletal tissue regeneration [140]. There are a number of benefits to using fibronectin in tissue engineering. These include biocompatibility, biodegradability, and the fact that it promotes cell adhesion and proliferation [141].

Conclusion

In conclusion, biopolymers provide a variety of materials with unique properties that make them great for use in biomedicine. Antimicrobial and gene-delivery capabilities are shared by chitosan and chitin. Tissue engineering and visco supplementation are two applications of hyaluronic acid. Wound healing, tissue regeneration, and aesthetic surgery are just a few of collagen's many uses. The medical industry may benefit from each biopolymer in its own unique way. Biomedical technology is made better by alginates, silk fibroin, polyhydroxyalkanoates (PHA), poly(lactic-co-glycolic acid) (PLGA), gelatin, and various polysaccharides such as cellulose, starch, and pectin, all of which are biocompatible, naturally biodegradable, and have unique properties. The unique biological capabilities and structural features of keratin and elastin make them promising candidates for the regeneration of neural and soft tissues. Wound dressings, diagnostic tools, tissue engineering scaffolds, and drug delivery systems are just a few of the many applications for biopolymers. Exploring their potential in these areas is an ongoing scientific endeavor. Advances in cross-linking methods and material engineering have allowed biopolymers to overcome limitations in mechanical properties.

Overall, biopolymers are important in modern healthcare because they provide sustainable and eco-friendly alternatives to synthetic chemicals, and their wide range of biomedical applications demonstrates this. The potential for biopolymers to improve healthcare and patient outcomes is expanding as this area of study develops.

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