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Review Article

Biopolymers: An inclusive review

Great Iruoghene Edo [a,b,*], Winifred Ndudi [a], AliB.M. Ali [c], Emad Yousif [b], Agatha Ngukuran Jikah [d], Endurance Fegor Isoje [e], Ufuoma Augustina Igbuku [a], Alice Njolke Mafe [f], Rapheal Ajiri Opiti [a], Chioma Judith Madueke [g], Arthur Efeoghene Athan Essaghah [h], Dina S. Ahmed [i], Huzaifa Umar [j]

[a] Department of Chemistry, Faculty of Science, Delta State University of Science and Technology, Ozoro, Delta State, Nigeria
[b] Department of Chemistry, College of Sciences, Al-Nahrain University, Baghdad, Iraq
[c] Department of Air Conditioning Engineering, Faculty of Engineering, Warith Al-Anbiyaa University, Karbala, Iraq
[d] Faculty of Pharmacy, Department of Pharmacy, Near East University, Nicosia, Cyprus
[e] Faculty of Science, Department of Biochemistry, Delta State University of Science and Technology, Ozoro, Nigeria
[f] Department of Biological Sciences, Faculty of Science, Taraba State University Jalingo, Taraba State, Nigeria
[g] Department of Business Administration, Economic and Administrative Sciences, Near East University, Nicosia, Cyprus
[h] Faculty of Environmental Sciences, Department of Urban and Regional Planning, Delta State University of Science and Technology, Ozoro, Delta State, Nigeria
[i] Department of Chemical Industries, Institute of Technology-Baghdad, Middle Technical University, Baghdad, Iraq
[j] Operational Research Centre in Healthcare, Near East University, Nicosia, Cyprus

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ABSTRACT

Biopolymers are composed of recurring units of similar or same monomers joined together and are either derived from biological systems or manufactured from biological sources. Been a leading class of functional materials that are apposite for high-value applications, biopolymers are utilized in the food, petroleum, medical and pharmaceutical industries for various purposes. Moreover, naturally occurring biopolymers such as starch, proteins, rubber, cellulose, chitin, RNA, peptides and DNA been biodegradable, were thought of as suitable alternatives to the synthetic ones which came from fossil fuel sources and had adverse environmental effects. Moving forward, many biopolymers have and are still been produced to meet ever increasing demands. This paper presents an all inclusive review of biopolymers, their polymer backbone, impacts on environment, and methods of degradation, uses, chemical modification of biopolymers for the creation of hydrogels used in medicine, economic impact and future outlook.

1. Introduction

The rise in plastic production and the resultant environmental downsides have driven global interest in sustainable substitutes to conventional fossil-fuel based plastics [1]. The effects of the plastic pollution catastrophe and especially the single use plastics have in the past decade increasingly affected wildlife and ecosystems across the globe. Polymers obtained from renewable resources have emerged as promising substitutes providing lessened environmental footprints [2]. The primary advantage of these polymers over traditional plastics is that while synthetic plastics may take hundreds of years to degrade, these break down naturally in the environment. Biopolymers are among such polymers that are obtained from living organisms. There sources include; animals, fungi, bacteria, plants, ribonucleic acid and deoxyribonucleic acid, etc. Biopolymers are biodegradable and are composed of repeating units of nucleic acids, amino acids and sugars [3]. Been both biodegradable and biocompatible, biopolymers are greatly employed in the preservation and transmittance of genetic information, the storage of energy, cellular construction, in medical implants, edible films, as drug transport materials, as wound dressing materials, in tissue scaffolds and etc [4]. Biopolymers especially sugar based ones naturally decompose within the human body without producing harmful side effects, this no-toxicity property makes them relevant for medical applications [5]. Furthermore, besides their medical and pharmaceutical applications,

* Corresponding author. Department of Chemistry, College of Sciences, Al-Nahrain University, Baghdad, Iraq.
E-mail address: greatiruo@gmail.com (G.I. Edo).

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synthetic biopolymers are used for making mats; cellulose based biopolymers such as cellophane is used in making packaging material, food trays, wrapping films and pellets, as natural fertilizers and pesticides in agriculture and as anti-aging and skin care products in cosmetic industries [6]. Biopolymers are broadly grouped into three categories: proteins (gelatin, collagen), lipids (polyhydroxyalkanoates) and polysaccharides (chitosan, cellulose) [7]. This article provides an inclusive review of biopolymers. This paper presents an all inclusive review of biopolymers, their polymer backbone, impacts on environment, and methods of degradation, uses, chemical modification of biopolymers for the creation of hydrogels used in medicine, economic impact and future outlook.

2. The polymer backbone

Polymers refer to macromolecules that consist of a high number of chemically connected repeating basic units or monomers. These monomers determine the general properties and regulate interactions between the polymer chains. Because polymers usually have a broad range of morphologies, their structures can be described in several ways. The backbone of polymers may be arranged in diverse forms including grafted, block, alternating and random forms. Besides that, more complex structures such as ladders, branching, star-shaped, cross-linked, dendrimeric and ring-shaped can also be found along the mainstay of some polymers. Moreover, polymers can be heteropolymers which consist of a blend of different monomers or homopolymers which consist of a single monomer. Advanced classifications of heteropolymers can be made according to the arrangement of the monomers in the polymer mainstay [8]. Biopolymers are polymers made from living organisms and can be classified based on their polymer mainstay: polycarbonates, polyesters, polyamides, polysaccharides and vinyl polymers. Polycarbonates are basically produced via the cyclic carbonate ring-opening method or the alternating carbon dioxide copolymerization [9]. These polymers are usually employed in several applications such as consumer products and packaging materials because of their exceptional properties such as non-toxicity and biodegradability. Additionally, polycarbonates go through enzymatic degradation to ensure proper degradation under physiological circumstances [10]. In recent times, aliphatic polycarbonates were produced from glycerol, sugar molecules, trimethylolpropane, pentaerythritol and 1,3-dihydroxyacetone. These can be modified following polymerization to expand its physicochemical characteristics and potential applications [11]. Polyesters are polymers that carry a functional ester group in their chains and may be further divided into natural or synthetic polyesters. The polymerization of polyesters presents possibilities for a wide range of applications, including the manufacture of renewable, bio-assimilable and biodegradable polymeric materials [12]. Based on the monomer bonding, polyesters are categorized into poly-(alkylene dicarboxylates) which are produced through the polycondensation of diols and dicarboxylic acids and poly (hydroxy acids) which are produced through synthesis of hydroxy acids or ester synthesis [13]. Certain bio-based polyesters have polyesters that currently have applications in commercial industries include bio-polyester, polyhydroxyalkanoate, polycaprolactone, polylactic acid, poly (trimethyleneterephthalate) and polyglycolic acid [14]. Amongst these, polylactic acid has been widely studied and found to be a biocompatible and biodegradable polyester but with a high melting point [15].

Polyamides polymers are amide group polymers that are produced via polycondensation using dicarboxylic acid and diamines as repeating units [16]. Naturally occurring polyamides are similar to proteins [17]. Polyamides have vast potential because of their structural variety, availability as natural building blocks, biodegradability and mechanical strength. Moreover, pure polyamides resins are diversely used to produce films and fibers with much enhanced durability, flexibility and strength. Although these polymers are moisture-absorbent, the contents absorbed act as plasticizers and thus regulates the properties of the end products [18]. Nylons number amongst the well-known polyamides that have desirable and advantageous qualities of abrasion resistance, high strength and high durability [19]. These make them apposite for employment in clothes making, engineering plastics, electrical devices and furniture. Generally, non-reactive and compatible qualities of polyamides to human tissues and fluids have lead to their use in the production of transfusion equipment and dilation catheters [18].

2.1. Types of biopolymers

In general, biopolymers can be classified into four types: biodegradable polymers, repeating unit, polymer backbone and bio-based polymers [20] starch [21]. These are discussed below.

