Review

Pharmaceutical Applications of Biomass Polymers: Review of Current Research and Perspectives

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Abstract

Polymers derived from natural biomass have emerged as a valuable resource in the field of biomedicine due to their versatility. Polysaccharides, peptides, proteins, and lignin have demonstrated promising results in various applications, including drug delivery design. However, several challenges need to be addressed to realize the full potential of these polymers. The current paper provides a comprehensive overview of the latest research and perspectives in this area, with a particular focus on developing effective methods and efficient drug delivery systems. This review aims to offer insights into the opportunities and challenges associated with the use of natural polymers in biomedicine and to provide a roadmap for future research in this field.

Keywords: biomass; polymers; biodegradability; biocompatibility; pharmaceutical applications

1. Introduction

In recent developments, heightened exploration concern in environmental sustainability has shifted focus from synthetic polymers to natural biopolymers. Their synthesis can be categorized as microbial, chemical, or natural, and they exhibit comparable behavior to synthetic counterparts from the applications, performance, and configuration points of view. Altered functionalities can be introduced to biopolymers, enhancing their maneuverability, chemistry, and accuracy for applications in pharmaceutical, environmental, and medical fields, reducing plastic excess. However, challenges such as expense and inefficiencies in synthesis, improvement, and subsequential processing procedures hinder the widespread adoption of biopolymers in industries [1–4].

A biomaterial is a substance that is purposefully designed to interact with biological systems with the primary aim of facilitating direct medical interventions, requiring biocompatibility and capability to fulfill its intended function. Moreover, the physical, chemical, and biological attributes of a substance designated as a biomaterial for applications in tissue engineering and drug delivery devices play a crucial role in influencing the host response and necessitate precise adjustment. Polymers, with diverse properties, are commonly used in biomaterial assemblies, and degradable polymers undergo a process of disintegration, resulting in low molecular weight products that can be self-reabsorbed or excreted [5–8].

Natural polymers, categorized into proteins, polysaccharides, and polyesters, depending on their chemical structures, are utilized for biomedical purposes through co-polymerization, merging polysaccharides like chitosan, starch, and cellulose with other polymers, and employing average protein-based biopolymers such as lignin, gelatin, and albumin for the creation of drug delivery nanomolecules due to their advantageous properties, such as minimal toxicity, narrowness, biodegradability, and prolonged stability [9–11].

Biomass polymers, with inherent biocompatibility and chemical functionalities, are utilized in creating nanomaterials for diverse biomedical applications, ensuring efficient body clearance and eliminating the need for retrieval or explanation. Degradable polymers undergo hydrolytic or enzymatic cleavage, producing soluble degradation by-products and enhancing properties like bioavailability, stability, and controlled release for applications in tissue engineering (e.g., cartilage scaffolds) and prosthetic implants. Refinement of physical, chemical, and biological attributes of these polymers is achieved through strategies like blending, cross-linking, and forming interpenetrating networks (IPNs), while recent efforts focus on synthesizing macromolecular biomaterials with optimized thermal and mechanical properties using chemical modification on their nanoconstructs. Techniques such as physicochemical cross-linking, polyion complexes (PICs), blends/nanocomposites, coating onto nanoparticles, and layer-by-layer assembly offer avenues for developing multiphase polymer systems tailored for biomedical applications [12–18].

Biopolymer composites, incorporating metals, natural fibers, and metal oxides as fillers, have been engineered for upgraded performances. The study of adsorptive, mechanical, and thermal properties of biocomposites is facilitated by a range of characterization techniques, including ultraviolet (UV) spectroscopy, thermogravimetric analysis, atomic absorption spectrometry (AAS), X-ray diffraction, transmission electron microscopy, Raman spectroscopy, scanning electron microscopy (SEM), and Fourier-transform infrared (FT–IR) spectroscopy. Ongoing research supports the development of cost-effective biocomposites, with improved thermochemical and physicomechanical features at a reduced cost [19–23].

Natural biopolymers, like lactic acid, cellulose, starch, chitosan, pectin, and synthetic biomass polymers such as polylactic acid (PLA), polycaprolactone (PCL), and polyglycolic acid (PGA), play crucial roles in various applications, including pharmaceutical preparations, purification membranes, hydrogels, prosthetics, drug delivery, and bone tissue engineering (Figure 1).

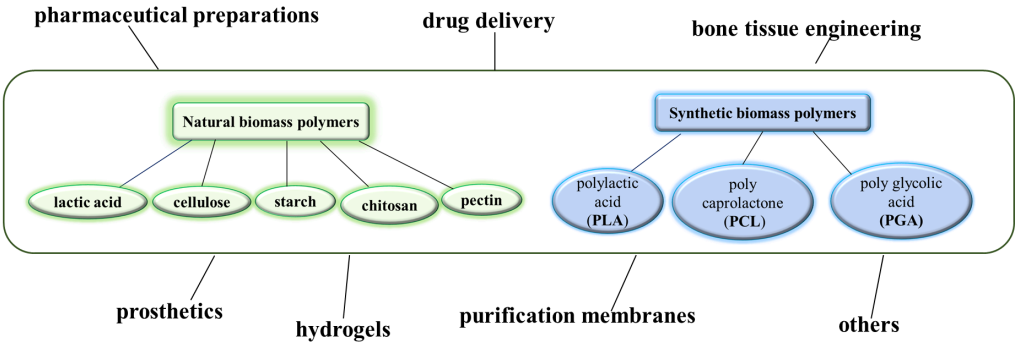

Figure 1. Schematic representation of principal biomass polymers and some of their main applications.

These biopolymers demonstrate unique properties, because they are biodegradable, biocompatible, bioactive, and safe, filling the gap left by synthetic polymers. Enhancing the shelf life of food products, edible biopolymer packaging films derived from agricultural waste showcase nutraceutical, antimicrobial, and antioxidant properties. Furthermore, biopolymer particles generate gel-like structures in emulsion-based products, increasing texture, consistency, and stability [24–35].

Starch nanoparticles derived from cassava peel were interpreted to assess their structural features for potential application as transport systems. Additionally, pullulan biopolymer was integrated into silver nanoparticles for diverse applications in pharmaceuticals and water treatment. In the field of drug delivery systems (DDS), various biopolymers, selected for their biocompatibility, were synthesized through different methods to serve as effective carriers. These non-toxic biopolymers show promise in implantable devices and prosthetics, facilitating targeted compound distribution. Biopolymer composites find extensive use in various medical areas, including skin scaffolds, cardiology, ophthalmology, and surgery. Moreover, skin regenerative biomass polymers like chitosan contribute to the production of films, gels, and wound dressing materials, supplied with therapeutic agents for lesion alleviation. Beyond the realms of biomedical and pharmaceutical industries, biopolymers play a crucial role in treating potable water by eliminating pollutants *via* mechanisms such as adsorption and photocatalysis [36–48].

2. Biopolymers

Biopolymers, originating from living organisms and composed of monomeric units such as amino acids, saccharides, and nucleic acids, are gaining prominence in medical and pharmaceutical industries, due to their key attributes: eco-friendliness, sustainability, biodegradability, non-toxicity, renewability, and compatibility. Biopolymers derived from natural biomass, exhibiting inherent biodegradability, are directly obtained from the natural environment and possess considerable economic value. Commercially, a myriad of biopolymers serves diverse purposes in biomedical devices, hygiene items, agriculture, and the food industry. Despite their advantages, the fabrication of biopolymers faces a major drawback in substantial financial expenditures, prompting ongoing research into cost-minimization methods, involving purification procedures, high-yielding microorganisms, and substrate selection [1,49,50].

Biopolymers are sourced economically from diverse natural origins including plants, algae, microorganisms, animals, and agricultural residues. Agricultural provenances encompass barley, cotton, tapioca, corn, banana, cassava, yams, sorghum, potatoes, wheat, rice, and maize, while animal-derived biopolymers comprise mainly cattle and pigs. Biomass-derived materials, such as green waste and residues from wood, paper, crops, and agrotechnology, along with marine sources like shrimps, lobsters, fish, sponges, and corals, contribute to the availability of biopolymers. Crucially, microbial origins like fungi, algae, and yeasts play a pivotal role in accomplishing a circular economy and mitigating greenhouse gas emissions. Additionally, vegetable oils extracted from meadow foam, fish, castor, linseed, tung, jojoba, rapeseed, safflower, castor, sunflower, corn, and soybean serve as rich sources of triglycerides, functioning as possible monomers, in combination with appropriate catalysts and co-monomers [51–53].

Biopolymers are categorized based on their biodegradability, origin, thermal response, and composition. The biodegradable and non-biodegradable distinction is evident, along with their classification as derived from natural origins or fossil fuels. Thermal condition response classifies them into thermosets, thermoplastics, and elastomers, while their composition leads to groups such as composites, laminates, and blends. Among the prominent systematization standards is the provenience of raw materials, resulting in natural, synthetic, and microbial biopolymers. Naturally sourced biomass polymers encompass proteins (e.g., collagen, soy protein) and polysaccharides (e.g., chitosan, cellulose). Chemically synthesized polymers comprise PLA and petroleum-based polymers, such as polyethylene, polycaprolactone (PCL), and polyglutamic acid. Biopolymers from microbial generation, like

polyhydroxyalkanoates (PHAs), bacterial cellulose, and gellan, serve diverse applications in medical, agro-industrial, and environmental sectors [1,54–57].

2.1. Polysaccharides

Polysaccharides, natural polymers with functional hydroxyl, amino, and carboxylic groups, have garnered significant attention due to their inert, biocompatible, non-toxic, and cost-effective nature, coupled with excellent water stability. These versatile entities can be easily cross-linked, derivatized, or transformed into multiphase polymer systems such as polyblends, IPNs, graft, and block copolymers, while charged polysaccharides contribute to the formation of valuable polyion complexes [58,59]. This discussion focuses on the key biomedical polysaccharides.

2.1.1. Homoglycans

2.1.1.1. Starch

Starch is a natural polysaccharide that comprises linear chains of amylose and branched amylopectin segments, primarily derived from α-glucose units and prominently present in cereal grains, fruits, roots, and legumes. Amylose features glucose units linked by α-(1,4) bonds, while amylopectin includes α-(1,4) and α-(1,6) linkage (Figure 2).

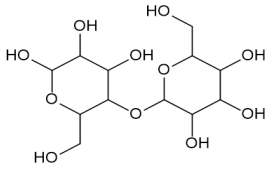

Figure 2. Starch – chemical structure.

Properties of starch vary based on the plant source and its degree of maturity. Chemically altered starch, along with its physical mixtures or IPNs, serve as significant biomaterials in bone and tissue engineering, exhibiting enhanced characteristics. Nevertheless, starch's inherent brittleness, premature degradation before reaching its melting temperature, inferior mechanical features, and challenging processability constrain its application as a standalone material [60–63].

2.1.1.2. Dextran

This bacterial homopolysaccharide encompasses glucans formed through the polymerization of α-D-glucopyranosyl moieties of sucrose catalyzed by dextransucrase enzyme. The main chain features glucose segments connected by α-(1,6) bonds, while branches exhibit α-(1,4), α-(1,3), and α-(1,2) units (Figure 3).

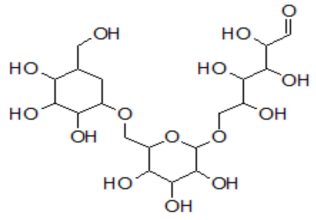

Figure 3. Dextran – chemical structure.

Properties like branching degree, molecular weight, and other attributes vary with the engaged microorganism. Dextran, with its remarkable rheological nature and plasma volume enlarging potency, undergoes chemical alterations, introducing thiol, (meth)acrylate, aldehyde, and phenol groups. As a biocompatible polysaccharide with no toxicity, dextran finds extensive applications in pharmaceutical and biomedical domains as an antithrombotic and bio-adhesive agent, in protein/drug delivery or tissue-engineered scaffolds. Injectable hydrogels are proposed as site-specific, trackable chemotherapeutic devices. Despite these advantages, challenges include high costs and limited availability

[64–67].

2.1.1.3. Cyclodextrins

Cyclodextrins are oligosaccharides formed by the enzymatic linkage of glucose units (α-D-glucopyranose) through α-(1,4) bonds, resulting in the production of α-cyclodextrin (six units), β-cyclodextrin (seven units), and γ-cyclodextrin (eight units) (Figure 4, a–c).

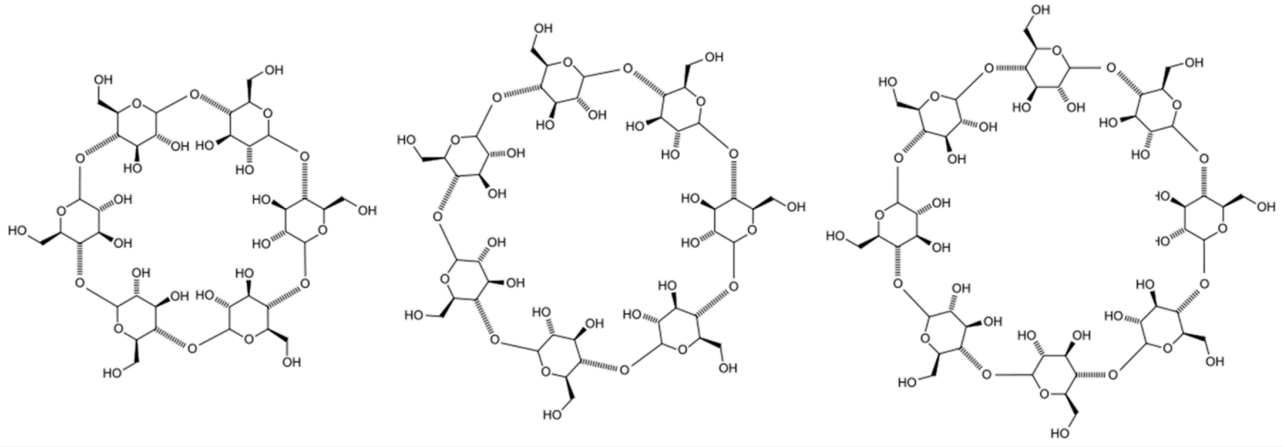

Figure 4. Chemical structure of α-cyclodextrin (a), β-cyclodextrin (b) and γ-cyclodextrin (c).

Characterized by a distinctive truncated cone-like structure, cyclodextrins feature an internal non-polar cavity with polar hydroxyl groups on the surface. This configuration allows hydrophobic substances, including drugs, to be encapsulated through hydrophobic interactions, forming host–guest supramolecular complexes driven by van der Waals and dipole–dipole interactions. A comprehensive scrutiny has been conducted on the chemistry and applications of cyclodextrins across various fields. These inclusion complexes are amenable to derivatization and appropriate chemical alterations [68,69].

2.1.1.4. Cellulose

The most abundant natural polysaccharide, cellulose consists of β-D-glucopyranose units linked by β-(1,4) glycosidic bonds (Figure 5), offering significant potential as an advanced polymeric material.

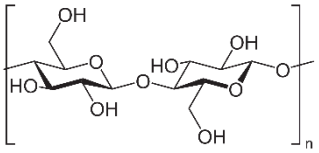

Figure 5. Cellulose – chemical structure.

Cellulose and its derivatives are versatile precursors, due to their biocompatibility, low toxicity, and cost-effectiveness. However, extensive intermolecular hydrogen bonding imparts high crystallinity, rendering cellulose insoluble in most solvents, posing processing challenges. Ionic liquids and deep eutectic solvents overcome this issue. Derivatization of cellulose produces environmentally friendly materials, such as methylcellulose, cellulose acetate, hydroxypropyl cellulose, cellulose nitrate, and carboxymethylcellulose. Cellulose nanomaterials, including nanocrystals, bacterial nanocellulose, and nanofibrils have been extensively researched. Nevertheless, cellulose has limitations such as low crease resistance, potential antigenicity, and lack of thermoplasticity [70–72].

2.1.1.5. Chitin and Chitosan

Chitin, a prominent constituent of sea crustacean shells, stands as the second most abundant biomacromolecule utilized across various industries such as pharmaceuticals, textiles, food, and agriculture. Exhibiting biocompatibility, non-toxicity, biodegradability, and mucoadhesive properties, chitin can be effortlessly extracted and chemically altered to yield diverse biomaterials (Figure 6a).

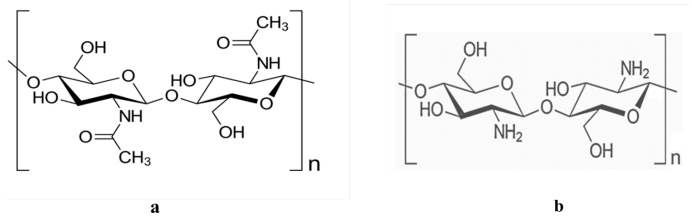

Figure 6. Chemical structure of chitin (a) and chitosan (b).

Chitosan, extracted from crabs and fungal cell walls, undergoes commercial production through the deacetylation of chitin. The degree of deacetylation, impurity composition, and molar mass distribution are based on the natural source and preparation method. As a cationic linear copolymer polysaccharide, chitosan is composed of β-(1→4) connected 2-amino-2-deoxy-D-glucose (D-glucosamine) and 2-acetamido-2-deoxy-D-glucose (N-acetyl-D-glucosamine) segments through glycosidic bonds (Figure 6b). The polymer's primary amino groups confer a positive charge on its surface, promoting inter and intramolecular hydrogen bonding. Additionally, chitosan exhibits antimicrobial activity against viruses, fungi, and bacteria, rendering it valuable in the biomedical domain. However, its drawback lies in reduced solubility at physiological pH. Despite variability in synthesis procedures, short-term human testing has shown no signs of allergic reactions [73–83].

2.1.2. Heteroglycans

2.1.2.1. Alginate

Alginate, a water-soluble anionic polymer comprising α-L-guluronic acid (G) and β-D-mannuronic acid (M) residues connected by 1,4-glycosidic bonds, is biodegradable, biocompatible, and exhibits no toxicity (Figure 7).

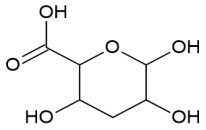

Figure 7. Alginate – chemical structure.

Derived economically from marine brown algae, alginate finds diverse biomedical applications, serving as three-dimensional scaffolding materials in forms such as foams, microcapsules, sponges, and hydrogels for tissue engineering. Physical or chemical alteration enhances alginate's properties, allowing precise tuning of cell affinity, mechanical strength, and gelation through combinations with other biomaterials, ligand immobilization, and cross-linking. Despite its sensitivity to hydrolysis in acidic environments and challenges in fabrication due to reduced solubility, alginate-based materials have undergone clinical investigations, demonstrating potential benefits such as managing hypertension and advancements in food industry [84–90].

2.1.2.2. Agarose

Agarose, an uncharged polysaccharide derived primarily from certain marine red algae, is a key component of agar. It is soluble in hot water, ionic liquids, and polar non-aqueous solvents. From a structural standpoint, agarose is a linear and neutral polysaccharide comprising alternating (1,3)-β-D-galactopyranose and (1,4)-linked 3,6-anhydro-α-L-galactopyranose units (Figure 8).

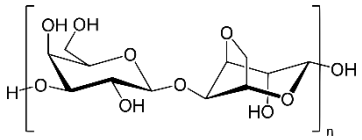

Figure 8. Agarose – chemical structure.

Its solution forms gels upon cooling below ~40°C, with flexible fiber chains capable of curling into helix structures, creating powerful gels with prominent hysteresis. Non-toxic and biocompatible, agarose is commonly employed as a gelling agent in various applications, including chromatography techniques, nucleic acid electrophoresis, cell culture media, tissue culture overlays, and gel plates. Its exceptional properties, including mechanical resilience and reduced gelling temperature, make it suitable for applications like bio-ink, where gelation forms a three-dimensional network of agarose fibers, disintegrating above 85°C [91–94].

2.1.2.2. Carrageenans

Carrageenans, a family of linear sulfated polysaccharides extracted from red algae (*Rhodophyta*), known as Irish moss, exhibit extensive and very flexible molecules capable of forming helical structures, resulting in viscous solutions or elastic gels. Comprising alternate segments of β-D-galactose and 3,6-anhydro-α-D-galactose connected by α-(1,3) and β-(1,4) glycosidic bonds, carrageenans yield three main types—kappa (κ-1 sulfate group/disaccharide), iota (ι-2 sulfate groups/

disaccharide), and lambda (λ-3 sulfate groups/disaccharide)—depending on extraction method and algae source (Figure 9).

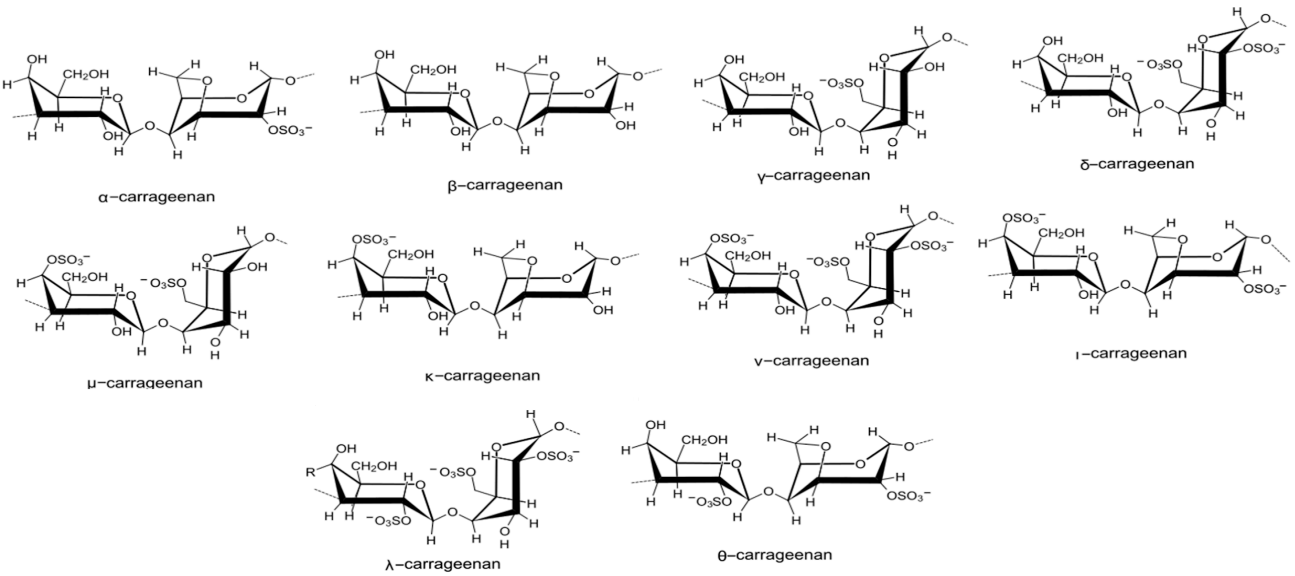

Figure 9. Chemical structures of main carrageenans.

Beyond their applications in pharmaceutical, cosmetic, and food industries for colloid stabilization, thickening, protein binding, and gelling, carrageenans also influence plant growth stimulation and serve as pathogen resistance generators, offering crop protection. Despite their versatile properties, reduced gel strength and anticoagulant effect remain notable disadvantages [95–98].

2.1.2.3. Pectins

Pectins, polysaccharides found in the cell walls of superior plants, feature structures composed of D-galacturonic acid segments linked by α-(1,4) bonds, creating a linear chain framework with interrupted extensively branched regions.

Variations in composition depend on the botanical origin (Figure 10).

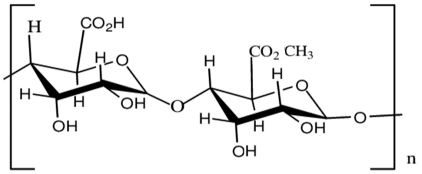

Figure 10. Chemical structure of pectins.

Notably, pectins exhibit limitations such as reduced water-vapor barrier and poor mechanical characteristics [99].

2.1.2.4. Arabic Gum

Comprising a complex combination of glycoproteins and polysaccharides (Figure 11), prominently featuring arabinose and galactose, Arabic gum is a water-soluble neutral polymer widely employed as a thickener, stabilizer and emulsifier in the pharmaceutical, cosmetics, and food industries.

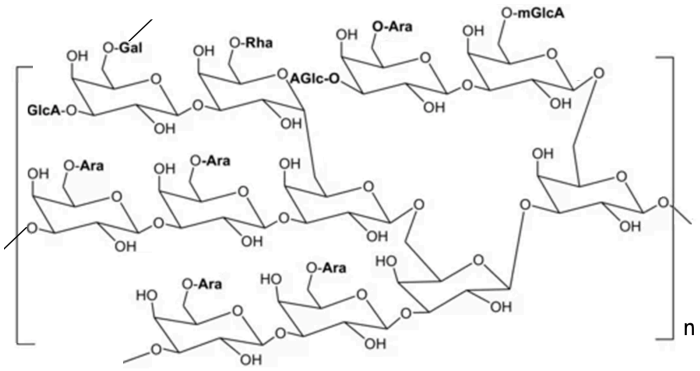

Figure 11. Chemical structure of Arabic gum.

Beyond its conventional uses, Arabic gum serves as a versatile excipient, contributing to the development of nanoscale scaffolds for drug delivery and biomedical practice. Strategies include cross-linking to form hydrogels, combination with other polymers, creating drug conjugates, and attaching to nanoparticles, showcasing potential biomedical implementation [100–107].

2.1.2.5. Guar Gum

Guar gum is a water-soluble polysaccharide with a high molecular weight, extracted from the seeds of *Cyamopsis tetragonolobus*. It consists of a primary chain of D-mannopyranose residues linked by β-(1,4) glycosidic bonds, connected to D-galactopyranose residues through α-(1,6) glycosidic bonds (Figure 12).

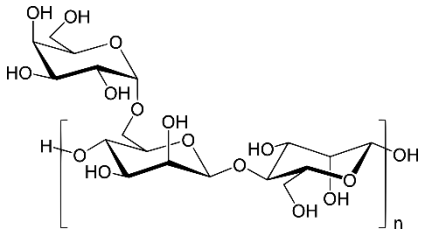

Figure 12. Chemical structure of guar gum.

Known for its emulsifying, thickening, and stabilizing properties, guar gum finds applications in the food, pharmaceutical, and cosmetic industries. Its cold water solubility is influenced by the galactose/mannose molar ratio. Modified through functionalization (carboxymethylation, hydroxyalkylation, or esterification), guar gum is tailored for biomedical applications, enhancing its mechanical features and reducing aqueous solubility. Guar gum and its derivatives are particularly suitable for oral drug delivery due to their heightened stability across a large pH range

[108–114].

2.1.2.6. Hyaluronic Acid

Hyaluronan or hyaluronic acid is a non-sulfated glycosaminoglycan with a linear structure, consisting in disaccharide repeat segments of β-1,4-D-glucuronic acid and β-1,3-N-acetyl-D-glucosamine connected by β-1,4-glycosidic bonds (Figure 13).

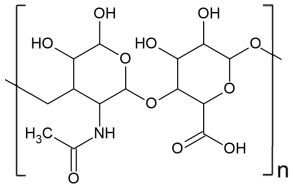

Figure 13. Chemical structure of hyaluronic acid.

Predominantly found in the extracellular matrix of vertebrate soft connective tissues, hyaluronic acid plays a crucial role in tissues like umbilical cord, synovial fluid, skin, and vitreous humor. Commercially sourced from rooster combs or bacterial fermentation, it is an anionic polysaccharide with the ability to absorb a significant amount of water, serving as a lubricant in native extracellular matrixes and influencing connective tissue viscoelasticity. Hyaluronic acid has the potential for chemical alteration through processes such as cross-linking and grafting. In numerous tumor and inflammation conditions, cluster of differentiation (CD)44 and CD168 serve as major ligands for hyaluronic acid. It also plays pivotal roles in biological processes such as cell proliferation, tumor invasion, tissue homeostasis, angiogenesis, and matrix organization through its interactions with cells. Despite its susceptibility to accelerated degradation, hyaluronic acid is extensively used in applications such as drug delivery, tissue engineering, and cutaneous rejuvenation. Challenges lie in the brittleness and aqueous solubility of hyaluronic acid hydrogels, leading to the development of useful biomaterials like derivatized hyaluronic acid and IPNs/polyion complexes of hyaluronic acid, albeit facing issues of increased cost and inferior mechanical features [115–124].

2.1.2.7. Chondroitin

Chondroitin sulfate, a primary component of hyaline cartilage in cartilage and at the bone calcification location, is a sulfated glycosaminoglycan with recurrent disaccharide segments of β-1,4-linked-D-glucuronic acid and β-1,3-linked N-acetyl galactosamine, featuring certain sulfated positions (Figure 14). The two major chondroitin sulfates vary in sulfate positions at 4 or 6.

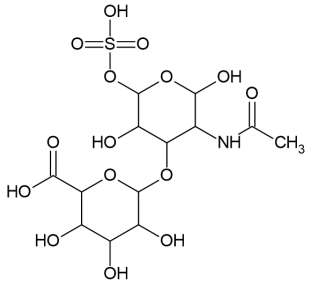

Figure 14. Chemical structure of chondroitin sulfate.

With polar carboxyl and hydroxyl groups, the polymer exhibits covalent/electrostatic interactions with other materials. Possessing antithrombosis, negative immunogenic, anticoagulant, antioxidant, and antiatherosclerosis actions, chondroitin sulfate serves as a valuable biomaterial. Widely employed in osteoarthritis treatment, it can target CD44 receptors on tumor cells, making it applicable for cancer management [125–130].