2.1.1. Biodegradable biopolymers

Biodegradable compounds are those that have ability of decompose into biomass, methane, water, carbon dioxide and inorganic compounds [19]. These groups of polymers are non-toxic and can undergo biological decomposition, basically via the action of microbial enzymes and various non-enzymatic processes including chemical hydrolysis [22]. Thus, carbon dioxide, inorganic salts, biomass are the end products of biodegraded polymers that provide possible advantage for green house gas emissions and other environmental effects. This property of biodegradable polymers has made them popular among because they satisfy the essential environmental criteria as does renewable. Additionally, biodegradable polymers can help to overcome the safety and environmental problems for several applications in medicine, pharmacy, agriculture and etc [23]. The benefits of biodegradable polymers are found in their ability to rapidly degrade under environmental conditions, which is their main environmentally desirable feature that lessens the possibility of their improper disposal [23]. Environmental conditions such as industrial composting, freshwater, land filling and seawater can enhance the degradation of the biodegradable polymers [24]. Additional to the environmental conditions, several other conditions can also affect the degradation of polymers these include molecular weight, chemical structure, polymer composition, molecular weight, breakdown products, reduction potential and hydrophilicity [25]. For instance, most water-soluble biopolymers degrade quickly and efficiently whereas water insoluble biopolymers degrade at substantially lower rates. The degradation process can be further enhanced by using bio-based polymers. Generally, biodegradable polymers can be classified into two major classification: bio-based polymers and petroleum based polymers. A more detailed division of these polymers is made into (1) polymers from biomass products, (2) polymers obtained from microbial production through an extraction method, (3) polymers obtained from agro-resources monomers, which are naturally or chemically produced and (4) polymers obtained directly from fossil fuels. As presumed, the first three classifications of polymers are from renewable bio-based sources, the fourth category is derived from the non-renewable petro--based resources [26]. Polylactide or polylactic acid is an example of biodegradable polymer that has recently gained a lot of attention among researchers due to its cheap cost and ready availability. Polylactide is aliphatic polyester that features lactic acid as its fundamental monomer and is produced by the controlled depolymerization of lactic acid monomers made through chemical synthesis and carbohydrates fermentation [27]. Unlike other polymers, the degradation of polylactide occurs in a stepwise mechanism with first step implicating simple chemical hydrolysis to a lower molecular weight and the second step involving lactic acid oligomers that get metabolized by microorganisms.

2.1.2. Repeating units

Based on their nature of repeating units, biopolymers are grouped into three major groups: Protein (gelatin, silk, zein, collagen and hyaluronic), polysaccharides (alginate, cellulose, chitosan, starch), and nucleic acid (DNA, RNA). Polysaccharides and oligosaccharides are bioactive materials that are widely produced in nature. Polysaccharides

are defined as polymeric carbohydrate structures consisting of repeating monosaccharide units connected together by glycosidic bonds. Generally, plants and animals generate the highest amounts of polysaccharides but microbes produce a greater range of diverse them. Repeating units as mentioned earlier are naturally occurring biopolymers that can be produced from a variety of natural and copious sources including plants, animals, microbes and algae [28]. They usually have amorphous or crystalline structures due to intermolecular hydrogen and chemical bonds. The physicochemical properties of polysaccharides are determined by their linking patterns and types, the variety of their monosaccharide content, molecular weight and structure and because of these, they have several and diverse product applications. One prevalent example of a polysaccharide is starch which can be easily obtained from plant materials of seeds, roots and stalks. The polysaccharide starch itself made up of two kinds of other polysaccharides that are completely composed of D-glucose monomers, these are amylopectin and amylase. The D-glucose monomers in the helical amylopectin are linked through α-(1 → 4) and α-(1 → 6) branch linkages while those in the linear amylase are only linked by α-(1 → 4) (R). Another plant and natural fibers prevalent polysaccharide is cellulose. Cellulose is recognized as the most abundant material on earth and is composed of linear chains of D-glucose linked α-(1 → 4) bonds [29]. Cellulose is a highly chemical and mechanically stable polysaccharide found as the primary cell wall component of plants and natural fibers like jute, cotton and flax. It has in recent years shown great promise in several fields such as biofuel manufacturing and medicine.

Proteins are heteropolymers composed of long repeating units of different amino acid monomers linked together by peptide bonds. For the synthesis of proteins, two major biosynthetic processes are implicated: the ribosomal and the non-rebosomal-multi-enzyme peptide synthesis. The multi-enzyme process can produce three poly amino acids, which are cynophycin, poly- α,β-aspartic acid and ε-poly-l-lysine [30]. The ease of processing and excellent mechanical strength encouraged the study of structural proteins for applications in biomedical fields. Gelatin and collagen are two familiar examples of these proteins. Collagen makes up the framework of tendons, muscles and bones giving them strength and integrity. In addition, the high tensile strength of collagen makes it abundant in the extracellular matrix and also accounts for its been incorporated in the structure of cells and tissues [31]. Since collagen performs numerous essential health functions, several health pathologies are related with its breakdown or depletion in the human body. Comparative to collagen, gelatin has less antigenicity which results in cell adhesion, differentiation and increased proliferation. Gelatin is thus appealing to cell regeneration researchers who are interested in its relevance as a multifunctional vehicle for administrating cell growth parameters [31]. Proteins may also be a relevant source of nitrogen which is readily accessible following protein degradation.

Nucleic acids are the third group of biopolymers and these play crucial roles in the production of proteins and storage of genetic information thus influencing the hereditary traits of all living things [32]. Nucleic acids were first discovered in the nucleus of eukaryotic cells but it soon came to be known that they are in the cells of all living things including archaea, viroids, bacteria and viruses and they determine the inherited traits of all living things through regulation of the process of protein synthesis [32]. To investigate microbial populations, nucleic acids can be directly isolated from soils. On the other hand, cells may be first isolated from the soil and then the nucleic acids extracted. Deoxyribonucleic acid and ribonucleic acid are the two basic types of nucleic acid but other than DNA, lipids, carbohydrates and proteins, RNA is another very significant biological macromolecule. It is a nucleotide heteropolymer and homopolymer of four neucleotides including adenosine, cytosine, uridine and guanosine. The RNA nucleotide consists of a ribose sugar linked to a nucleobase and a phosphate group. Although alike to DNA in some ways, the macromolecule differs from DNA in its homogeneity.

2.1.3. Bio-based polymers

In comparison to petroleum-based products, the utilization of bio-based materials in the development of environmentally friendly-tech products may beget materials that are equivalent with if not with better than qualities. Whilst the terms biodegradable and bio-based are often used interchangeably, they are significantly distinct; the physical and chemical properties of biodegradable polymers become deteriorated when subjected to certain conditions such as water, carbon-dioxide and methane. Contrarily, bio-based polymers are either produced or originate by chemical synthesis from renewable resources such as animals, plants or microorganisms hence they are divided into biodegradable or non-biodegradable [33]. These are hence not always biodegradable and can as such be as harmful to the ecological system as fossil fuels. Bio-based polymers are therefore defined as biomaterials produced by the reaction of a naturally occurring enzyme and certain agricultural resources. Additionally, bio-based polymers can also be obtained from biomass. Biomass provides the fuel for plants to photosynthesize carbon dioxide into organic carbon compounds. Although biomass has often been utilized for the partial combustion in the past, its utilization for the production of chemical building and polymers is uncommon. Hence, the use of biomass resources for chemical and polymer production is crucial for the environment. Moreover, bio-based polymers consist of non-fossil fuel components and have noteworthy benefits of reducing carbon dioxide emissions [34]. In the arena of commercial applications and scientific developments, research on bio-based polymers has made tremendous progress in contemporary times. Therefore, bio-based polymers have gained significant recognition through research and development efforts that focus on their engineering, industrial applications and scientific applications. These bio-based polymers can be divided into three groups based on their nature and route of production. The first group of bio-based polymers produced mainly from agro-polymers (starch, chitosan, cellulose, protein and lignin). These can be modified either by physical or chemical means and can also be utilized alone or in combination with other polymers. The second group of this group of polymers are produced from genetically modified microorganisms or crops (polyhydroxyalkanoates) and the third group of bio-based polymers that are derived from agro-resources or are petro-based through fermentation and or conventional chemistry (polyurethanes, poly-lactic acid, polyimides). Generally, the first and second groups can be directly used with or without purification from their natural sources especially for use in applications where biodegradability is needed. The polymers produced from these two groups may exhibit the desired functionalities, they possess chemical structures that have limited flexibility [35]. The third group of bio-based polymers seem to be the ones with the most potential. These are usually produced either by breaking down naturally occurring macromolecules or from bio-derived monomers such as fatty acids, their derivatives and from the digestion of natural polymers [36]. Moreover, the monomers can also be generated from proteins through biological, chemical and thermochemical methods and utilized as building blocks in the synthesis of polymers. Even though producing polymers through these breakdown methods usually results in highly variable chemical structures, they polymers are found to have high structural flexibility. Technically, contemporary synthetic polymer petro-based production systems can be modified to include monomers from the 3rd group of bio-based polymers. These are however are not compatible with normal biological cycles once used and hence, most of them basically reduce environmental effects only by carbon foot print.

2.2. Impacts of biopolymers on the environment

In an attempt to positively respond to the increased demand to limit the emission of green house gases and protect the ecosystem, engineers currently attempt to incorporate environmental needs into their innovative developments [36]. Utilizing renewable material in the manufacture of polymer materials accomplishes this in dual ways: Firstly,

utilizing renewable resources for the production of biopolymers is results in biodegradable end products. This helps to prevent the environmental pollution caused by plastics since biopolymers decompose after usage. Secondly since biopolymers are made from renewable resources, they are replaceable, either via intentional intervention by humans or by natural cycles. An investigation reported that in underdeveloped nations, there is almost a complete recycling of plastics, one reason for this is because of the positive return this has on the economy [37]. The economic return makes this recycling process seem positive at its onset, but because the systems by which these plastics are recycled are open, toxic gases are emitted into the environment. Hence, the recycling which appeared to be a practical way of lessening air pollution and its consequent environmental damage did not serve the complete purpose. It therefore became obvious that making plastics from resources that are both renewable and biodegradable was a better choice than recycling conventional plastics since the end products being organic matter, does not emit toxic substances into the environment. Concerns about garbage disposal have grown in recent years, landfills are filed up and new sites for other landfills are difficult to find. For plastics made from biopolymers however, once deposited into landfills, decomposition is carried out on them by microorganisms. Plastic plates and cutleries for instance are designed with the intention that they will be thrown into compost heaps together with leftover foods. Compostable plastics biologically degrade during compositing and give off water, inorganic compounds, biomass and carbon dioxide [38]. As an added benefit, odors emitted from composite piles are lessened when biodegradable plastics are mixed with it. The decomposition of compost produces ammonia and the biodegradable plastics in the mix degrade and produce acidic intermediates which neutralize the ammonia content thus reducing the odors [39]. Integration of waste management techniques for biodegradable plastics that both effective for their designed use and disposable must hence continue.

2.3. Methods of biopolymer biodegradation

Generally, the degradation of polymers occurs by chemical degradation, microbial action and photodegradation. The three methods are classified under biodegradation because they all have end products with stability in nature. Biopolymers are produced to be disposed in composites, soils or landfills, these materials get broken down in the presence of the appropriate microorganisms. Water and normal soil bacteria are generally all that is required. Biopolymers made from naturally grown materials can be easily broken down by microbes. For a case where the materials for the plastics are conventional plastic mix and starch is only an additive, microbe's only digest the starch following disposal of the plastic, leaving the sponge like, porous structure with a high interfacial area. Once the starch is degraded, the polymer matrix also begins to degrade by enzyme attack with each reaction resulting in the scission of a molecule thus lessening bulk of the matrix until the entire material is completely degraded [40]. Another method for microbial decomposition of biopolymers implicates budding microbes specifically intended for digesting polymer materials. This process however, costs much as it is more intensive. The microbes to be grown are intended to target and breakdown plastics made from plastics [41]. Photodegradable polymers are usually degraded by sunlight. Such polymers that undergo this degradation are photochemically attacked and break down to smaller pieces. Following this however, microbial degradation must also occur for true biodegradation to be attained. Polyolefins are the polymers that are most predisposed to photodegradation [42]. Some approaches that may aid in the development of photodegradable biopolymers have been proposed, some of these include integrating additives that hasten the photochemical reactions, producing new polymers with light sensitive groups and adjusting the composition of the polymers to incorporate more UV absorbing groups. Some biodegradable polymers undergo a rapid dissolution when upon exposure to particular aqueous solutions. Once dissolved, the remaining solution consists of glycerol and polyvinyl. Like with many photodegradable plastics, full biodegradation of the aqueous solution is later carried out via microbial digestion. Biopolymer materials that disintegrate after been exposed to aqueous solutions are desired for discarding and transporting medical wastes and biohazards. Industrial washing machines are produced to soften and wash away the aqueous solutions for additional microbial digestion [42].

3. Uses of biopolymers

Biodegradable polymers have been introduced by research as useful materials or application in diverse fields. Some industries that have integrated biopolymers in their productions are the packaging, medical, automotive and agricultural industries. Packaging materials of biopolymer source have gained more attention than biopolymer materials produced for any other purpose [10]. Governments bodies at different levels principally in Germany and China are approving the applications of biodegradable packaging material in order to lessen the amount of inert materials constantly being disposed of in landfills and taking up scarcely available space. An estimated 41 % of plastics are employed in the packaging industry. BASF, a global leader in the plastic and chemical industry is currently launching for the manufacture of biodegradable plastics from starch and polyester [43]. Ecoflex is another completely degradable plastic material that is resistant to grease and water. This makes it important for use as a hygienic disposable wrapping, decomposable in normal compositing systems. Accordingly, it has found applications in packaging for wrapping. Depart is another biodegradable plastic made from polyvinyl alcohol which used for the injection molding, extrusion and blow molding. It is used for making catheter bags, food service items and agricultural products [44]. The renewable and biodegradable properties of biopolymers are what make them appealing for inventive applications in packaging. The starch biopolymer is also used to make biodegradable loose-fill packaging materials. When treated through post extrusion steaming, acetylation and chemical treatments, starch material is made mechanically stable and truly biodegradable. In agriculture, the applications of biopolymers are more than for production of film covers. The use of polymers for disposable composting containers and biodegradable plant pots has been investigated [45]. These pots are directly seeded into the soil and get broken down as the plants begin to grow. Chemical storage and fertilizer bags that degrade are also other applications of biopolymers in agriculture. Compostable polymers are particularly important in agriculture as their decomposition have added benefits of supplementing the nutrient cycle of the soils where they are used.

3.1. In the medical field

Biopolymers have been reported to be on trial for an attempt in the development of organs in tissue engineering for transplantation into humans. Biopolymers have thus been developed that have adhesion sites that act as cell hosts in giving shapes that imitate different organs. Bioglass is commonly employed in making artificial bone material that can integrate and adhere to the bones of the body. The bioactive material releases medication at a rate determined by its enzymatic degradation. Furthermore, using drug delivery techniques to increase the effectiveness of bioactive chemicals is an important part of illness treatment, and the field has made great strides in this area. Here, systems for drug delivery are often created using natural, semi-synthetic, as well as synthetic polymers [46]. Biopolymers have also been employed as controlled drug delivery, isolation, adhesion, anchoring, suturing, covering, occlusion, and contact inhibition [47]. Moreover, biodegradable polymers are used in the drug delivery; once the medicines are released from the body, these polymers can be removed naturally without the need for surgery. An increased understanding of the potential of biomaterials for multimodal scaffolds with unique geometries and physical-chemical properties have resulted from the search for more

advanced as well as tissue-focused implanted devices [48]. These scaffolds possess multifunctional or multimodal qualities due to their integration of many topographies not generally found in each material, which could make them more significant in regenerative medical treatments [49]. Additionally, polymers have an important role in the creation of artificial extracellular matrix (ECM) settings and 3-D templates for tissue repair [50]. Natural polymers made from natural resources including fibrin gels, agarose/alginate, collagen, gelatin, and hyaluronic acid (Table 1) are frequently employed in regenerative medicine; however, they must be cleansed beforehand to prevent foreign body reactions after implantation. Generally, well-known biomedical applications that use biopolymers include soft-tissue replacement, vascular grafts, artificial hearts, intraocular lenses, breast implants, parts of extracorporeal contact lenses, plasmapheresis units, sutures, oxygenators, adhesives, and blood substitutes; liver, pancreas, dialyzers, kidney, bone cement, catheters, bladder, external and internal ear repairs; coatings for pharmaceutical tablets and capsules; cardiac assist devices; implantable pumps; pacemakers; encapsulations; artificial blood vessels; joint replacements; dentistry; drug delivery; and targeting sites of tumors or inflammation [51]. PHAs can also be utilized in biomedical applications because they are able to degrade naturally. Particularly, poly (3-hydroxyoctanoate) is very adaptable, which makes it a potentially suitable biopolymer for the delivery of drug formulations and features of future tissue engineering [52].