2.2. Proteins

2.2.1. Collagen

Collagen is the oldest protein structure identified in dinosaur fossils. Approximately 30% of the total animal protein is represented by collagen, which is indispensable in maintaining the biological integrity of the connective tissues. Currently, there are 29 types of collagens, characteristic of different tissues of the human body. Figure 15 shows the chemical structure of collagen I (α chain).

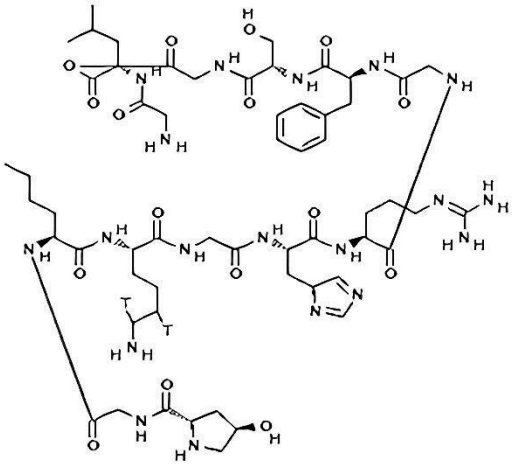

Figure 15. Chemical structure of collagen I (α chain).

This wide variety of collagen types presents diversity and complexity in terms of structure, splicing possibilities, presence of non-helical domains, assembly and function [131]. The hierarchical structure of collagen is characterized by four distinct levels: primary, secondary, tertiary, and quaternary. The primary structure, defined by the sequence of amino acids within the collagen molecule, influences its tissue-specific properties and cellular interactions. Hydrogen bonds between the single polypeptide chains contribute to the secondary structure, forming a triple helix arrangement rich in glycine, hydroxyproline, and proline. Tertiary structure refers to the three-dimensional shape resulting from various interactions, while quaternary structure involves the spontaneous assembly of collagen molecules into a crystalline network. Collagen exists in two main categories: fibrillar and non-fibrillar, with type I fibril collagen predominant in providing mechanical support to tissues like bones. Non-fibrillar collagen encompasses various subcategories, each contributing to specific structural and functional roles within tissues. Despite their diversity, all collagen types share a common molecular structure comprising three α chains forming a triple helix domain [132,133].

The predominant sources of collagen, mainly from bovine origin due to favorable biocompatibility and low immunogenicity, with potential alternatives from marine organisms like fish, are commonly utilized despite associated challenges such as difficulty in sterilization, susceptibility to bacterial contamination, batch variability, and immunogenicity, necessitating ongoing research into extraction, purification, and industrial-scale production of modified recombinant collagen [134,135]. Common collagen extraction methods involve solubilization in neutral saline, acidic solutions, and acidic solutions with enzymes, albeit at high costs due to requisite chemical treatments for bond elimination, crucial for yield optimization in research-oriented collagen production. Marine collagen, while offering biological safety without disease transmission risks, exhibits lower stability attributed to a lower denaturation temperature compared to mammalian collagen [136,137].

Collagen's amino acid composition, varying across species, influences its physical and chemical properties, thermal stability, solution viscosity, and crosslinking potential, enabling its utilization in wound healing, ophthalmic treatment, drug delivery, and genetic engineering. Key considerations for employing collagen in biomaterial matrices include

thermal stability, mechanical resistance, and specific biomolecular interactions. Its excellent biocompatibility and biodegradability render it ideal for various medical implants, such as porous sponges, membranes, and surgical threads, as well as cell culture substrates. While collagen-based supports often incorporate synthetic components for enhanced mechanical strength, they serve diverse purposes, including drug delivery, tissue engineering, and epithelial barrier formation to promote tissue regeneration. Despite collagen's inherent biological advantages, its mechanical properties and structural stability may require enhancement through crosslinking treatments, allowing for tailored matrix modifications without compromising cellular responses. Combining natural and synthetic polymers further expands the potential of collagen-based systems to address multifaceted biomedical needs [138–143].

Overall, collagen stands as a fundamental protein, essential for providing structural support within the human body's intercellular space. With its characteristic rod-shaped polymer structure and susceptibility to enzymatic degradation, collagen plays a vital role in maintaining the integrity of the extracellular matrix through the release of amino acids. Both naturally derived and recombinant forms of collagen hold significant value as biomaterials, widely utilized in diverse fields such as tissue engineering and cosmetic surgery. Recognized by regulatory authorities like the U.S. Food and Drug Administration, collagen's versatility extends to its incorporation into composite materials with hydroxyapatite and tricalcium phosphate as a biodegradable synthetic bone graft alternative and its use in various drug and gene delivery applications. To conclude, collagen's adaptable utility underscores its indispensable role in biomedical advancements and therapeutic interventions [144–148].

2.2.2. Gelatin

Gelatin, a naturally occurring biopolymer derived from collagen, is abundant in connective tissues, skin, and bones, finding extensive utility across the food, pharmaceutical, and cosmetic industries. Resulting from the partial hydrolysis of collagen, gelatin comprises a heterogeneous ensemble of peptides and proteins, characterized by its hydrophilic nature due to the presence of numerous amino and hydroxyl groups, facilitating water absorption and gel formation (Figure 16).

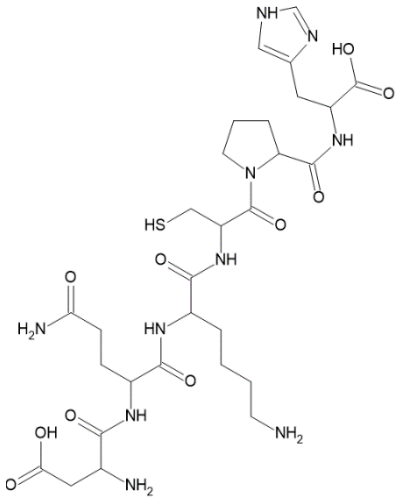

Figure 16. Chemical structure of gelatin.

Its biocompatibility, biodegradability, and capacity for forming stable hydrogels have positioned gelatin as a prominent candidate for drug delivery systems, particularly due to its thermo-reversible properties, enabling gel formation at physiological temperatures suitable for injectable drug delivery applications. Furthermore, gelatin's versatility allows for facile modification to achieve specific drug release profiles through chemical cross-linking or blending with other polymers, thus tailoring mechanical and release properties as needed for diverse therapeutic applications. Additionally,

gelatin's inherent bioactivity supports cell adhesion, rendering it suitable for tissue engineering endeavors, with the integration of bioactive molecules enhancing its potential for regenerative medicine and targeted drug delivery. Nevertheless, challenges such as potential immunogenicity and rapid in vivo degradation necessitate strategies such as cross-linking and polymer blending to address these limitations and ensure the stability and sustained release of encapsulated drugs [149–153]. Cross-linking serves as a pivotal mechanism in bolstering the stability of gelatin structures, averting premature degradation and upholding the integrity of drug delivery systems. Through cross-linking, the porosity and mesh size of gelatin matrices are modulated, thereby influencing the diffusion kinetics of drugs and affording precise control over release mechanisms. This flexibility enables the creation of tailored release profiles, encompassing sustained, controlled, and stimuli-responsive release patterns. Researchers adeptly manipulate the hydrophilicity, mechanical strength, and degradation rate of gelatin matrices by judiciously selecting cross-linking agents and methodologies. Chemical cross-linking agents like glutaraldehyde, genipin, or carbodiimides foster covalent bond formation among gelatin molecules, while physical cross-linking exploits external stimuli such as temperature, pH, or ionic interactions to induce cross-linking, particularly advantageous for preserving the bioactivity of delicate drugs. Additionally, enzymatic cross-linking utilizing transglutaminase catalyzes cross-link formation within gelatin matrices, furnishing a biocompatible and precise approach for enhancing stability and functionality [154–156].

Blending gelatin with other polymers represents a prevalent strategy aimed at augmenting the properties and performance of gelatin-based materials, particularly within drug delivery systems. The selection of polymers for blending hinges upon the desired characteristics of the resultant composite material. Notably, poly(lactic-*co*-glycolic acid) (PLGA) is frequently amalgamated with gelatin to bolster mechanical strength and regulate degradation rates. Conversely, polyethylene glycol (PEG), another hydrophilic polymer, serves to enhance water solubility and stability of gelatin-based materials, concurrently mitigating protein adsorption, thereby offering potential benefits in specific biomedical applications. Furthermore, blending gelatin with chitosan finds extensive exploration in crafting wound dressings, tissue engineering scaffolds, and drug delivery systems. Additional materials conducive to blending with gelatin encompass polyvinyl alcohol (PVA), hyaluronic acid, recognized for its exceptional biocompatibility, and poly(ethylene oxide) (PEO), commonly utilized in the fabrication of hydrogels and films for diverse drug delivery applications [157–159].

2.2.3. Silk Proteins

Insects, such as silkworms and spiders, generate silk, the most robust natural protein fiber, known for its exceptional mechanical features, including flexibility, increased tensile strength, biodegradability, resistance to compression, and reduced immunogenicity, making it biomedically significant. Silkworm silk consists mainly of fibroin (Figure 17a) and sericin (Figure 17b), with fibroin exhibiting histocompatibility, hydrophobicity, minimal immunogenicity, non-toxicity, and insolubility.

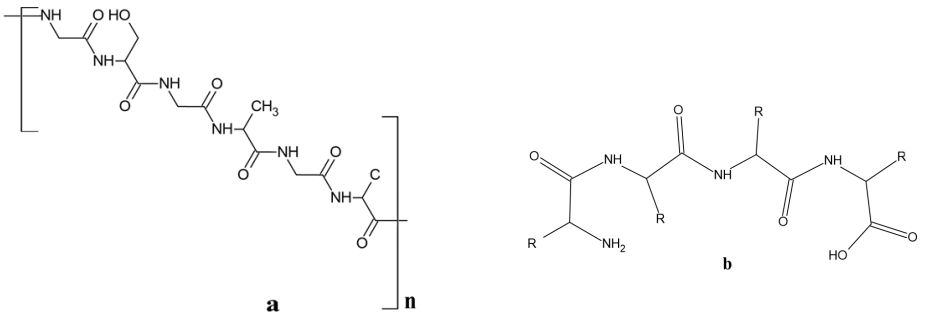

Figure 17. Chemical structure of fibroin (a) and sericin (b).

Derived from silkworm cocoons, fibroin, composed of amino acids (alanine, serine, and glycine), forms various

structures like nanoparticles, fibers, gels, hydrogels, scaffolds, and membranes. Its biodegradability, biocompatibility, along with mechanical strength and malleability, position fibroin as a promising candidate for drug delivery domain. Sericin, a water soluble hydrophilic protein, acts as a glue, offering intrinsic antioxidant and anticancer properties in its nanoparticle form [160–177].

2.2.4. Albumin

A protein existing in both animal and plant physiological fluids/tissues, albumin plays crucial roles such as maintaining osmotic pressure, neutralizing free radicals, and connecting and transporting numerous substances like drugs and hormones in the circulatory system. It acts as an interface between cells and scaffold materials like collagen, facilitating their integration in tissue engineering. Serum albumin, a biodegradable, stable, and non-toxic protein, significantly influences pharmacokinetics and drug distribution/metabolism through drug attaching. Consequently, albumins have surfaced as prospective drug carriers, finding implementation in biosensors, contrast agents, theranostics, and implants for various conditions. The structure and functional groups of albumins (Figure 18) enable linking and capping of inorganic nanoparticles, increasing compatibility and bioavailability, with low toxicity and selective bioaccumulation [178,179].

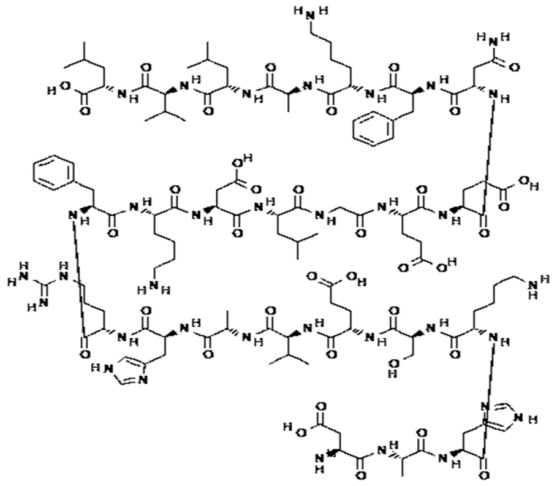

Figure 18. Chemical structure of albumin (serum albumin).

2.2.4.1. Bovine Serum Albumin

Albumin, a critical blood plasma protein, serves essential functions in maintaining plasma pressure, nutritional equilibrium, and chemical transport. Its concentration in bodily fluids correlates closely with overall health, with elevated levels in urine signaling potential liver or renal disorders. Concerns arise regarding human exposure to BSA through consumption of bovine-derived products like meat and milk, as it is linked to various diseases including insulin-dependent diabetes mellitus, membranous nephropathy, and bovine spongiform encephalopathy (BSE). Conversely, reductions in blood bovine serum albumin (BSA) in cattle can also precipitate disease. BSA plays a pivotal role in fetal bovine serum (FBS) used in vaccine production, necessitating its accurate detection for compliance with regulatory standards. Molecularly imprinted polymers (MIPs), inspired by Fischer's lock and key theory, have emerged as promising artificial receptors for protein detection, offering high selectivity and affinity. Their stability, simplicity in preparation, and adaptability for diverse applications, including vaccine production and clinical diagnostics, position MIPs as valuable tools in biomedical and laboratory settings, facilitating sensitive assays and detection methodologies [180–187].

Proteins, integral to all living organisms, fulfill essential physiological functions, yet their quantification poses

challenges due to susceptibility to structural alterations under harsh conditions, making protein detection particularly demanding with stringent environmental controls and minimal detection concentrations crucial for various biomedical and clinical applications, driving research towards simple, label-free, environmentally friendly, and highly sensitive nano- and micrometer-scale sensing devices capable of detecting analytes at low concentrations with high specificity to achieve precise measurements and address the key goal of accurate protein sensing [188–193].

Human serum albumin (HSA) and BSA are extensively studied major serum proteins, with HSA constituting about 60% of human blood serum, playing a multifunctional role in transporting various substances and influencing their solubility and distribution in the body through its heart-shaped globular structure containing three main domains and two binding sites, while BSA, sharing structural similarities with HSA, is characterized by its acidic nature and negatively charged hydrophobic cavities, and both albumins have applications in biological and medical fields, including the preparation of albumin nanoparticles such as Abraxane for treating metastatic breast cancer [194–198].

Various traditional colorimetric investigations, including Bradford and Lowry assays, bicinchoninic acid, ultraviolet–visible absorption measurement, alongside specific procedures like chromatographic methods, Western blot analysis, and enzyme-linked immunosorbent assay, are employed for the detection and quantification of BSA, although these methods often have limitations such as complexity, narrow linear range, and limited sensitivity, leading to a growing interest in developing alternative techniques utilizing nanoscale materials combined with spectroscopic methods for sensitive and quantitative BSA analysis [199–201].

Molecular imprinting technology (MIT), recognized for its utility in crafting selective artificial receptors for sensing target molecules, operates by creating specific cavities within a polymer matrix through a three-step process involving arrangement of functional monomers around the template molecule, polymerization in the presence of cross-linker monomers, and template removal; MIT employs two main strategies, covalent and non-covalent imprinting, with covalent imprinting forming well-designed cavities but requiring harsh conditions for template removal, while non-covalent imprinting offers a milder approach but may exhibit potential reversibility in complex formation, prompting the introduction of semi-covalent imprinting, which combines the advantages of both methods, with an effective modification employing a “sacrificial spacer” to enhance precision in molecular imprinting [202,203]. Despite advancements in molecular imprinting, persistent challenges exist in developing artificial materials for detecting biological macromolecules like BSA, primarily due to their molecular instability, conformational flexibility, large size, diverse functional groups, and the need for mild imprinting conditions associated with proteins, which often require aqueous environments for stability, prompting the exploration of alternative techniques such as surface molecular imprinting technology (SMIT), epitope-mediated imprinting, micro-contact imprinting, imprinted ionic liquids, and imprinted hydrogels to improve the efficiency of prepared MIPs for selective BSA detection [204].

SMIT has been employed to develop BSA-MIPs, offering benefits such as homogeneous distribution of binding sites, improved mass transfer, and enhanced adsorption dependency by creating molecular recognition sites on the support substrate surface, notably making the created molecular recognition sites readily accessible to protein molecules; the integration of magnetic nanoparticles (MNPs) with MIPs results in magnetic molecularly imprinted polymers (MMIPs), facilitating efficient and rapid separation processes, as demonstrated by studies utilizing chitosan-coated MNPs, surface-imprinted magnetic polymers, and atomic transfer radical polymerization (ATRP)-synthesized BSA imprinted polymers, showcasing improved recognition properties and selective adsorption for BSA compared to non-imprinted polymers; furthermore, various innovative approaches involving quantum dots, chitosan, multi-walled carbon nanotubes, surface imprinted tubular carbon nanofibers, and silica beads have been explored for BSA recognition and separation, highlighting advancements in biosensing and chromatography techniques for protein detection and purification [205–217].

BSA-epitope-based MIPs (EMIPs) utilize small sections of the BSA protein, known as epitopes, as substitute templates to overcome the challenge of imprinting large molecules. Nishino et al. expanded this approach by imprinting epitopes derived from BSA, cytochrome c (cyt c), and alcohol dehydrogenase (ADH) C-terminus domains on silica surfaces or clean glass, resulting in EMIPs with reasonable affinity. A novel EMIPs system for BSA recognition was developed using a synthetic peptide from the C-terminus of BSA, exhibiting high specificity and direct fluorescence intensity measurement. EMIPs-coated cadmium telluride quantum dots nanospheres demonstrated enhanced adsorption capacity and imprinting factor, effectively separating BSA from bovine blood samples. Microcontact imprinting, ideal for macromolecule recognition through surface coating, involves forming a protein stamp on a glass surface and then imprinting it onto a monomer-coated substrate for ultraviolet polymerization, resulting in specific recognition sites for the protein. Thin surface-imprinted polymer films based on 2-(dimethylamino) ethyl methacrylate as the functional monomer exhibited increased BSA recognition and selective recognition relative to competing proteins, showing promise for various bioassay and biosensor applications [203,218–221].

Ionic liquids (ILs) have enabled the development of sensitive electrochemical sensors for detecting BSA, with chitosan/IL–graphene modified electrodes and MIPs showing promising results. Molecularly imprinted hydrogels, responsive to environmental stimuli, offer a dynamic platform for selective protein recognition, particularly with temperature-sensitive components. Utilizing sodium alginate (NaA) and thermo-sensitive polymers, high-toughness hydrogel films were prepared, exhibiting enhanced BSA adsorption capabilities. Additionally, surface-imprinted materials incorporating hollow magnetite microspheres demonstrated specific BSA recognition, highlighting their potential for biosseparation and biosensor development [222–232].

2.3. Lignin

Lignin, comprising up to 35% of lignocellulosic biomass, is the second most abundant biopolymer, after cellulose (Figure 19).

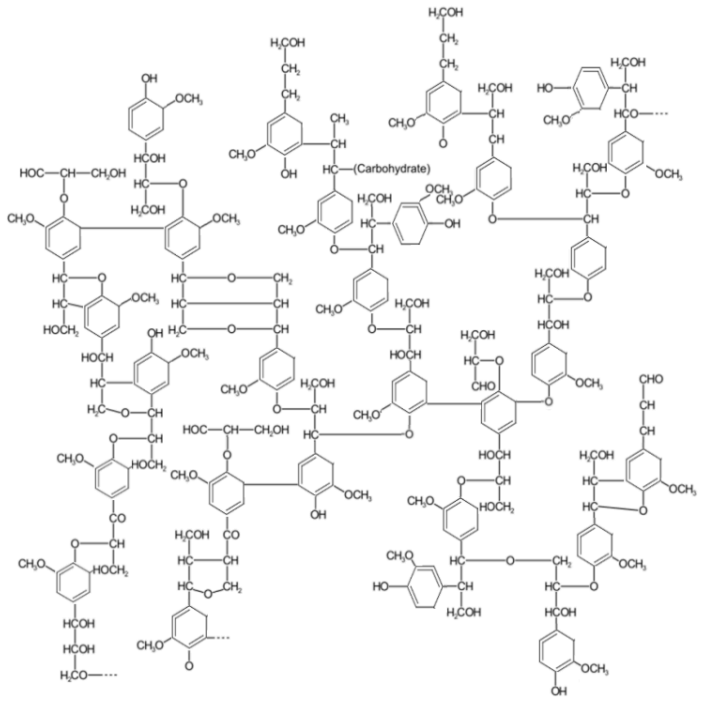

Figure 19. Chemical structure of lignin.

Its attributes, including biocompatibility, high carbon content, increased adhesive properties, superior thermal stability, biodegradability, cost-effective production, and non-toxicity, render lignin and its composite materials significant for

biomedical implementations. These applications encompass drug delivery carriers, tissue engineering scaffolds, and wound dressing materials, showcasing lignin's potential in diverse biomedical contexts [233–236].

3. Chemical Modifications of Biopolymers

3.1. Cross-Linking

Cross-linking involves the formation of a network in polymer solutions, enhancing mechanical features and viscoelastic behavior. The unstable bonds, produced through physical or chemical cross-linking, can be disintegrated under physiological conditions. Chemical cross-linking, utilizing covalent agents, enhances mechanical stability but may impact polymer integrity and increase toxicity. The ionic gelation procedure involves interactions between polymers with opposite charges and cross-linking agents with complementary charges. In contrast, polyelectrolyte complexation relies only on electrostatic interactions among positively or negatively charged polyions, without the use of cross-linking agents. Innovative dual cross-linking combines both physical and chemical factors, reducing toxicity and improving stability. Interfacial cross-linking allows nanocapsule preparation without additional agents. Alginate readily cross-links via ionic interactions with calcium ions, forming gels employed for encapsulating bioactive molecules. Cationic polysaccharides like chitosan can be cross-linked with glycerol-phosphate disodium salt [237–249].

3.2. Functionalization and Conjugation

Biodegradable polymers, especially polysaccharides, possess diverse functional groups that can undergo covalent modifications with hydrophobic or hydrophilic substances, enhancing their suitability for biomedical approaches. Chemical alterations, such as PEGylation, polymer chain grafting, and polysaccharide-drug conjugation, can modify the physical properties and solution behavior of polysaccharides for specific utilization. Ionic liquids serve as effective solvents for water-insoluble polysaccharides, and the solubility of charged polysaccharides, such as chitosan or alginic acids can be manipulated by adjusting the solution's pH. Various strategies, including etherification, esterification, and enzymatic modifications, yield polysaccharide derivatives with improved biological, chemical, and physical features. Reactive functional groups introduced by phosphorylation, sulfation, acylation, and alkylation significantly impact inherent hallmarks. Additionally, enzymatic modifications, involving glycosylation, ester emergence, amidation, oxidation, and molecular weight depletion, have been designed for diverse pharmaceutical employments [12,250–255].

3.3. Interpenetrating Polymer Networks

Interpenetrating polymer networks (IPNs) consist of two or more incompatible polymers synthesized together, with one system polymerized in the presence of another. For instance, an aqueous solution containing a water-soluble polymer and a vinyl/acryl monomer can be polymerized to form intertwined polymer chains. Unlike polymer blends, IPNs expand but do not dissolve in solvents, reducing flow/creep conduct. They rely on physical forces like electrostatic and hydrogen bonding, making them suitable as vehicles for DDS and scaffolds for tissue engineering. IPN hydrogels are innovative biomaterials for drug delivery, with polysaccharide based IPNs, particularly using chitosan and alginates, offering unique enlargement ability, mechanical strength and specificity [256–274].

3.4. Graft Copolymers

Grafting serves as a versatile strategy to enhance compatibility between synthetic and natural polymers, particularly in the chemical alteration of polysaccharides. Various polysaccharides, like cellulose, hyaluronic acid, chitosan and starch, have been successfully employed in grafting processes. The "grafting through/on/from" approaches enable the incorporation of hydrophilic or hydrophobic polymeric moieties onto the polysaccharide backbone, with microwave

irradiation emerging as an efficient method, offering improved attributes in terms of flame resistance, water repellence, thermal stability, and opposition to acid–base aggression. Polysaccharide-based graft copolymers, especially those with amphiphilic characteristics, find relevance in the biomedical domain, showcasing potential as biomaterials or conveyances for DDS [275–290].

3.5. Block Copolymers

Biodegradable block copolymers have garnered significant attention in medical and pharmaceutical studies on account of their customizable biodegradability, biocompatibility, and self-assembly characteristics. These polymers serve as effective vehicles for DDS, forming drug-loaded nanoparticles that undergo degradation in biological circumstances and are subsequently evacuated via the renal system. The precise control over the structure of block copolymers, achieved through advancements in polymerization techniques like atom transfer radical polymerization (ATRP) and reversible addition–fragmentation chain-transfer (RAFT) processes, coupled with modern nanoaggregate interpretation methods, has heightened their relevance in various biomedical purposes [291–293].

3.6. Polyion Complexes

Polyelectrolytes, water-soluble charged polymers, undergo dissociation in aqueous solutions, resulting in the formation of a macroion and counterion. The conduct of polyelectrolytes in solution is significantly affected by the existence of salts, as well as pH and temperature variations. Natural polyelectrolytes find extensive applications in various industries. Charged polymers interrelate with oppositely charged ones, forming soluble polyion complexes (PICs) or insoluble coacervates, which have biological significance. Examples include PICs of oppositely charged polysaccharides like chitosan and alginates, and those involving charged proteins/polysaccharides and oppositely charged little molecules or polymers. Dilute solutions of polyelectrolytes, when mixed with oppositely charged substances, can generate the spontaneous formation of a new phase via powerful electrostatic interactions. Nevertheless, a comprehensive interpretation of the physical status (solid/liquid-like) is essential. The presence of supporting electrolytes significantly affects the origination and qualities of these complexes [291,294–300].

3.7. Polyblends and Bio/Nanocomposites

Polyblends are combinations of polymers with inorganic materials like metal/metal oxide nanoparticles, clays, and silica, creating bio/nanocomposite materials with enhanced characteristics. When preparing polyblend nanofibers from natural and synthetic polymers, they serve as biomimetic nanostructures for biomedical approaches, offering mechanical strength and biological cues for DDS and tissue engineering. Biocomposites, combining various polymers, demonstrate exceptional attributes suitable for pharmaceutical and biomedical implementation. Nanostructured polymer composites, particularly those incorporating polysaccharides, hold significant technological relevance in the development of novel biomaterials with higher performance and adequate biological function [301–312].

4. Pharmaceutical and Biomedical Applications of Biopolymers

The applications of biomass polymers are economically, socially, and environmentally sustainable, finding utility across various domains. Ongoing extensive research further explores their potential in diverse fields. Their inherent biocompatibility, biodegradability, and minimal immune response induction position them as promising candidates for applications in tissue engineering, as well as in drug and gene delivery systems [313].

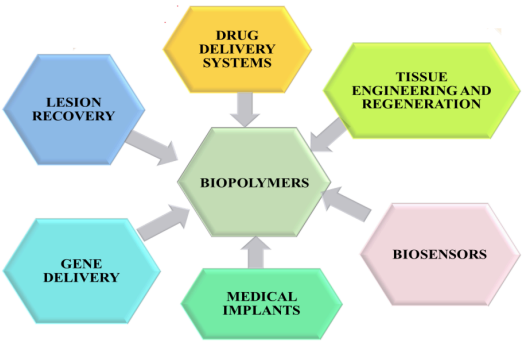

Figure 20. Schematic representation of the main biomedical applications.

Current advancements in biopolymers have garnered attention across numerous domains due to their improved features and facile commercialization. Typical biopolymers, including elastin, silk, chitosan, keratin, and collagen, have been strategically mixed with synthetic polymers to amplify their actions as composites. The escalating demand for biodegradable natural polymers is particularly notable in the production of packaging film materials, with applications spanning medical, pharmaceutical, and food industries. The contemporary trend emphasizes a burgeoning focus on biopolymers, especially the synergistic blend of synthetic and natural polymers in composite materials. In the medical and pharmaceutical sectors, these polymers play pivotal roles in gene therapy, bone tissue engineering, and cell-based transplantation, contributing to the development of products such as implantable medical devices, three-dimensional scaffolds, artificial skin, wound dressing materials, and dialysis systems [49,57,314,315].

4.1. Drug Delivery Systems

Drug delivery systems (DDS) encompass the conveyance of natural compounds, genes, or synthetic pharmaceutical drugs to the accurate location without inducing negative effects on biological systems [38].

DDS necessitate comprehensive considerations, including high drug loading, cellular uptake, programmed target specificity, clearance, metabolism, pharmacokinetics, toxicity, and excretion. An ideal system should enhance drug efficiency and enable controlled release from a biocompatible nanocarrier, promoting patient compliance. Passive accumulation at the target site, facilitated by the enhanced permeability and retention (EPR) effect, contributes significantly to DDS efficacy. Traditional DDS, characterized by immediate release and potential toxicity, often require frequent administration for therapeutic levels. To address these limitations and enhance pharmacokinetics, second and third-generation DDS explore modified particle surfaces for improved stealth effects, utilizing hydrophilic blocks like PEG to reduce plasma protein adsorption and rapid clearance. Stealth effects, influenced by factors such as size, shape, and core composition, increase blood circulation and accumulation in highly vascularized areas. Despite these advancements, clinical translation of formulations based on biodegradable polymers remains limited [316,317].