3.1.1. *Protein-based biopolymers in used in medicine*

Medical applications have heavily depended on protein-based biopolymers. Their potential is enormous, and their use in implanted devices is growing quickly [53]. Protein synthesis enables the creation of precisely designed nanoparticles since the secondary structures of proteins determine their molecular sizes [54]. Table 2 provides an overview of the properties of various kinds of biodegradable nanoparticles [55]. Collagen, keratin, gelatin, sericin, as well as fibroin, are the building blocks of films, hydrogels, nanofibers, pickering emulsions, nanogels, linked porous scaffolds, as well as 3D-printed scaffolds [56]. Hydrogel [57], hydrospheres, nanoparticles, electrospun fiber, as well as sponges based on collagen are utilized in tissue engineering and therapeutic molecular delivery (gene, drug, and protein delivery).

3.1.2. *Chitosan in therapeutic uses*

Because chitosan is biodegradable and biocompatible, it is very frequently employed in medicine. Furthermore, chitosan is crucial for cell adhesion and development because of its characteristics, it is primarily used in implants for skin, stent, liver, nerve, tendon, bone, ligament, and cartilage regeneration. Numerous matrices based on chitosan have also been identified for use in bone applications. Chitosan must however, be combined with other components for tissue engineering of bones because of its mechanical weakness [58]. Interesting characteristics of chitosan-formed nanoparticles include permeability, low toxicity, excellent absorbability, moisture retention, and easy degradation. They are highly susceptible to changes in pH and temperature in the environment, which impacts the degradation rate [59]. Furthermore, polylactic acid materials are used for medical devices such as pins, resorbable screws and statures. These materials decrease the need for doctor visits, lessen the risk of tissue reactions to the devices and curtail recovery time [60].

Table 1
Several biopolymers and their medical applications are illustrated.

Biopolymers	Medical Uses
Collagen	Covering the tissue culture plate's surface, Easy-to-use gels for cellular culture.
The acid hyaluronic	Taking care of injured joints, lubricating them, and mending cutaneous and corneal wounds
Alginate	Tissue engineering, Regenerative medicine
Fibrin	Wound healing, Tumor growth, and blood clotting. Surgical glue, sealant, and hemostatic agent
Agarose	Regeneration of skeletal tissues, kidneys, and fibroblasts through encapsulation
Silk fibroin	Clinical Regenerative.Therapy Wound healing and tissue bioengineering
Fibronectin	Heart repair, bone regeneration, and wound healing
Carrageenan	Regeneration of skeletal tissues and cell delivery mechanism
Elasticin	Orthopedics, cell encapsulation, and soft-tissue reconstruction
PHAs	Medication delivery methods and a single tissue regeneration.
Keratinized cornea	Skin regeneration, corneea tissue engineering
Starch	Treatment for spinal cord injuries, cartilage and bone regeneration

Table 2
Lists the features of several kinds of biodegradable nanoparticles.

Nanoparticles	Characteristics
Chitosan	Antitumor, antioxidant, antibacterial, blood-viable, non-toxic, affordable, and biodegradable.
Nanoparticles of superparamagnetic iron oxide	Paramagnetic and superparamagnetic.
Poly-L-lysine	Targeted distribution, biodegradability, and high loading capacity.
Lactide polymer co-glycolide	Non-toxic, biocompatible byproducts
Liposomes	Biocompatible and include hydrophobic substances.
Gold	Hyperthermia and Biocompatible
Alginate.	Biocompatible and soluble in water
Micelles	Drug-soluble and capable of transporting.

3.2. *In the automotive industry*

Biobased polymers which are lighter and need less fuel are been introduced. Additionally, glass fibers now substitute natural fibers as reinforcement materials the plastic parts of automobiles. These natural fibers are also used in forming the interior parts of automobiles. Biopolymers are also integrated in engine lubricants, adhesives, construction materials and paints. Biodegradable fishing hooks and golf trees have also been invented from biopolymers [33].

3.3. *Food industry*

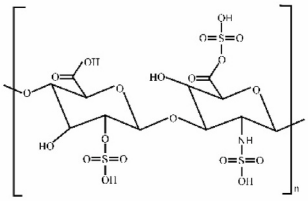
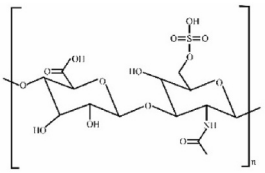
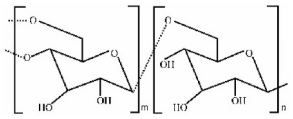
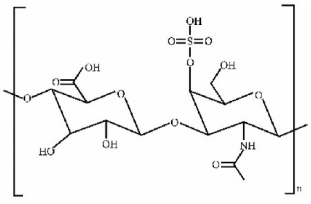
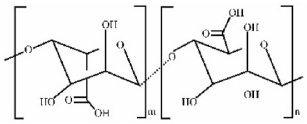
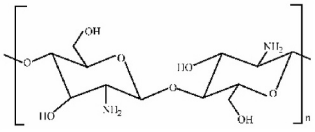
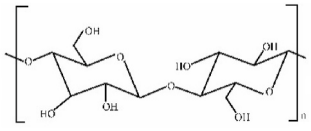
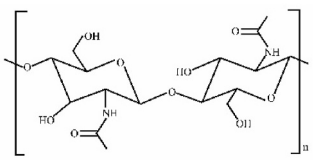
There has been a growing demand for and functional foods preparations in contemporary times, a general growing interest in foods that are rich in bioactive constituents due to an increasing awareness of the health benefits of these constituents has surged [61]. Minor food constituents such as fatty acids, antioxidants, microorganisms (prebiotics and probiotics), antioxidants and vitamins have been studied for their health benefits [62]. Some of the bioactive substances have been shown by reports from these studies to demonstrate antioxidant and anti-inflammatory effects. Moreover, they also function to prevent chronic inflammatory diseases whilst also promoting good health. These bioactive constituents also act to reduce the levels of free radicals and reactive oxygen species resulting in anti-aging effects [63]. Biopolymers have also been widely employed for applications in nutraceuticals, functional foods and pharmaceuticals. Amongst the main classifications of polymers which are proteins, nucleic acid and polysaccharides, polysaccharides are demonstrated to be the key naturally occurring polymers. They possess a large carbohydrate family found in the form of cellulose, alginate and starch. Polysaccharides are inexpensive and available in several structures with several properties. Some polysaccharides promise health benefits such as prevention of cancer, improvement of colonic health and reduction of cholesterol [64]. Polysaccharides are easy to modify using biochemical or chemical methods. The biodegradability, excellent gel-forming, hydrophilic properties and highly stable properties of this class of polymers make them ideal for use in functional foods [65]. They serve as coagulants, gelling agents, binders, suspending agents, stabilizers, and emulsifiers.

The interest for use for biopolymers in all these areas is due to the fact that biopolymers are derived from renewable sources and thus, reduce dependence on fossil fuels.