Biopolymers have become integral in pharmaceutical applications, serving as accurate DDS with diverse structures for various physiological and medical needs. Structural, protective, and reserve polysaccharides, exhibit capability in constructing conjugates with lipids and proteins, facilitating drug transport. Common biopolymers like chitosan, fibroin, starch, gelatin, cellulose, and collagen are harnessed for drug delivery through suspensions, employing methods such as freeze drying, microemulsion, electrospraying, and supercritical fluid extraction. Biopolymer composites, labeled as excipient materials, are gaining attention in the pharmaceutical industry for drug delivery due to their renewable character, biodegradability, endurance, and reduced toxicity. The focus on targeted drug delivery systems (TDDS) using polymeric DDS is increasing, exploring avenues like elastin-like polypeptides (ELPs) for intra-articular delivery and albumin microspheres for controlled drug release. Bacterial nanocellulose (BNC) shows promise in delivering proteins with maintained integrity and activity, emphasizing controlled release kinetics, biocompatibility, and hydrophilicity. The

abundance of naturally available biopolymers facilitates the cost-effective development of hydrogels and nanogels through various crosslinking polymerization techniques, offering potential applications in cancer treatment [39, 318–321]. Various nanomaterials, encompassing organic polymers and inorganic compounds, have been explored as transportation for DDS, including liposomes, dendrimers, polymersomes, nanoparticles, nanogels, polymer micelles, nanofibers, nanocapsules, and nanocomposites. These nanocarriers play a crucial role in drug delivery, but precise adjustments in shape, size, porosity, polydispersity, and also in surface charge and characteristics are necessary for their specific applications [322–332]. Drug loading and encapsulation efficiencies (DLE and DEE) are crucial parameters in the representation of DDS. The encapsulation efficiency, drug release profile, and overall performance of polymeric nanoparticles or self-assembled nanoaggregates are influenced by factors like shape, size, surface features, charge, stimuli responsiveness, and polymer biodegradation kinetics. Optimization of these parameters is essential for achieving regulated drug delivery to target sites with optimal doses. Experimental research and theoretical modeling are conducted to configure nanoparticles with specific control over drug discharge, offering expansive and promising applications in clinical medicine. An optimal nanoparticle-based delivery system should exhibit elevated loading capacity, accomplished through drug incorporation during nanoparticle preparation or post-incubation diffusion. Understanding drug release mechanisms, influenced by desorption, diffusion, and erosion of the nanoparticle matrix, is vital for tailoring drug delivery kinetics. The kinetics of drug delivery are influenced by the biodegradation, diffusion, solubility, and loading effectiveness of the matrix materials. For biodegradable polymers, drug dissolution, swelling, erosion, and diffusion may happen at the same time, inducing zero-order release kinetics, while nanoparticle size influences the release pattern [343,334]. The regular course of drug administration via oral ingestion faces challenges with hydrophobic drugs exhibiting reduced bioavailability and protein-based drugs being exposed to enzymatic disintegration in the gastrointestinal tract. To address this, innovative DDS are engineered for controlled and targeted release, encapsulating or solubilizing drugs using nanosized elements like inorganic nanoparticles, dendrimers, polymersomes, polymer micelles, liposomes, solid lipid dispersions, and mesoporous materials. Amphiphilic block and graft biomass polymers play a crucial role in these systems, forming nanostructures with enhanced drug-loading ability. Thermo- and pH-responsive polymers are commonly engaged, reacting to the acidic pH of tumor cells and increased concentrations of glutathione triphosphate (GSH), making them suitable for targeted drug delivery. Biomass polymers, through controlled degradation into biocompatible by-products, offer constant discharge at targeted locations within therapeutic concentration ranges. The provocation lies in designing multiple-functionalized DDS to ensure on-request, manageable drug dispensation under various external stimuli [293,335–344].

4.2. Gene Delivery

Gene therapy is a promising approach to address various metabolic, neoplastic, cardiovascular, neurological, and genetic disorders. It utilizes DNA and RNA, therapeutic gene molecules, to modify mutated, absent, or abnormal genes. To overcome challenges like the brittle character of therapeutic genes and biological impediments, non-viral vectors, including lipid-based nano-assemblies and cationic polyelectrolytes, are developed for gene delivery. Polyplexes formed by cationic polyelectrolytes like polyethylene imines and poly(L-lysine) show potential, but careful consideration of polymer design, degradability, and toxicity is crucial. Non-toxic protein-based vectors, such as albumin and gelatin, are widely used due to their biocompatibility and biodegradability. Cationic polysaccharides, such as chitosan, though limited by solubility, are explored, with chemical alterations to enhance gene complexation [345–347].

4.3. Lesion Recovery

Wound healing is an intricate biological and cellular mechanism, including phases of inflammation, hemostasis,

proliferation, and remodeling triggered by tissue severance. Cutaneous injuries create vulnerabilities for pathogenic bacteria, leading to virulence factor production that hinders tissue integrity, often associated with biofilm formation. Various dressings are employed for severe wounds, possessing high absorption capacity, wound visibility, pain-free removal, and non-allergenic properties. Biomass polymers are utilized in wound dressing formulations such as hydrogels, films, hydrocolloids, membranes, and foams. Polysaccharides like hyaluronic acid, cellulose, chitosan, and alginate stand out as adaptable biomacromolecules due to their increased chelation ability, non-toxicity, biodegradability, biocompatibility, multifunctional groups, and simple chemical alteration, making them effective in the management of cutaneous infections [348–360].

4.4. Targeted Diagnosis

Targeted therapy involves the use of ligand-functionalized nanoparticles to accurately recognize receptors overexpressed in malignant tumor cells, enabling tumor-selective DDS. Various ligands, including antibodies, aptamers, transferrin, peptides, and folic acid, have been explored to enhance the specificity of DDS. Nanoparticles derived from biomass polymers, particularly chitosan, show promise in anti-tumor targeting due to their ability to promote cellular uptake and adhesion to mucosal surfaces. This targeted approach aims to improve drug release directly to cancer cells, enhancing therapeutic efficacy [361–367].

4.5. Tissue Engineering and Regeneration

Tissue engineering integrates regulations of engineering and medical sciences to elaborate biological tissue replacements for improving, maintaining, or restoring function. The engineered tissue can be developed *in vivo* or *in vitro* and transplanted, serving diagnostic purposes as well. Scaffolds, valuable in this particular field, rely on biodegradable polymers, such as biomass polymers, from natural sources. Perfectly, scaffolds should be mechanically powerful, biocompatible, biodegradable without toxic byproducts, possess an appropriate surface morphology for cell interaction, and sustain cell attachment, proliferation, and differentiation. Proteins like silk, gelatin, and collagen, along with polysaccharides like chitosan, hyaluronic acid, and alginate, are universal natural scaffold materials. Nevertheless, due to the intricate structure of biomass polymers and concerns like immunogenicity, synthetic polymers like polyurethanes, polyphosphazenes, polyanhydrides, and polyesters gain significance. In bone tissue engineering, the challenge lies in regenerating bone deficiencies caused by tumors, fractures, or trauma, where polymers, ceramic materials, and metals serve as scaffolds to encourage new tissue formation. Inorganic materials like titanium and steel and degradable biomass polymers show promise, with hydroxyalkanoate composites, acrylate polymers polyblends, and magnesium-based compounds demonstrating excellent mechanical and cell adhesion features for orthopedic applications [368–379].

4.6. Biosensors

Advanced diagnostic instruments often rely on automated analyzers, but their maintenance is both expensive and time-consuming. The demand for more accelerated, compact, and cost-effective devices in laboratory testing has led to the rise of biosensors. These diagnostic tools recognize precise biochemicals by utilizing immobilized biomolecules, such as receptors, antibodies, or enzymes, on electrodes, offering elevated specificity, maneuverability, utilizer accessibility, and rapid response duration. Biosensors, incorporating biological constituents and transducers, can monitor medical conditions through the examination of clinical samples or real-time physiological modifications inside the human organism. Chitosan-based films have been instrumental in enhancing the sensitivity of biosensors, particularly in applications like cholesterol detection [380–384].

4.7. Medical Implants

Various biopolymers, like chitosan and PLA, have found extensive use in pharmaceutical purposes, due to their biocompatibility and biodegradability when employed as implantable medical devices. For example, chitosan serves as implants in surgery (e.g., nerve regeneration), cardiology (e.g., heart valves), and ophthalmology (e.g., contact lenses). Composites of chitosan are applied for tissue regeneration, bioartificial livers, and bone scaffolds, whereas hyaluronic acid implants aid in tissue maturation in otolaryngology. Gelatin serves multiple purposes, such as three-dimensional biomatrix in dermatology, bone replacement in orthopedics, and graft in cardiology. Collagen, a ubiquitous biopolymer in mammals, is utilized as cardiovascular implants, bone marrow, and bone scaffolds, while PHAs are employed in nerve, vascular, and esophageal implants. Moreover, polyhydroxybutyrate (PHB) serves as cell culture scaffolds and surgical implants. Biopolymers derived from biomass are designed via techniques such as leaching, freeze drying, three-dimensional bioprinting, electrospinning, and casting, serving as medical implants, such as barrier membranes and stents, as well as carriers in cell, gene, drug, and growth factor delivery systems [41,315,385,386].

5. Applications of Biopolymers in Food Industry

Currently, there has been a surge in the global food industry, with consumers increasingly favoring naturally derived nutrition for health benefits. This has led to a demand for degradable or edible food packaging materials and active, smart packaging systems to detect foodborne pathogens, particularly in ready-to-eat food products. Consequently, researchers have intensified efforts to produce biopolymers using novel techniques or improving traditional methods. Incorporating biopolymers such as pullulan, modified starch, alginate, and gelatin into food products helps preserve physicochemical features like quality, stability, and shelf life, while offering unique characteristics, including film-forming capacity, antimicrobial properties, water retention, biodegradability, and oxygen impermeability. Biopolymers serve various functions in the food industry, acting as gelling agents, colorants, texturizers, fillers, seasonings, and thickeners, with protein-based biopolymers particularly flexible and surface-active, suitable for distributing nutraceuticals. Nevertheless, certain biomass polymers require thermal and mechanical attributes, demanding chemical alteration to enhance appropriate characteristics. Modern advancements involve increasing nutritional quality through the inclusion of additives via micro/nanoencapsulation, employing bioactive polymers as drug vehicles, while scientists concentrate on ingenious fabrication and purification approaches to cost-efficiently commercialize biopolymers from agricultural residues [387–390].

6. Conclusions and Perspectives

Biomass polymers, originating from natural sources, offer a diverse range of compounds with significant potential in various pharmaceutical and biomedical applications. Through techniques such as cross-linking, functionalization, conjugation, IPNs, polyblends, nanocomposites, and PICs, along with chemical alterations leading to amphiphilic copolymers and stimuli-receptive block and graft copolymers, these compounds exhibit unparalleled properties. Their applications span drug and gene delivery systems, lesion therapy, focused diagnostics, biomedical sensors, and also tissue engineering and regeneration. This paper emphasizes the characterization of biomass polymers and their versatile derivatization for promising biomedical and pharmaceutical applications, addressing especially DDS. Nonetheless, in the matter of DDS, focusing on challenges related to durable stability, human cell interaction, and *in vivo* bioactivity is crucial for their extensive use in practical pharmaceutical applications. For developing cost-efficient and customized DDS, collaborative efforts among scientists in the fields of physics, engineering, biology, and chemistry are essential.

Biopolymers are recently being engineered into various nanomaterials such as injectable hydrogels, cross-linked

hydrogels, nanoemulsions, nanogels, and nanoparticles, serving as distribution systems in pharmaceutical, biomedical and food employments, aiming to increase nutritional values and extend shelf life, including the production of moderate sweeteners and low-calorie products for diabetic individuals. Smart biopolymers exhibit significant potential in biomedical industry, due to their shape-shifting capacity in response to external stimuli, temperature, and pH, offering facile shaping, strength, flexibility, non-thrombogenicity, and biocompatibility, thus finding applications in drug, protein, and gene transportation, as well as tissue engineering, encouraging interdisciplinary research in chemistry and biology. Nanofibers generated via electrospinning of biopolymers serve multiple functions as DDS, catalytic dressings, and filters, aiding in skin regeneration, decreasing polyphenol oxidase activity to avoid food depreciation, and advancing antimicrobial packaging materials to mitigate disease transmission and infection dissemination. Supramolecular polymers, formed through non-covalent interactions of molecular building blocks, are employed in tissue engineering and regenerative medicine, featuring bioactive peptide sequences and enzymatic biodegradability into natural amino acids, though they require design guidelines, urging further research to create functional biomaterials by integrating macromolecules and supramolecular compounds to combat diseases effectively. Therefore, biopolymers are tailored to exhibit exceptional benefits in DDS, biomedical agents, lesion recovery, and food packaging/processing [389,391–393].

Modern advancements in sustainable energy and environmental conservation have spurred the quest for green materials, notably the discovery and synthesis of biopolymers and their composites, poised to supplant synthetic polymers owing to their remarkable features. Recognized for their biodegradability, non-toxicity, and biocompatibility, biopolymers offer an eco-friendly option in the burgeoning market. Characterization methods, including diffraction, spectroscopic, and microscopic studies, have been instrumental in interpreting the structural integrity of biopolymers, affirming their efficacy across various sectors. From DDS to implantable devices, wound healing materials, tissue engineering scaffolds, and food processing additives, biopolymers exhibit versatile applications, boasting extraordinary optical, mechanical, thermal, and physical attributes, essential for pharmaceutical industry.

Despite the promising market for biopolymer products, challenges persist, notably the expensive fabrication prompting research into cost-effective biomass substrates and the imperative to enhance biopolymer performance to rival synthetic polymers. Embracing biopolymers in industries through strategic alterations or mixtures holds promise for their widespread adoption and commercialization, heralding a pivotal shift away from synthetic polymers toward eco-friendly alternatives. In conclusion, biopolymers play a crucial part in advancing sustainable practices, underscoring the need for intensified efforts to eliminate synthetic polymers entirely.

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References

1. George, A.; Sanjay, M.R.; Srisuk, R.; Parameswaranpillai, J.; Siengchin, S.; A comprehensive review on chemical properties and applications of biopolymers and their composites, *Int. J. Biol. Macromol*. **2020**, *154*: 329–338.
2. Lopez, A.S.; Ramos, M.P.; Herrero, R.; Vilarino, J.M.L; Synthesis of magnetic green nanoparticle–molecular imprinted polymers with emerging contaminants templates, *J. Environ. Chem. Eng*. **2020**, *8*:103889.
3. Hassan, M.; Bai, J.; Dou, D.-Q.; Biopolymers; definition, classification and applications, *Egypt. J. Chem*. **2019**, *62*.
4. Rao, M.G.; Bharathi, P.; Akila, R.M.; A comprehensive review on biopolymers, *Sci. Rev. Chem. Commun*. **2014**, *4*: 61–68.
5. Merlettini, A.; Micro-nanostructured polymeric materials with specific functionalities for advanced biomedical applications. Ph.D. Thesis, Università di Bologna, Bologna, Italy, **2019**.
6. Prajapati, S.K.; Jain, A.; Jain, A.; Jain, S. Biodegradable polymers and constructs A novel approach in drug delivery. *Eur. Polym. J*. **2019**, *120*: 109191–109206.
7. Pushpamalar, J.; Veeramachineni, A.K.; Owh, C.; Loh, X.J. Biodegradable polysaccharides for controlled drug delivery. *ChemPlusChem* **2016**, *81*:504–514.
8. Song, R.; Murphy, M.; Li, C.; Ting, K.; Soo, C.; Zheng, Z. Current development of biodegradable polymeric materials for biomedical applications. *Drug Des. Devel Ther*. **2018**, *12*:3117–3145.
9. Rong, S.Y.; Mubarak, N.M.; Tanjung, F.A.; Structure-property relationship of cellulose nanowhiskers reinforced chitosan biocomposite films, *J. Environ. Chem. Eng*. **2017**, *5*: 6132–6136.
10. Aravamudhan, A.; Ramos, D.M.; Nada, A.A.; Kumbar, S.G.; Natural polymers, in: Nature and Synthetic Biomedical Polymers, Elsevier, **2014**, pp. 67–89, https:// doi.org/10.1016/B978-0-12-396983-5.00004-1.
11. Soltani, R.; Pishnamazi, M.; Pelalak, R.; Rezakazemi, M.; Marjani, A.; et.al., Preparation of COOH-KCC-1/polyamide 6 composite by in situ ring-opening polymerization: synthesis, characterization, and Cd (II) adsorption study, *J. Environ. Chem. Eng*. **2020**:104683.
12. Liu, X.; Holzwarth, J.; Ma, P.X. Functionalized synthetic biodegradable polymer scaffolds for tissue engineering. *Macromol. Biosci*. **2012**, *12*:911–919.
13. Samrot, A.V.; Sean, T.C.; Kudaiyappan, T.; Bisyarah, U.; et.al. Production characterization and application of nanocarriers made of polysaccharides proteins bio polyesters and other biopolymers A review. *Int. J. Biol. Macromol*. **2020**, *165*:3088–3105.
14. Mokhtarzadeh, A.; Alibakhshi, A.; Yaghoobi, H.; Hashemi, M.; Hejazi, M.; Ramezani, M. Recent advances on biocompatible and biodegradable nanoparticles as gene carriers. *Expert Opin. Biol. Ther*. **2016**, *16*:771–785.
15. Manavitehrani, I.; Fathi, A.; Badr, H.; Daly, S.; Negahi Shirazi, A.; Dehghani, F. Biomedical applications of biodegradable polyesters. *Polymers* **2016**, 8:20.
16. Tu, Y.; Peng, F.; André, A.A.; Men, Y.; Srinivas, M.; Wilson, D.A. Biodegradable hybrid stomatocyte nanomotors for drug delivery. *ACS Nano* **2017**, *11*:1957–1963.
17. Ulery, B.D.; Nair, L.S.; Laurencin, C.T. Biomedical applications of biodegradable polymers. *J. Polym. Sci. Part. B Polym. Phys*. **2011**, *49*:832–864.
18. Chen, C.K.; Huang, P.K.; Law, W.C.; Chu, C.H.; Chen, N.T.; Lo, L.W. Biodegradable polymers for gene delivery applications. *Int. J. Nanomed*. **2020**, *15*:2131–2150.

19. Ilyas, R.A.; Sapuan, S.M.; Kadier, A.; Krishnan, S.; et.al. Mechanical testing of sugar palm fiber reinforced sugar palm biopolymer composites, in: Advanced Processing, Properties, and Applications of Starch and Other Bio-Based Polymers, Elsevier, **2020**, pp. 89–110.
20. Abidi, N.; Cabrales, L.; Haigler, C.H.; Changes in the cell wall and cellulose content of developing cotton fibers investigated by FTIR spectroscopy, *Carbohydr. Polym*. **2014**, *100*:9–16.
21. Ansari, M.; Alam, A.; Bera, R.; Hassan, A.; Goswami, S.; Das, N.; Synthesis, characterization and adsorption studies of a novel triptycene based hydroxyl azo- nanoporous polymer for environmental remediation, *J. Environ. Chem. Eng*. **2020**, *8*:103558.
22. Eltz, F.Z.; Vebber, M.C.; Aguzzoli, C.; Machado, G.; da Silva Crespo, J.; Giovanela, M.; Preparation, characterization and application of polymeric thin films containing silver and copper nanoparticles with bactericidal activity, *J. Environ. Chem. Eng*. **2020**, *8*:103745.
23. Mohammed, L.; Ansari, M.N.M.; Pua, G.; Jawaid, M.; Islam, M.S.; A review on natural fiber reinforced polymer composite and its applications, *Int. J. Polym. Sci*. **2015**, *2015*:1–15.
24. Lodhi, G.; Kim, Y.-S.; Hwang, J.-W.; Kim, S.-K.; Jeon, Y.-J.; et.al.; Chitooligosaccharide and its derivatives: preparation and biological applications, *Biomed Res. Int.* **2014**, 2014:1–13.
25. Ponmurugan, K.; Al-Dhabi, N.A.; Maran, J.P.; Karthikeyan, K.; et.al.; Ultrasound assisted pectic polysaccharide extraction and its characterization from waste heads of *Helianthus annus*, *Carbohydr. Polym*. **2017**, *173*:707–713.
26. Maran, J.P.; Priya, B.; Al-Dhabi, N.A.; Ponmurugan, K.; Moorthy, I.G.; Sivarajasekar, N.; Ultrasound assisted citric acid mediated pectin extraction from industrial waste of *Musa balbisiana*, *Ultrason. Sonochem*. **2017**, *35*:204–209.
27. Bajaj, I.; Singhal, R.; Poly (glutamic acid) - an emerging biopolymer of commercial interest, *Bioresour. Technol.* **2011**, *102*:5551–5561.
28. Udayakumar, G.P.; Kirthikaa, G.B.; Muthusamy, S.; Ramakrishnan, B.; Sivarajasekar, N.; Comparison and evaluation of electrospun nanofiber membrane for the clarification of grape juice, in: Sustainable Development in Energy and Environment, Springer, **2020**, pp. 77–92, https://doi.org/10.1007/978-981-15- 4638-9_7.
29. Al Battashi, H;. Al-Kindi, S.; Gupta, V.K.; Sivakumar, N.; Polyhydroxyalkanoate (PHA) production using volatile fatty acids derived from the anaerobic digestion of waste paper, *J. Polym. Environ*. **2020**, *29*(1):1-10.
30. Amini, M.; Yousefi-Massumabad, H.; Younesi, H.; Abyar, H.; Bahramifar, N.; Production of the polyhydroxyalkanoate biopolymer by Cupriavidus necator using beer brewery wastewater containing maltose as a primary carbon source, *J. Environ. Chem. Eng*. **2020**, *8*:103588.
31. Al-Battashi, H.; Annamalai, N.; Al-Kindi, S.; Nair, A.S.; Al-Bahry, S.; et.al.; Production of bioplastic (poly-3-hydroxybutyrate) using waste paper as a feedstock: optimization of enzymatic hydrolysis and fermentation employing *Burkholderia sacchari, J. Clean. Prod.* **2019**, *214*:236–247.
32. Annamalai, N.; Sivakumar, N.; Production of polyhydroxybutyrate from wheat bran hydrolysate using Ralstonia eutropha through microbial fermentation, *J. Biotechnol.* **2016**, *237*:13–17.
33. Campos, C.A.; Gerschenson, L.N.; Flores, S.K.; Development of edible films and coatings with antimicrobial activity, *Food Bioprocess Technol*. **2011**, *4*:849–875.
34. Tavassoli-Kafrani, E.; Shekarchizadeh, H.; Masoudpour-Behabadi, M.; Development of edible films and coatings from alginates and carrageenans, *Carbohydr. Polym*. **2016**, *137*:360–374.
35. Dickinson, E.; Biopolymer-based particles as stabilizing agents for emulsions and foams, *Food Hydrocoll*. **2017**, *68:*219–231.

36. Archana, K.; Sivarajasekar, N.; Prasad, N.; Synthesis and characterization of starch nanoparticles from cassava peel, *J. Bioresour. Bioprod*. **2018**, *3*:161–165.
37. Al-Owasi, Y.; Elshafie, A.; Sivakumar, N.; Al-Bahry, S.; Synthesis of pullulan- mediated silver nanoparticles (AgNPs) and their antimicrobial activities, *Sultan Qaboos Univ. J. Sci.* **2020**, *24*:88.
38. Tian, J.; Yang, G.; H. Huang, M. Liu, L. Liu, X. Zhang, Y. Wei, Recent progress and development for the fabrication of antibacterial materials through mussel- inspired chemistry, *J. Environ. Chem. Eng*. **2020**, *8*:104383.
39. Jacob, J.; Haponiuk, J.T.; Thomas, S.; Gopi, S.; Biopolymer based nanomaterials in drug delivery systems: a review, *Mater. Today Chem*. **2018**, *9*:43–55.
40. Madikizela, L.M.; Chimuka, L.; Synthesis, adsorption and selectivity studies of a polymer imprinted with naproxen, ibuprofen and diclofenac, *J. Environ. Chem. Eng*. **2016**, *4*: 4029–4037.
41. Bhatt, R.; Jaffe, M.; Biopolymers in medical implants, in: Excipient Applications in Formulation Design and Drug Delivery, Springer, **2015**, pp. 311–348.
42. Okamoto, M.; John, B.; Synthetic biopolymer nanocomposites for tissue engineering scaffolds, *Prog. Polym. Sci.* **2013**,*38*:1487–1503.
43. Demir, A.; Cevher, E.; Biopolymers as wound healing materials: challenges and new strategies in Biomaterials Applications for Nanomedicine, Prof.Rosario Pignatello (Ed.), InTech **2011,** https://doi.org/10.5772/ 25177, ISBN: 978-953-307-
661-4,
44. Bano, I.; Arshad, M.; Yasin, T.; Ghauri, M.A.; Younus, M.; Chitosan: a potential biopolymer for wound management, *Int. J. Biol. Macromol.* **2017**, *102*:380–383.
45. Pereira, F.A.R.; Sousa, K.S.; Cavalcanti, G.R.S.; França, D.B.; et.al.; Green biosorbents based on chitosan-montmorillonite beads for anionic dye removal, *J. Environ. Chem. Eng.* **2017**, *5*:3309–3318.
46. Zhang, Y.; Aguila, B.; Ma, S.; Zhang, Q.; Comparison of the use of functional porous organic polymer (POP) and natural material zeolite for nitrogen removal and recovery from source-separated urine, *J. Environ. Chem. Eng*. **2020**, *8*:104296.
47. To, V.H.P.; Nguyen, T.V.; Vigneswaran, S.; Bustamante, H.; Higgins, M.; van Rys, D.; Novel methodologies for determining a suitable polymer for effective sludge dewatering, *J. Environ. Chem. Eng*. **2018**, *6*:4206–4214.
48. Tran, M.L.; Fu, C.-C.; Chiang, L.-Y.; Hsieh, C.-T.; Liu, S.-H.; Juang, R.-S.; Immobilization of TiO_2 and TiO_2-GO hybrids onto the surface of acrylic acid- grafted polymeric membranes for pollutant removal: analysis of photocatalytic activity, *J. Environ. Chem. Eng*. **2020**, 8:104422.
49. Gowthama, P.U.; Subbulakshmi, M.; Bharathi, S.N.; et.al.; Biopolymers and composites: Properties, characterization and their applications in food, medical and pharmaceutical industries, *Journal of Environmental Chemical Engineering,* **2021**, 9(4):105322.
50. Francis, R.; Sasikumar, S.; Gopalan, G.P.; Synthesis, structure, and properties of biopolymers (natural and synthetic), in: Polymer Composite, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany, **2013**, pp. 11–107, https://doi.org/ 10.1002/9783527674220.ch2.
51. Flaris, V.; Singh, G.; Recent developments in biopolymers, *J. Vinyl Addit. Technol*. **2009**, *15*:1–11,
52. Devadas, V.V.; Khoo, K.S.; Chia, W.Y.; Chew, K.W.; et.al.; Algae biopolymer towards sustainable circular economy, *Bioresour. Technol*. **2021**:124702.
53. Sharma, V.; Kundu, P.P.; Addition polymers from natural oils—A review, *Prog. Polym. Sci*. **2006**, *31*:983–1008,
54. Awe, O.W.; Zhao, Y.; Nzihou, A.; Minh, D.P.; Lyczko, N.; A review of biogas utilisation, purification and upgrading technologies, *Waste Biomass Valorization* **2017**, *8*: 267–283.

55. Lelkes, P.I.; Marcinkiewicz, C.; Lazarovici, P.; Baharlou, S.M.; Gerstenhaber, J.A.; et al., Soy-derived bioactive peptides for use in compositions and methods for wound healing, Patent WO/2017/015488
56. Othman, S.H.; Bio-nanocomposite materials for food packaging applications: types of biopolymer and nano-sized filler, *Agric. Agric. Sci. Procedia* **2014**, *2*: 296–303.
57. Chaabouni, E.; Gassara, F.; Brar, S.K.; Biopolymers synthesis and application, in: Biotransformation Waste Biomass into High Value Biochem, Springer, New York, New York, NY, **2014**, pp. 415–443, https://doi.org/10.1007/978-1-4614-8005-1_ 17.
58. Atanase, L.I.; Desbrieres, J.; Riess, G. Micellization of synthetic and polysaccharides-based graft copolymers in aqueous media. *Prog. Polym. Sci*. **2017**, *73*:32–60.
59. Atanase, L.I. ; Micellar drug delivery systems based on natural biopolymers. *Polymers* **2021**, *13*:477.
60. Sakeer, K.; Ispas-Szabo, P.; Benyerbah, N.; Mateescu, M.A. Ampholytic starch excipients for high loaded drug formulations: Mechanistic insights. *Int. J. Pharm*. **2018**, *535*:201–216.
61. Kaur, L.; Singh, J.; Liu, Q. Starch—A potential biomaterial for biomedical applications. in Nanomaterials Nanosystems for Biomedical Applications; Springer: Berlin/Heidelberg, Germany, **2007**; pp. 83–98.
62. Lu, D.; Xiao, C.; Xu, S. Starch-based completely biodegradable polymer materials. *Express Polym. Lett*. **2009**, *3*:366–375.
63. Xiao, H.; Yang, T.; Lin, Q.; Liu, G.-Q.; Zhang, L.; Yu, F.; Chen, Y. Acetylated starch nanocrystals: Preparation and antitumor drug delivery study. *Int. J. Biol. Macromol*. **2016**, *89*:456–464.
64. Chen, F.; Huang, G.; Huang, H. Preparation and application of dextran and its derivatives as carriers. *Int. J. Biol. Macromol*. **2020**, *145*: 827–834.
65. Banerjee, A.; Bandopadhyay, R. Use of dextran nanoparticle: A paradigm shift in bacterial exopolysaccharide based biomedical applications. *Int. J. Biol. Macromol*. **2016**, *87*:295–301.
66. Chenglong, W.; Shuhan, X.; Jiayi, Y.; Wencai, G.; Guoxiong, X.; Hongjing, D. Dextran-based coacervate nanodroplets as potential gene carriers for efficient cancer therapy. *Carbohydr. Polym*. **2020**, *231*:115687–115711.
67. Huang, S.; Huang, G. Design and application of dextran carrier. *J. Drug Deliv. Sci. Technol*. **2020**, *55*:101392–101416.
68. Rakmai, J.; Cheirsilp, B. Continuous production of β-cyclodextrin by cyclodextrin glycosyltransferase immobilized in mixed gel beads: Comparative study in continuous stirred tank reactor and packed bed reactor. *Biochem. Eng. J.* **2016**, *105*:107–113.
69. Mejia-Ariza, R.; Graña-Suárez, L.; Verboom, W.; Huskens, J. Cyclodextrin-based supramolecular nanoparticles for biomedical applications. *J. Mater. Chem. B* **2017**, *5*:36–52.
70. Liu, W.; Liu, R.; Li, Y.; Kang, H.; Shen, D.; Wu, M.; Huang, Y. Self-assembly of ethyl cellulose-graft-polystyrene copolymers in acetone. *Polymer* **2009**, *50*:211–217.
71. Wang, D.; Tan, J.; Kang, H.; Ma, L.; Jin, X.; Liu, R.; Huang, Y. Synthesis, self-assembly and drug release behaviors of pH-responsive copolymers ethyl cellulose-graft-PDEAEMA through ATRP. *Carbohydr. Polym*. **2011**, *84*: 195–202.
72. Kamel, R.; El-Wakil, N.A.; Dufresne, A.; Elkasabgy, N.A. Nanocellulose: from an agricultural waste to a valuable pharmaceutical ingredient. *Int. J. Biol. Macromol*. **2020**, *163*:1579–1590.
73. Merlusca, I.P.; Ibanescu, C.; Tuchilus, C.; Danu, M.; Atanase, L.I.; Popa, I.M. Characterization of neomycin-loaded xanthan-chitosan hydrogels for topical applications. *Cellul. Chem. Technol*. **2019**, *53*:709–719.