4. Chemical modification of biopolymers for the creation of hydrogels used in medicine

Polysaccharides and polypeptides are the two main groups of biopolymers utilized to generate hydrogels. The different biopolymer qualities are guided by their repeating units, which are made up of peptides or sugars. Chemically modifying biopolymers to induce interpolymer crosslinking, charge-based assembly (due to specific functionality), or polymer entanglement (due to high molecular weight) or high concentrations of polymers can result in the formation of biopolymer hydrogels. This section discusses the various biopolymers that are modified chemically to produce hydrogels, their general properties and past uses in consumer goods are also discussed.

Table 3
Represents sources, functions, and chemical structures of different polysaccharide biopolymers modified to create biomedical hydrogels.

Name	Chemical structure	Original function	Type	Source
Heparin Sulfate		Stored in human mast cells and released into the bloodstream in response to injury	Linear	From animals (e.g., intestines of porcines)
Hyaluronic Acid		A significant ECM component in human connective tissues	Linear	Culture of bacteria; cockscomb
Dextran		A component of certain ECM microorganisms	Branched	Culture of bacteria
Chondroitin Sulfate		A significant ECM component in human connective tissues	Linear	From animals (e.g., porcine nasal septa, cow trachea)
Alginate		Seaweed's structural support	Linear	Algae brown
Chitosan		n/a	Linear	Deacetylated chitin derivative
Cellulose		Plant cell walls' structural support; an element of some bacteria's extracellular matrix	Linear	Culture of bacteria
Chitin		Insect and crustacean exoskeletons: structural reinforcement	Linear	Shells from shrimp and crabs that come from food production waste

4.1. Polysaccharides

In living things, polysaccharides—which are made up of repeating units of mono- or disaccharide—have crucial structural and biochemical roles (Table 3) Polysaccharides are frequently extracted for use in biomaterials from renewable sources like plants and microbes. They could also come from the fish and animal waste. Numerous polysaccharides have undergone chemical modification to provide naturally occurring hydrogels possessing an extensive array of mechanical as well as biological attributes (see Table 4).

4.1.1. Hyaluronic acid

Hyaluronic acid (HA), a linear glycosaminoglycan (GAG), is made up of repeating units of D-glucuronic acid along with N-acetyl-D-glucosamine that alternate and are joined by β-1,4 as well as β-1,3 glycosidic bonds [66]. Naturally found in the body, HA is a part of the matrix of extracellular cells and can be present in a variety of tissues, including muscles, skin, cartilage, and voice folds [67]. HA can also be obtained from animal sources, including rooster combs, or through streptococcal fermentation cultures for use in research and clinical applications. Using 1,4-butanediol diglycidal ether (BDDE) or divinyl sulfone (DVS), unmodified HA can be crosslinked more widely to improve the mechanical strength of its hydrogels [68] or more loosely to raise the viscosity of its solutions. In its original state, the mass of HA can range from about 100 kDa in serum to about 8000 kDa in vitreous fluid [69]. Through its structure as well as chemical composition, HA influences both the mechanical and biological activities of native tissues as well as cellular responses in wound healing [70]. HA mainly serves the purpose of preserving low-friction tissue interactions and viscoelasticity, such as those found in synovial and vitreous fluids [71]. Cells adhere to HA via surface receptors such as the glycoprotein CD44 [72]. Many biological processes rely substantially on HA-CD44 binding interactions, such as chondrocyte proliferation as well as matrix production in cartilage tissue. HA can be broken down, oxidative species and enzymes, including hexosaminidase, glucuronidase, and hyaluronidase [73]. HA has been used in numerous clinical applications since the 1960s, such as wound dressings, intra-articular injections to treat osteoarthritis symptoms, and dermal fillers in soft-tissue augmentation [68]. Many chemical alterations have so far been made to HA in order to broaden the variety of the features of its hydrogels in biomedical applications.

4.1.2. Heparin

As a linear GAG, heparin is made up of repeating units of D-glucosamine and uronic acid connected via β-1,4 glycosidic bonds [74]. It is extracted from sources derived from animals, most frequently the gut of pigs, for use in biomedicine. Heparin is recognized to be crucial for tissue growth, angiogenesis, and anticoagulation and is present on the surface of cells as well as in the extracellular matrix [75]. Heparin and the sulfated derivative in heparin polysaccharides, heparan sulfate (HS), combine with proteins to produce PG coatings around cells that facilitate interactions between the cells and several signaling molecules [76]. Heparin binds to a wide range of biomolecules, including fibronectin [77], growth factors, cytokines, as well as adhesion proteins. Naturally occurring heparin can have a molecular weight of 5–1000 kDa.30. Higher MW heparin is preferentially bound by macrophages and endothelial cells. Heparin and HS can be broken down by enzymes like heparinase, which is crucial for ECM remodeling and upkeep [78]. Heparin is employed as a blood thinner in clinical settings to stop blood clots from forming. Heparin has been one of the medications from antiquity that has remained in clinical use and one of the few polysaccharide medications with clinical approval [79]. It is listed as one of the world's essential medicines by the World Health Organization, or WHO [80]. Heparin is frequently categorized as pure low-MW heparin (LMWH) or unfractionated heparin (UFH). MW heparin can cling to endothelial cells as well as macrophages and obstruct their ability to function as anticoagulants; hence clinical usage of LMWH has replaced UFH due to its potential for greater efficacy. Again because greater MW heparin has greater attraction for endothelial cell adhesion, it may be useful as a scaffold for tissue engineering.

4.1.3. Dextran

The extremely branched polysaccharide referred to as dextran is formed by the combination of α-1,6-linked glucose monomers and α-1,3 branching [81]. Dextran is a crucial part of the bacterial extracellular matrix (ECM) [82], which facilitates the formation of biofilms and surface adhesion. Dentistry has conducted a great deal of research on dextran since streptococci bacteria secrete it to form gelatinous plaques on teeth. Dexttran's molecular weight can vary from approximately 10–150 kDa with a 5–30 % degree of branching [83], depending on the type of bacteria and the purification process used. Bacteria with a degree of branching [84] of less than 5 % are used to create the majority of dextran used in industries. Dexttranase [85] is capable of enzymatically breaking down dextran. Dextran has found widespread application across numerous industries owing to its biocompatibility and ease of manufacture. By attaching itself to platelets, erythrocytes, and vascular endothelium, dextran functions as an antithrombotic drug in clinical settings to diminish vascular thrombosis by reducing aggregation [86]. Additional uses for dextran include lubricating eye drops [87] and adding it to intravenous fluids. In therapeutic settings, Dex-40 (40 kDa MW) as well as Dex-70 (70 kDa MW) are the most commonly used variants of dextran. Dextran is a possible substrate for tissue engineering because of its easy accessibility and track record of efficacy in clinical settings.

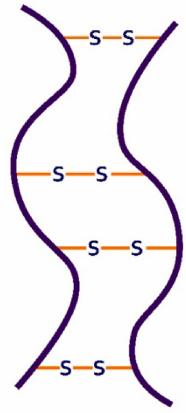
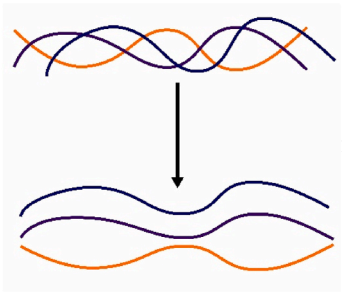
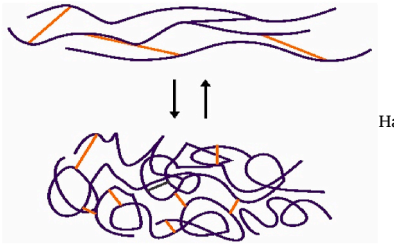
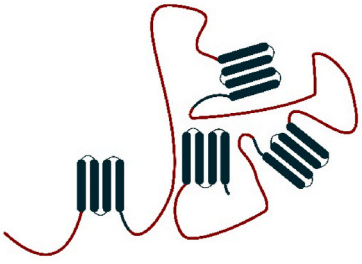
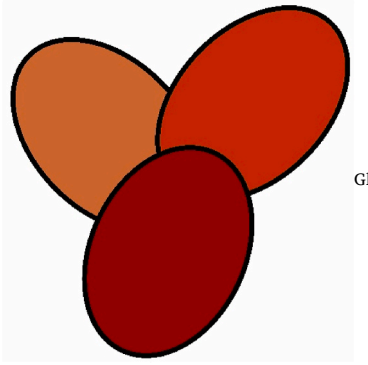
4.1.4. Alginate