74. Rata, D.M.; Cadinoiu, A.N.; Popa, M.; Atanase, L.I.; Daraba, O.M.; Popescu, I.; Romila, L.E.; Ichim, D.L. Biocomposite hydrogels for the treatment of bacterial infections: physicochemical characterization and in vitro assessment. *Pharmaceutics* **2021**, *13*:2079.
75. Zargar, V.; Asghari, M.; Dashti, A. A review on chitin and chitosan polymers: Structure, chemistry, solubility, derivatives, and applications. *ChemBioEng Rev*. **2015**, *2*:204–226.
76. Ahsan, S.M.; Thomas, M.; Reddy, K.K.; Sooraparaju, S.G.; Asthana, A.; Bhatnagar, I. Chitosan as biomaterial in drug delivery and tissue engineering. *Int. J. Biol. Macromol*. **2018**, *110*: 97–109.
77. Paul, P.; Kolesinska, B.; Sujka, W. Chitosan and its derivatives-biomaterials with diverse biological activity for manifold applications. *Mini Rev. Med. Chem*. **2019**, *19*:737–750.
78. Ahmad, S.I.; Ahmad, R.; Khan, M.S.; Kant, R.; Shahid, S.; Gautam, L.; Hasan, G.M.; Hassan, M.I. Chitin and its derivatives: Structural properties and biomedical applications. *Int. J. Biol. Macromol.* **2020**, *164*:526–539.
79. Park, J.H.; Saravanakumar, G.; Kim, K.; Kwon, I.C. Targeted delivery of low molecular drugs using chitosan and its derivatives. *Adv. Drug Deliv. Rev.* **2010**, *62*:28–41.
80. Thakur, V.K.; Thakur, M.K. Recent advances in graft copolymerization and applications of chitosan: A review. *ACS Sustain. Chem. Eng*. **2014**, *2*:2637–2652.
81. Sonia, T.; Sharma, C.P. Chitosan and its derivatives for drug delivery perspective. In Chitosan for Biomaterials; Springer: Berlin/Heidelberg, Germany, **2011**; pp. 23–53.
82. Bernkop-Schnürch, A.; Dünnhaupt, S. Chitosan-based drug delivery systems. *Eur. J. Pharm. Biopharm*. **2012**, *81*:463–469.
83. Garcia-Fuentes, M.; Alonso, M.J. Chitosan-based drug nanocarriers: Where do we stand? *J. Control. Release* **2012**, *161*:496–504.
84. Lee, K.Y.; Mooney, D.J. Alginate: Properties and biomedical applications. *Prog. Polym. Sci.* **2012**, *37*:106–126.
85. Sarei, F.; Dounighi, N.M.; Zolfagharian, H.; Khaki, P.; Bidhendi, S.M. Alginate nanoparticles as a promising adjuvant and vaccine delivery system. *Indian. J. Pharm. Sci*. **2013**, *75*:442–449.
86. Venkatesan, J.; Nithya, R.; Sudha, P.N.; Kim, S.-K. Role of alginate in bone tissue engineering. *Adv. Food Nutr. Res*. **2014**, *73*:45–57.
87. Sun, J.; Tan, H. Alginate-based biomaterials for regenerative medicine applications. *Materials* **2013**, *6*:1285–1309.
88. Sosnik, A. Alginate particles as platform for drug delivery by the oral route: State-of-the-art. *Int. Sch. Res. Not.* **2014**, *2014*:926157.
89. Severino, P.; Oliveira, D.; Chen, M.; Souto, E.B. Advanced applications of alginates in biomedical. In Applications of Advanced Green Materials; Woodhead Publishing: Sawston, UK, **2021**; pp. 321–337.
90. Mollah, M.Z.I.; Zahid, H.M.; Mahal, Z.; Mohammad, R.I.F.; Khandaker, M.U. The usages and potential uses of alginate for healthcare applications. *Front. Mol. Biosci*. **2021**, *8*:719972.
91. Pokusaeva, B.G.; Karlova, S.P.; Nekrasova, D.A.; Zakharova, N.S.; Khramtsova, D.P.; et.al.; Agarose gels with bioresorbable additives: the kinetics of the formation, structure, some properties. *Chem. Eng. Trans*. **2019**, *74*:1171–1176.
92. Salati, M.A.; Khazai, J.; Tahmuri, A.M.; Samadi, A.; Taghizadeh, A.; Taghizadeh, M.; et al. Agarose-based biomaterials: opportunities and challenges in cartilage tissue engineering. *Polymers* **2020**, *12*:1150.
93. Zarrintaj, P.; Manouchehri, S.; Ahmadi, Z.; Saeb, M.R.; Urbanska, A.M.; Kaplan, D.L.; Mozafari, M. Agarose-based biomaterials for tissue engineering. *Carbohydr. Polym*. **2018**, *187*:66–84.
94. López-Marcial, G.R.; Zeng, A.Y.; Osuna, C.; Dennis, J.; García, J.M.; O'Connell, G.D. Agarose-based hydrogels as suitable bioprinting materials for tissue engineering. *ACS Biomater. Sci. Eng*. **2018**, *4*:3610–3616.

95. Liu, J.; Zhan, X.; Wan, J.; Wang, Y.; Wang, C. Review for carrageenan-based pharmaceutical biomaterials: Favourable physical features versus adverse biological effects. *Carbohydr. Polym*. **2015**, *121*:27–36.
96. Yegappan, R.; Selvaprithiviraj, V.; Amirthalingam, S.; Jayakumar, R. Carrageenan based hydrogels for drug delivery, tissue engineering and wound healing. *Carbohydr. Polym*. **2018**, *198*:385–400.
97. Qureshi, D.; Nayak, S.K.; Maji, S.; Kim, D.; Banerjee, I.; Pal, K. Carrageenan: A wonder polymer from marine algae for potential drug delivery applications. *Curr. Pharm. Des*. **2019**, *25*:1172–1186.
98. Rode, M.P.; Batti Angulski, A.B.; Gomes, F.A.; da Silva, M.M.; Jeremias, T.d.S.; de Carvalho, R.G. Carrageenan hydrogel as a scaffold for skin-derived multipotent stromal cells delivery. *J. Biomater. Appl*. **2018**, *33*:422–434.
99. Munarin, F.; Tanzi, M.C.; Petrini, P. Advances in biomedical applications of pectin gels. *Int. J. Biol. Macromol.* **2012**, *51*:681–689.
100. Patel, S.; Goyal, A. Applications of natural polymer gum arabic: A review. *Int. J. Food Prop.* **2015**, *18*:986–998.
101. Alkarib, S.Y.; MohamedElhassan, D.E.; Nur, A.O. Evaluation of gum Arabic as a film coating former for immediate release oral tablet formulation. *World J. Pharm. Pharmaceut Sci*. **2016**, 5:32–41.
102. Butstraen, C.; Salaün, F. Preparation of microcapsules by complex coacervation of gum Arabic and chitosan. *Carbohydr. Polym*. **2014**, *99*:608–616.
103. Li, M.; Li, H.; Li, X.; Zhu, H.; Xu, Z.; Liu, L.; Ma, J.; Zhang, M. A bioinspired alginate-gum arabic hydrogel with micro-/nanoscale structures for controlled drug release in chronic wound healing. *Appl. Mater. Interfaces* **2017**, *9*:22160–22175.
104. Gamal-Eldeen, A.M.; Moustafa, D.; El-Daly, S.M.; El-Hussieny, E.A.; Saleh, S.; et al. Photothermal therapy mediated by gum Arabic-conjugated gold nanoparticles suppresses liver preneoplastic lesions in mice. *J. Photochem. Photobiol. B Biol*. **2016**, *163*:47–56.
105. Sarika, P.; James, N.R.; Kumar, P.A.; Raj, D.K.; Kumary, T. Gum arabic-curcumin conjugate micelles with enhanced loading for curcumin delivery to hepatocarcinoma cells. *Carbohydr. Polym*. **2015**, *134*:167–174.
106. Sarika, P.; Cinthya, K.; Jayakrishnan, A.; Anilkumar, P.; James, N.R. Modified gum arabic cross-linked gelatin scaffold for biomedical applications. *Mater. Sci. Eng*. **2014**, *43*:272–279.
107. Gerola, A.P.; Rubira, A.F.; Muniz, E.C.; Valente, A.J. Gum Arabic: A Remarkable biopolymer for food and biomedical applications. in Engineering Technology and Industrial Chemistry with Applications; Apple Academic Press: New York, NY, USA, **2018**; pp. 281–312. ISBN 9781315100449.
108. Dodi, G.; Pala, A.; Barbu, E.; Peptanariu, D.; Hritcu, D.; Popa, M.I.; Tamba, B.I. Carboxymethyl guar gum nanoparticles for drug delivery applications: Preparation and preliminary in-vitro investigations. *Mater. Sci. Eng. C* **2016**, *63*:628–636.
109. Singh, V.K.; Banerjee, I.; Agarwal, T.; Pramanik, K.; Bhattacharya, M.K.; Pal, K. Guar gum and sesame oil based novel bigels for controlled drug delivery. *Colloids Surf. B Biointerfaces* **2014**, *123*:582–592.
110. Prabaharan, M. Prospective of guar gum and its derivatives as controlled drug delivery systems. *Int. J. Biol. Macromol.* **2011**, *49*:117–124.
111. Das, S.; Subuddhi, U. pH-Responsive guar gum hydrogels for controlled delivery of dexamethasone to the intestine. *Int. J. Biol. Macromol*. **2015**, *79*:856–863.
112. Seeli, D.S.; Prabaharan, M. Guar gum oleate-graft-poly (methacrylic acid) hydrogel as a colon-specific controlled drug delivery carrier. *Carbohydr. Polym*. **2017**, *158*:51–57.
113. Chen, F.; Yang, Y.; He, J.; Bu, T.; He, X.; He, K.; Xiang, C.; Yu, Z.; Wu, H. The gelation of hydroxypropyl guar gum by nano-ZrO_2. *Polym. Adv. Technol*. **2018**, *29*:587–593.

114. George, A.; Shah, P.A.; Shrivastav, P.S. Guar gum: Versatile natural polymer for drug delivery applications. *Eur. Polym. J.* **2019**, *112*:722–735.
115. Huang, G.; Huang, H. Hyaluronic acid-based biopharmaceutical delivery and tumor-targeted drug delivery system. *J. Control. Release* **2018**, *278*:122–126.
116. Šmejkalová, D.; Muthný, T.; Nešporová, K.; Hermannová, M.; Achbergerová, E.; et.al. Hyaluronan polymeric micelles for topical drug delivery. *Carbohydr. Polym*. **2017**, *156*:86–96.
117. Tiwari, S.; Bahadur, P. Modified hyaluronic acid based materials for biomedical applications. *Int. J. Biol. Macromol.* **2019**, *121*:556–571.
118. Li, C.; Cao, Z.; Li, W.; Liu, R.; Chen, Y.; Song, Y.; Liu, G.; Song, Z.; et al. A review on the wide range applications of hyaluronic acid as a promising rejuvenating biomacromolecule in the treatments of bone related diseases. *Int. J. Biol. Macromol.* **2020**, *165*:1264–1275.
119. Khanlari, A.; Schulteis, J.E.; Suekama, T.C.; Detamore, M.S.; Gehrke, S.H. Designing crosslinked hyaluronic acid hydrogels with tunable mechanical properties for biomedical applications. *J. Appl. Polym. Sci*. **2015**, *132*:42009.
120. Vasvani, S.; Kulkarni, P.; Rawtani, D. Hyaluronic acid: A review on its biology, aspects of drug delivery, route of administrations and a special emphasis on its approved marketed products and recent clinical studies. *Int. J. Biol. Macromol.* **2020**, *151*: 1012–1029.
121. Xu, X.; Jha, A.K.; Harrington, D.A.; Farach-Carson, M.C.; Jia, X. Hyaluronic acid-based hydrogels: From a natural polysaccharide to complex networks. *Soft Matter* **2012**, *8*:3280–3294.
122. Collins, M.N.; Birkinshaw, C. Hyaluronic acid based scaffolds for tissue engineering—A review. *Carbohydr. Polym*. **2013**, *92*:1262–1279.
123. Zhai, P.; Peng, X.; Li, B.; Liu, Y.; Sun, H.; Li, X. The application of hyaluronic acid in bone regeneration. *Int. J. Biol. Macromol.* **2020**, *151*:1224–1239.
124. Burdick, J.A.; Prestwich, G.D. Hyaluronic acid hydrogels for biomedical applications. *Adv. Mater.* **2011**, *23*:H41–H56.
125. Khan, A.R.; Yang, X.; Du, X.; Yang, H.; Liu, Y.; Khan, A.Q.; Zhai, G. Chondroitin sulfate derived theranostic and therapeutic nanocarriers for tumor-targeted drug delivery. *Carbohydr. Polym*. **2020**, *233*:115837–115894.
126. Wang, L.; Wang, X.; Wu, H.; Liu, R. Overview on biological activities and molecular characteristics of sulfated polysaccharides from marine green algae in recent years. Mar. Drugs **2014**, *12*:4984–5020.
127. Varghese, O.P.; Liu, J.; Sundaram, K.; Hilborn, J.; Oommen, O.P. Chondroitin sulfate derived theranostic nanoparticles for targeted drug delivery. *Biomater. Sci*. **2016**, *4*:1310–1313.
128. Kwon, H.J.; Han, Y. Chondroitin sulfate-based biomaterials for tissue engineering. *Turk. J. Biol*. **2016**, *40*:290–299.
129. Pal, D.; Saha, S. Chondroitin: A natural biomarker with immense biomedical applications. *RSC Adv.* **2019**, *9*: 28061–28077.
130. Venkatesan, J.; Anil, S.; Rao, S.; Bhatnagar, I.; Kim, S.-K. Sulfated polysaccharides from macroalgae for bone tissue regeneration. *Curr. Pharm. Des*. **2019**, *25*:1200–1209.
131. Karami, A.; Tebyanian, H.; Sayyad Soufdoost, R.; Motavallian, E.; Barkhordari, A.; Nourani, M.R.; Extraction and characterization of collagen with cost-effective method from human placenta for biomedical applications. *World J Plast Surg* **2019**; 8:352-8.
132. Salvatore, L.; Gallo, N.; Natali, M.L;. Terzi, A.; Sannino, A.; Madaghiele, M.; Mimicking the hierarchical organization of natural collagen: toward the development of ideal scaffolding material for tissue regeneration. *Front Bioeng Biotechnol* **2021**, *9*:6445.