Alginate comprises a linear polysaccharide made up of repeating units of α-L-guluronic acid (G) and β-D-mannuronic acid (M) residues that are 1,4-linked [88]. Brown algae (Phaeophysceae) have cell walls that contain alginate, which acts as a flexible mechanical framework to shield seaweed from harm caused by vigorous water motion [89]. When divalent cations (like Ca2+) are present, alginate crosslinks as a result of ionic interactions with G residues. For many years, macromolecules and cells have been encapsulated via this ionic crosslinking technique. Alginate is often investigated for use in biomedical applications because of its low cost, low toxicity, and biocompatible ionic gelation mechanisms [90]. While various bacterial strains and brown algae cell walls can be used to produce purified alginate, commercially available alginate comes only from algal sources [91]. Alginate is accessible in molecular weights ranging from around 30 to 400 kDa [92]. Alginate has been utilized in numerous therapeutic applications, such as those that reduce reflux of the gastrointestinal tract, hasten wound healing, and fill in musculoskeletal defects [90]. Besides its use in biomedicine [93], alginate has been widely used in the food industry as a thickening as well as gelation additive, sausage, as well as colloid stabilizer casing material.

4.1.5. Cellulose

Cellulose, a linear polysaccharide is made up of repeated D-glucose units joined by β-1,4 glycosidic linkages [94]. Cellulose is thought to be the most prevalent organic polymer [95], on earth. It is a key component of plant cell walls, where it crystallizes into robust microfibril structures that have remarkable mechanical properties [96]. Plant-based cellulose is widely utilized in the manufacture of cotton textiles, paper, and lumber [97]. Cellulose is usually obtained from bacterial sources for use in biological applications [98,99]. In addition to dental implants, microbially generated cellulose has been utilized in burn and ulcer treatments [100]. In culinary and cosmetic goods also, cellulose is very frequently used as an emulsion stabilizer [101]. Etherification processes are used to produce water-soluble cellulose derivatives that are used in the food and pharmaceutical industries [102]. Carboxymethyl cellulose (CMC) as well as hydroxypropyl cellulose (HPC) are the most often utilized cellulose derivatives in the production of hydrogels [103]. There

Table 4
Biopolymers Based on Polypeptides. Typical sources, architectures, and functions of different polypeptide biopolymers that have undergone modifications to create biomedical hydrogels.

Polypeptides	Chemical structure	Original function	Source
Keratin	 High cysteine concentration necessary for the production of disulfide bonds.	Essential structural and protective element of hard tissues, including horns, wool, feathers, hooves, skin, hair, and nails.	Human hair, derived from animals (such as wool and feathers)
Gelatin	 RGD motif is present for cell adhesion.	Collagen's denatured derivative (a structural element of the extracellular matrix in mammals).	animal sources (skin of pigs, for example).
The elastic protein	 Has hydrophobic domains for mechanical robustness (VPGXG, for example).	Is in charge of the vertebrate connective tissue's retraction reaction when stress is introduced.	Either animal sources (such as cows or mice) or human donors
Silk fibrin	 Contains the crystalline β-sheet-forming sequences.	Component structural of the silk fibers that certain arthropods manufacture	Silkworm, or Bombyx mori
Albumin	 Globular, heart-shaped protein.	Produces oncotic pressure of blood plasma and modifies the distribution of fluid	Blood plasma from humans (HSA) or cattle (BSA)

is an astonishingly wide range of applications for chemically modified plant cellulose. Numerous thickening agents, fibers, and gels are made from derivatives of cellulose. Product categories for CMC are skin care products, food items, detergents, adhesives, ceramics, toothpaste, shampoo, and latex paints. Additionally, a water-soluble substance with numerous uses in the oil sector is hydroxyethylcellulose (HEC). HEC is utilized in cementing to serve as fluid-loss agent and thickening agent in drilling fluids. It finds application in the coating of medicinal tablets, paper coatings, molding processes, as well as an additive in inks, cleansers, and polishes. In the field of medicine, hydroxypropylmethylcellulose has demonstrated great potential as a blood cholesterol-lowering medication. Furthermore, plastic-grade cellulose acetate is a material that is frequently used in packaging, especially for windows in folding or just setup boxes, blisters, skins, and transparent rigid containers. Again, some textiles and pressure-sensitive write-on tape (like credit card receipts) are made of cellulose acetate. Numerous culinary products, such as pie fillings, baked foods, and salad dressings, have also included cellulose in their preparations. Cellulose is also being actively pursued as a possible source for liquid fuels.

4.1.6. Chitosan and chitin

Chitin constitutes a linear polysaccharide that resembles cellulose in structure, but instead of a hydroxyl group, an acetamide group is substituted, creating repeating units [104] of N-acetyl-D-glucosamine. Chitin monomers are joined by β-1,4 glycosidic linkages, just like cellulose. When compared with cellulose alone, the acetamide group promotes hydrogen bonding, which strengthens the chitin fibrillar matrix. The main component of crustacean and insect exoskeletons, moreover, chitin can be found in the beaks of cephalopods, fish scales, and fungal cell walls. After cellulose [105], chitin is the 2nd most prevalent occurring naturally occurring biopolymer on Earth. Mostly derived from the shells of shrimp as well as crabs, which are byproducts of the food business, chitin is utilized in biological applications [106]. Chitin's ability to form hard structures in applications for tissue engineering is facilitated by its inherent hydrophobicity [106]. For biological materials that have electrical conductivity, chitin's electrical properties have also been studied [107]. Water-soluble chitin derivatives are widely used to make hydrogels. After being isolated from crustaceans, chitin is either chemically or enzymatically deacetylated to produce chitosan [108]. N-acetyl-D-glucosamine and glucose are the repeating units [109]that make up this compound. Deacetylation can range from 30 to 95 % [110], and this can affect the rate of chitosan breakdown as well as its hydrophilicity. The primary enzyme in humans that breaks down chitosan is called lysozyme [111]. In clinical settings, chitosan has been investigated for use as a vaccine adjuvant [112] and utilized in chitosan-based hemostatic dressings.

4.2. Polypeptides

When a polypeptide contains more than 50 amino acids, it is classified as a protein (Table 2). Polypeptides are biopolymers made up of repetitive units of amino acids. Because they may integrate several cell interaction sites as well as imitate the natural functions of extracellular matrix, hydrogels based on polypeptides and proteins are highly attractive for use in biomedical applications. Polypeptides can be synthesized using peptide synthesizers or recombinant protein production, or they can be extracted from animal, human, or plant sources. Numerous biomedical applications find polypeptide materials appealing due to their accuracy and diversity.

4.2.1. Keratin

Keratin is a fibrous protein that is naturally present in animal integuments such as skin, scales, wool, hair, nails, feathers, as well as horns. It is rich in cysteine residues [113]. In many different animals, keratinous tissues have structural and defensive roles [114]. Keratin, present in several human epithelial tissues, such as the corneal epithelium and epidermis, plays a protective function in these tissues [115]. Keratinous tissue has robust and durable mechanical qualities because of the production of disulfide bonds made possible by its abundant cysteine content [115]. Keratins are commonly categorized as α-keratins, which form α-helices, or β-keratins, which form β-sheets [116]. Keratin has been utilized as a raw ingredient in textile manufacturing for centuries [117]. Keratin can be extracted from several materials such as human hair and wool, as well as feathers for use in biomedicine [118]. Since millions of tons from wool and feathers are produced yearly as byproducts of the animal industries, keratin is becoming more and more attractive to the biomedical industry as a cheap and durable raw material. In its natural state, keratin is not soluble in most solvents, not even water [118]. Hydrogel formation requires the creation of water-soluble keratin first, often requiring the addition of a reducing agent to break down disulfide bonds [119]. After undergoing these processes, keratins have free thiol groups that are capable of being used for additional functionality or crosslinking [120].

4.2.2. Gelatine

The mammalian connective tissue extracellular matrix (ECM) is mostly composed of collagen, which can be hydrolyzed and denatured to generate gelatin. Mammals are composed of 25–35 % protein overall, of which collagen makes up the majority [121]. The collagen proteins found in animal sources most frequently pig skin are usually extracted from their skin and bones using acidic or alkaline treatments, and then the proteins are separated by heat to create gelatin [122]. Market-available clinical-grade gelatin's molecular weight can vary from around 103 to 106 Da(R) due to variations in animal sources and the gelatin isolation techniques. While producing gelatin, a large portion of the native collagen's triple-helix structure is denatured; yet, gelatin's chemical makeup is still similar to that of collagen. Additionally, the cell attachment site RGD sequence (Arg-Gly-Asp) found in gelatin interacts with integrins [123]. In numerous applications, it has been demonstrated that adding gelatin (and hence RGD) to biomaterials enhances cell integration as well as tissue repair [124]. Collagenase and metallo-proteases [125] are two proteases that can break down gelatin in the body. Numerous businesses, including those in the culinary, photography, and pharmaceutical sectors, have made extensive use of gelatin. For instance, gelatin is employed as an emulsifier, texturizer, thickener, and stabilizer in culinary science, and employed as an emulsion-making medium in photography [126].

In the medical field, gelatin is a common component of both soft and hard capsules and in tablet formulation. Gelatin sponges and particles are also frequently utilized as hemostatic agents as well as to repair bone and cartilage defects [126]. Gelatin's RGD sequence allows it to replicate native extracellular matrix capabilities, which is a significant benefit when it comes to tissue engineering [124]. Two crosslinkers that may be used to directly create hydrogels employing gelatin [127] are glutaraldehyde (GTA) and genipin. Additionally, gelatin can undergo hydrogel formation by chemically altering it with functional groups, improving mechanical performance and broadening the spectrum of mechanical properties that can be achieved.

4.2.3. The elastic protein

The elasticity and resilience of numerous vertebrate connective tissues, such as skin and cartilage, are attributed to elastic fibers, a crucial structural element of the extracellular matrix [128]. About 90 % of elastic fibers are formed of the protein elastin with a complex microfibrillar structure consisting of several other macromolecules [129]. Tropoelastin precursors build up in the microfibrillar skeleton and eventually form elastin. Human elastin is a very resilient biopolymer with minimal turnover in healthy tissue because of its half-life of about 70 years. Proteolytic elastase enzymes can break down elastic fibers as we age or become sick [130]. Numerous cell types engage in interactions with elastin, such as those mediated by integrins and elastin receptors [131]. Since elastin contains several hydrophobic domains, it is

insoluble in water; yet, polymers containing water-soluble elastin have been investigated for the purpose of hydrogel formation.

There are many elastin formulations available, including α-Elastin, the elastin derivative that was solubilized with oxalic acid as well as being water soluble, and tropoelastin, which's water soluble at low temperatures [132]. Hydrogels [132] can be produced by extracting elastin-containing materials from animals or human cadavers and treating them to produce derivatives that are soluble in water. Synthetic protein engineering [133] is also used to create elastin-like polypeptides (ELPs) for biological applications. ELPs include the hydrophilic motif Val-Pro-Gly-X-Gly (VPGXG), where X can be any amino acid other than Pro [134]. VPGXG is one of the main hydrophobic motifs that contribute to the unique mechanical properties of natural elastin.

Crosslinkers like GTA, disuccinimidyl suberate, as well as disuccinimidyl glutarate can be used to crosslink elastin-based biopolymers without requiring any chemical alteration. Elastin-based materials are of special relevance for the formation of hydrogel scaffolds for applications for tissue engineering because of their various biological and mechanical properties. These properties stem from the unusual robust behavior of elastin polypeptides [135].

4.2.4. *Silk fibrin*

A variety of proteins found in the glands of some arthropods, including bees, spiders, scorpions, and silkworms, are utilized to make silk (4R). Sericin, a protein that resembles glue and coils encircling silk fibroin to hold threads together, and silk fibroin, its semi-crystalline protein that gives structural rigidity and strength, are the two main proteins that make up silk [136]. Due to its great mechanical strength and biodegradability, as well as global availability, silk fibroin is of interest in biomedical applications. The semi-crystalline polypeptides that make up silk fibroin are connected by a single disulfide bond [137] between their heavy (MW ~390 kDa) and light (MW ~26 kDa) chains. The amino acids Gly (43 %), Ala (30 %), as well as Ser (12 %) make up the majority of silk fibroin, which is harvested directly from the Bombyx mori silkworm for use in medicinal purposes. Because silk fibroin has hydrophobic regions, steady anti-parallel β-sheet crystallites can form there [138]. The textile industry has employed silk fibroin for millennia. Silk has been utilized to be a suture material in clinical applications for centuries [139]. Surgical meshes and ligament grafts are among the FDA-approved silk fibroin-based products. Research has demonstrated that it is possible to create silk fibroin to facilitate the adhesion and development of both human and animal cells. Reduce the amount of β-sheet crystalline content on silk fiber scaffolds to speed up their breakdown by hydrolysis and enzymes, which can both occur in vivo. In order to aid in tissue regeneration and repair, chemically altered silk fibrin scaffolds are currently being investigated extensively.

4.2.5. *Albumin*

The endogenous protein known as albumin is mostly synthesized by the liver and secreted in the blood plasma [140]. About 50–60 % of the total protein content in blood plasma is made up of human serum albumin (HSA), which is the most prevalent protein. HSA, which provides around 80 % of the total blood plasma oncotic pressure, mostly controls fluid flow. HSA is a globular protein with a molecular weight of 66 kDa [141] composed of 585 amino acids. X-ray crystallography has revealed the tertiary structure of HSA, which is a heart-shaped protein backed up by 17 disulfide bridges formed between amino acids. HSA has been used as a plasma expander in clinical settings for many years in order to help stabilize and restore blood volume after trauma, surgery, and blood loss. Human blood plasma can be separated from HSA using a variety of techniques, such as liquid chromatography [142] following plasma fractionation. For biomedical research, albumin can be obtained from human blood plasma; however, bovine serum albumin, or BSA, is currently being extensively researched as a less expensive and more commonly available replacement.

5. Economic impacts of biopolymers

Biopolymers obtained from renewable resources are of great advantage in the industrial sector due to their inexpensiveness. An investigation reported that cost is a limiting factor in the manufacture of biodegradable plastic materials when compared with the conventional plastics. Like is the case with any novel material, manufacturers must expect a minimum of two years of losses before a profit is returned [143]. The same study also reported that a key factor limiting progress in the biopolymer industry is the infrastructure for categorization and composting organic waste which is growing more slowly than was expected initially. Despite this, other reports demonstrate a more positive picture for the economic aspect of biopolymers. For instance Ref. [144], gave the report of several major chemical companies beginning to gain interest in the production of technologies utilized for manufacturing products from renewable resources. Tharanathan (2003) reported that biodegradable materials can never totally replace man-made plastics. He however believes that where the development of biodegradable plastics is feasible, there will be an opportunity for manufacturers to make large profit [145]. The automotive industry is one sector in which profits from the use of biopolymers exist. For instance, fibre reinforcements that are widely used in traditional glass are abrasive and hence, quickly wear down. The biodegradable flax fibre is however less coarse. This lengthens the life of the processing equipments [146]. Williams and Pool (2000) also showed that natural fibres been less expensive and more available than the synthetic ones have greater advantage [147]. The growth of flax fibre integration in the automobile parts is a positive advancement for Canada's agricultural industry especially in its diversification attempts. There has been the report for another use of natural fibre in China's utilization of reed fibre to support transport pallets. This was economically beneficial, as the China reed pallets have the same mechanical stability as conventional ones, additionally, they are less costly to manufacture and require a shorter lifespan for cost recovery. Logistically, the reed pallets of China having less mass than the conventional ones, have require less fuel for transport [148]. Work is still ongoing in enhancing the biopolymer industry to a point where it is totally economically competitive with the conventional plastic industry. For the present, the production of synthetic plastics is usually done on a large scale however; biopolymers are only produced on a small scale. As biopolymer manufacture grows and expands, so will it services also. For instance, industries where flax straw is decorticated and processed into fibres are essential for advancement of flax fibre integration for material strengthening [10]. For microbially grown polymers, huge fermentation and separation amenities are required for the continual use of such materials. In synopsis, time will eventually lead to greater economic strength for the integration of biopolymer material into society.

6. Limitations of biopolymers

Although often purported as environmentally friendly, the applications of biopolymers in packaging has a number of trade-offs, limitations and challenges. To make biopolymers viable for packaging, they much possess specific attributes such as sufficient mechanical strength, adequate heat resistance and effective barrier properties [10]. Another limitation of biopolymers is in integrating reinforcement and active agents to improve its properties especially for use in active and intelligent packaging systems. This integration process is complicated and needs careful consideration. A delicate balance must be struck between the renewability of biopolymers and their desirable biodegradability as well as their ability to meet the mechanical demands of packaging materials. Additionally, despite the promise these materials hold as alternatives to conventional petroleum-based plastics, substantial research is still required. This research will focus on improving their performance, fostering wider application and reducing their cost [9]. In other words, while biopolymers have potential as more sustainable packaging solution, their path to widespread adoption is fraught with technical,

practical and economic challenges that require ongoing research. A summary of benefits and limitations of biopolymers is provided in Table 5.

7. Future outlook for biodegradable plastics

The biodegradable plastic industry has room for growth and expansion. It is estimated that the generation of plastic waste increases by 15 % per year for the next decade. Carbon dioxide emissions from the formation and disposal of conventional plastics are all time high. Completely substituting fossil fuel based plastics with renewable ones will result in a balance of atmospheric carbon dioxide levels [10]. It will nevertheless be ridiculous to expect a complete substitution of conventional polymers by their biodegradable alternatives anytime soon. Integration into specific niche markets rather seem to be the most feasible option. Researchers on the global scale are interested in biopolymers. The German government for instance has put in place rigorous policies regarding acceptable emission levels. The same government in the year 1990, made a call for research and development of biodegradable thermoplastics [149]. Because of this, many German material scientists and engineers now focus work on biodegradable plastics that are environmentally stable. Several materials have been produced by these researchers including Bayer BAK line which in 1996 was introduced in injection and extrusion molding grades. Additionally, an Italian company, Novamont invented the Mater-Bi line for related purposes. In England, the plastic department of Queen Mary University London is actively working on the development of biocomposite. In general, European nations are anticipated to follow the European packaging directive which is aimed at the recovery of packaging waste. Organic recovery is the most commonly utilized waste reduction method usually employed [150]. European countries are also estimated to integrate 15 % w/w of recycled plastics into the production of packaging materials. Although the European countries are at the front line of biopolymers research but remarkable developmental work has occurred and is still ongoing in other countries. China for example is has a large population on a small land base hence, its responsibility to conserve the space by proper waste disposal. Because of this, Chinese researchers have turned attention to the refinement of microbially produced PHA [150]. The acceptance of the Kyota Accord by the Canadian government is also increasing the need for the reduction of fossil fuel utilization and an increase in the use of renewable alternatives. As the biopolymer industry grows, production issues will be sorted. Some areas of concern are known to researchers, areas on which they are currently focusing. The search for a perfect processing technique to circumvent this problem continues. Following this, Verhoogt and team (1995) have opined that more starch content be added into thermoplastic mix to increase its flexibility but this decreases its mechanical strength. Standards organizations including ISO and ASTM have published methods for material tests on biodegradable plastics. There has also been an observation of the need to improve these tests with the expansion in the biopolymer industry. Non-homogenities are particularly created in polymer materials by the clamps used for tensile tests [151]. The nature of natural materials obliges more considerations to be taken into account than their synthetic counterparts. The biopolymer industry has great potential which is manly driven by the consequent environmental benefits from using renewable resources. The expected goal for researchers working in biopolymer development is to find a material that has complete biodegradability and optimum technical performance.

8. Conclusion

Over the years, industries have increasingly shown interest in biopolymers. Biopolymers include pectins, pullulan, hemicellulose, starch, xanthan gum, and carboxymethyl cellulose, among other materials made from renewable resources. The need for novel materials of biopolymer origin for the future is expected to grow extensively. These days, bio-based polymers are commonly used in consumer products as well as tech ones, owing to greater public awareness and biotechnology research and development. Food packaging for instance is essential for protecting the food from external contamination and maintaining its quality, safety, and purity during shelf life. The food industry mostly uses synthetic polymer-based materials for packaging due to their low cost, ease of manufacturing, affordability, flexibility and lightweight nature. Moreover, the development and application of biodegradable polymer compounds is required to address environmental challenges. These show great potential as alternatives to traditional petroleum-based food packaging materials in lessening the effects of green house gasses on the environment. Biodegradable polymer-based plastic packaging is rapidly assuming the lead in terms of social responsibility and promotion of a sustainable and healthy lifestyle. Additionally, the unique properties of biopolymers, such as their biodegradability and biocompatibility, present a number of benefits and increase the likelihood that they will be used in implanted medical applications and hence the use of biopolymers such as PLA silk and chitosan, is also being extensively studied. These biopolymers play a critical role in medicine since synthetic materials are unable to meet the demands of biological systems. Consequently, current research has demonstrated that the combination of biopolymers and synthetic materials possesses the capacity to totally revolutionize medicine. The many materials used in the synthesis of biodegradable polymers have been examined by scientists and engineers in order to determine their efficacy, safety, and influence on the environment. Biodegradable plastics that contain cellulose and or starch appear to be the most likely to experience continual growth in use. Mirobially grown plastics while scientifically sound require expensive infrastructure to commercially expand their use. Making plastics that retain competitive strength and durability but which can still easily breakdown is an anticipated breakthrough in the plastics industry.

CRediT authorship contribution statement

Great Iruoghene Edo: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Winifred Ndudi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **AliB.M. Ali:** Writing – review & editing, Writing – original draft, Visualization, Validation. **Emad Yousif:** Writing – review & editing, Writing – original draft, Visualization, Validation. **Agatha Ngukuran Jikah:** Writing – review & editing, Writing – original draft, Visualization, Validation. **Endurance Fegor Isoje:** Writing – review & editing, Writing – original draft, Visualization, Validation. **Ufuoma Augustina Igbuku:**

Table 5
The benefits and drawbacks of biopolymers.

Biopolymers	Benefits	Drawbacks
Organic Biopolymers.	biocompatible, biodegradable, biorenewable, non-toxic, bioadhesive, and biofunctional materials.	less stable, more complicated architecturally, low melting point, and high surface tension.
Artificial Biopolymers.	Improved mechanical and chemical stability, repeatability, and biocompatibility	Toxic, expensive production process, and non-biodegradable.

Writing – review & editing, Writing – original draft, Visualization, Validation. **Alice Njolke Mafe:** Writing – review & editing, Writing – original draft, Visualization, Validation. **Rapheal Ajiri Opiti:** Writing – review & editing, Writing – original draft, Visualization, Validation. **Chioma Judith Madueke:** Writing – review & editing, Writing – original draft, Visualization, Validation. **Arthur Efeoghene Athan Essaghah:** Writing – review & editing, Writing – original draft, Visualization, Validation. **Dina S. Ahmed:** Writing – review & editing, Writing – original draft, Visualization, Validation. **Huzaifa Umar:** Writing – review & editing, Writing – original draft, Visualization, Validation.

List of abbreviations

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Consent for publication

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Availability of data and material

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