133. Vijayalekha, A.; Anandasadagopan, S.K.; Pandurangan, A.K.; An overview of collagen-based composite scaffold for bone tissue engineering. *Appl Biochem Biotechnol*. **2023**,*195*(7):4617-4636.
134. Terzi, A, Gallo N, Bettini S, Sibillano, T.; Altamura, D.; Madaghiele, M.; De Caro, L.; et.al.; Sub- and supramolecular X-Ray characterization of engineered tissues from equine tendon, bovine dermis, and fish skin type-I collagen. *Macromol Biosci*. **2020**, *20*(5):e2000017.
135. Sorushanova, A.; Delgado, L.M.; Wu, Z.; Shologu, N.; Kshirsagar, A.; Raghunath, R.; et.al.; The collagen suprafamily: from biosynthesis to advanced biomaterial development. *Adv Mater.* **2019**, *31*(1):e1801651.
136. Sharma, S.; Rai, V.K.; Narang, R.K.; Markandeywar, T.S.; Collagen-based formulations for wound healing: A literature review. *Life Sci.* **2022**, *290*:120096.
137. Geahchan, S.; Baharlouei, P.; Rahman, A.; Marine collagen: A promising biomaterial for wound healing, skin anti-aging, and bone regeneration. *Mar Drugs.* **2022**, *20*(1):61.
138. Martínez-Puig, D.; Costa-Larrión, E.; Rubio-Rodríguez, N.; Gálvez-Martín, P.; Collagen supplementation for joint health: the link between composition and scientific knowledge. *Nutrients.* **2023**, *15*(6):1332.
139. Davison-Kotler, E.; Marshall, W.S.; Garcia-Gareta, E.; Sources of collagen for biomaterials in skin wound healing. *Bioengineering* (Basel) **2019**,*6*.
140. Bax, D.V.; Smalley, H.E.; Farndale, R.W.; Best, S.M.; Cameron, R.E.; Cellular response to collagen-elastin composite materials. *Acta Biomater.* **2019**, *86*:158-170.
141. Marin, M.M.; Ianchis, R.; Leu Alexa, R.; Gifu, I.C.; Kaya, M.G.A.; et.al.; Development of new collagen/clay composite biomaterials. *Int J Mol Sci*. **2021**, *23*(1):401.
142. Kaczmarek-Szczepańska, B.; Polkowska, I.; Małek, M.; Kluczyński, J.; Paździor-Czapula, K.; et.al.; The characterization of collagen-based scaffolds modified with phenolic acids for tissue engineering application. *Sci Rep*. **2023**,*13*(1):9966.
143. Meng, D.; Lei, X.; Li, Y.; Kong, Y.; Huang, D.; Zhang, G.; Three-dimensional polyvinyl alcohol scaffolds modified with collagen for HepG2 cell culture. *J Biomater Appl.* 2020, 35(4-5):459-470.
144. Parenteau-Bareil, R.; Gauvin, R.; Berthod, F.; Collagen-based biomaterials for tissue engineering applications. Materials **2010**, 3:1863–1887.
145. Ferreira, A.M.; Gentile, P.; Chiono, V.; Ciardelli, G. Collagen for bone tissue regeneration. *Acta Biomater*. **2012**, *8*, 3191–3200.
146. Chattopadhyay, S.; Raines, R.T. Collagen-based biomaterials for wound healing. *Biopolymers* **2014**, *101*:821–833.
147. Khan, R.; Khan, M.H.; Use of collagen as a biomaterial: An update. *J. Indian. Soc. Periodontol*. **2013**, *17*:539–542.
148. Sahiner, M.; Alpaslan, D.; Bitlisli, B.O.; Collagen-based hydrogel films as drug-delivery devices with antimicrobial properties. *Polym. Bull.* **2014**, *71*:3017–3033.
149. Hoque, M.E.; Nuge, T.; Yeow, T.K.; Nordin, N.; Prasad, R. Gelatin based scaffolds for tissue engineering—A review. *Polym. Res. J.* **2015**, *9*:15–32.
150. Saraogi, G.K.; Gupta, P.; Gupta, U.; Jain, N.; Agrawal, G. Gelatin nanocarriers as potential vectors for effective management of tuberculosis. *Int. J. Pharm.* **2010**, *385*:143–149.
151. Rose, J.B.; Pacelli, S.; El Haj, A.J.; Dua, H.S.; Hopkinson, A.; White, L.J.; Rose, F.R. Gelatin-based materials in ocular tissue engineering. *Materials* **2014**, *7*:3106–3135.
152. Yasmin, R.; Shah, M.; Khan, S.A.; Ali, R. Gelatin nanoparticles: A potential candidate for medical applications. *Nanotechnol. Rev.* **2017**, *6*:191–207.
153. Foox M, Zilberman M. Drug delivery from gelatin-based systems. *Expert Opin Drug Deliv*. **2015**,12(9):1547-63.

154. Nouri-Felekori, M.; Khakbiz, M.; Nezafati, N.; Mohammadi, J.; Eslaminejad, M.B.; Comparative analysis and properties evaluation of gelatin microspheres crosslinked with glutaraldehyde and 3-glycidoxypropyltrimethoxysilane as drug delivery systems for the antibiotic vancomycin. *Int J Pharm*. **2019**, *557*:208-220.
155. Campiglio, C.E.; Contessi Negrini, N.; Farè, S.; Draghi, L.; Cross-linking strategies for electrospun gelatin scaffolds. *Materials* (Basel). **2019**, *12*(15):2476.
156. De Colli, M.; Massimi, M.; Barbetta, A.; Di Rosario, B.L.; Nardecchia, S.; Conti Devirgiliis, L.; Dentini, M.; A biomimetic porous hydrogel of gelatin and glycosaminoglycans cross-linked with transglutaminase and its application in the culture of hepatocytes. *Biomed Mater.* **2012**, 7(5):055005.
157. Han, J.; Lazarovici, P.; Pomerantz, C.; Chen, X.; Wei, Y.; Lelkes, P.I.; Co-electrospun blends of PLGA, gelatin, and elastin as potential nonthrombogenic scaffolds for vascular tissue engineering. *Biomacromolecules*. **2011**,*12*(2):399-408.
158. Gonçalves, A.S.C.; Rodrigues, C.F.; Fernandes, N.; de Melo-Diogo, D.; Ferreira, P.; Moreira, A.F.; Correia, I.J.; IR780 loaded gelatin-PEG coated gold core silica shell nanorods for cancer-targeted photothermal/photodynamic therapy. *Biotechnol Bioeng*. **2022**,*119*(2):644-656.
159. Ranganathan, S.; Balagangadharan, K.; Selvamurugan, N.; Chitosan and gelatin-based electrospun fibers for bone tissue engineering. *Int J Biol Macromol*. **2019**,*133*:354-364.
160. Kundu, J.; Chung, Y.-I.; Kim, Y.H.; Tae, G.; Kundu, S. Silk fibroin nanoparticles for cellular uptake and control release. *Int. J. Pharm.* **2010**, *388*:242–250.
161. Zhao, Z.; Li, Y.; Xie, M.-B.; Silk fibroin-based nanoparticles for drug delivery. *Int. J. Mol. Sci*. **2015**, *16*: 4880–4903.
162. Wongpinyochit, T.; Uhlmann, P.; Urquhart, A.J.; Seib, F.P.; PEGylated silk nanoparticles for anticancer drug delivery. *Biomacromolecules* **2015**, *16*:3712–3722.
163. Noori, A.; Ashrafi, S.J.; Vaez-Ghaemi, R.; Hatamian-Zaremi, A.; Webster, T.J. A review of fibrin and fibrin composites for bone tissue engineering. *Int. J. Nanomed.* **2017**, *12*:4937–4961.
164. Jo, Y.Y.; Kim, S.-G.; Kwon, K.-J.; Kweon, H.; Chae, W.-S.; Yang, W.G.; Lee, E.Y.; Seok, H. Silk fibroin-alginate-hydroxyapatite composite particles in bone tissue engineering applications in vivo. *Int. J. Mol. Sci.* **2017**, *18*:858.
165. Farokhi, M.; Mottaghitalab, F.; Samani, S.; Shokrgozar, M.A.; Kundu, S.C.; et.al.; Silk fibroin/hydroxyapatite composites for bone tissue engineering. *Biotechnol. Adv*. **2018**, *36*:68–91.
166. Seib, F.P.; Kaplan, D.L. Silk for drug delivery applications: opportunities and challenges. *J. Chem*. **2013**, *53*:756–766.
167. Nguyen, T.P.; Nguyen, Q.V.; Nguyen, V.-H.; Le, T.-H.; Huynh, V.Q.N.; Vo, D.V.; et.al.; Silk fibroin-based biomaterials for biomedical applications: a review. *Polymers* **2019**, *11*:1933.
168. Wu, P.; Liu, Q.; Li, R.; Wang, J.; Zhen, X.; Yue, G.; Wang, H.; et al.; Facile preparation of paclitaxel loaded silk fibroin nanoparticles for enhanced antitumor efficacy by locoregional drug delivery. *Appl. Mater. Interfaces* **2013**, *5*:12638–12645.
169. Ungaro, F.; Catanzano, O.; d'Angelo, I.; Diaz-Gomez, L.; Concheiro, A.; Miro, A.; et.al.; Microparticle-embedded fibroin/alginate beads for prolonged local release of simvastatin hydroxyacid to mesenchymal stem cells. *Carbohydr. Polym*. **2017**, *175*:645–653.
170. Gianak, O.; Kyzas, G.Z.; Samanidou, V.F.; Deliyanni, E.A.; A review for the synthesis of silk fibroin nanoparticles with different techniques and their ability to be used for drug delivery. *Curr. Anal. Chem*. **2019**, 15:339–348.

171. Gou, S.; Huang, Y.; Sung, J.; Xiao, B.; Merlin, D. Silk fibroin-based nanotherapeutics: application in the treatment of colonic diseases. *Nanomedicine* **2019**, 14:2373–2378.
172. Tian, Y.; Jiang, X.; Chen, X.; Shao, Z.; Yang, W. Doxorubicin-loaded magnetic silk fibroin nanoparticles for targeted therapy of multidrug-resistant cancer. *Adv. Mater*. **2014**, 26:7393–7398.
173. Subia, B.; Chandra, S.; Talukdar, S.; Kundu, S.C. Folate conjugated silk fibroin nanocarriers for targeted drug delivery. *Integr. Biol*. **2014**, 6:203–214.
174. Pham, D.T.; Saelim, N.; Tiyaboonchai, W.J. Paclitaxel loaded EDC-crosslinked fibroin nanoparticles: A potential approach for colon cancer treatment. *Drug Deliv. Transl. Res*. **2020**, *10*:413–424.
175. Totten, J.D.; Wongpinyochit, T.; Carrola, J.; Duarte, I.F.; Seib, F.P. PEGylation-dependent metabolic rewiring of macrophages with silk fibroin nanoparticles. *ACS Appl. Mater. Interfaces* **2019**, *11*:14515–14525.
176. Zhang, H.; Lai, L.; Wang, Y.; Ye, B.; Deng, S.; Ding, A.; Teng, L.; Qiu, L.; Chen, J. Silk fibroin for CpG oligodeoxynucleotide delivery. *ACS Biomater. Sci. Eng*. **2019**, *5*:6082–6088.
177. Crivelli, B.; Bari, E.; Perteghella, S.; Catenacci, L.; Sorrenti, M.; Mocchi, M.; et.al.; Silk fibroin nanoparticles for celecoxib and curcumin delivery: ROS-scavenging and anti-inflammatory activities in an in vitro model of osteoarthritis. *Eur. J. Pharm. Biopharm*. **2019**, *137*:37–45.
178. Aiyelabegan, H.T.; Zaidi, S.S.; Fanuel, S.; Eatemadi, A.; Ebadi, M.T.; Sadroddiny, E. Albumin-based biomaterial for lung tissue engineering applications. *Int. J. Polym. Mater. Polym. Biomater*. **2016**, *65*:853–861.
179. Tao, C.; Chuah, Y.J.; Xu, C.; Wang, D.-A. Albumin conjugates and assemblies as versatile bio-functional additives and carriers for biomedical applications. *J. Mater. Chem. B* **2019**, *7*:357–367.
180. Jahanban-Esfahlan, A.; Panahi-Azar, V.; Interaction of glutathione with bovine serum albumin: spectroscopy and molecular docking, *Food Chem*. **2016**, *202*:426–431.
181. Roufegarinejad, L.; Jahanban-Esfahlan, A.; Sajed-Amin, S.; Panahi-Azar, V.; Tabibiazar, M.; Molecular interactions of thymol with bovine serum albumin: spectroscopic and molecular docking studies, *J. Mol. Recognit.* **2018**, *31*:e2704.
182. Tabibiazar, M.; Davaran, S.; Hashemi, M.; Homayonirad, A.; Rasoulzadeh, F.; Hamishehkar, H.; Mohammadifar, M.A.; Design and fabrication of a food-grade albumin-stabilized nanoemulsion, *Food Hydrocolloids* **2015**, *44*:220–228.
183. Andishmand, H.; Roufegari Nejad, L.; Tabibiazar, M.; Nanostructure characterization of bovine serum albumin-resveratrol complex, *J. Res. Innov. Food Sci. Technol.* **2017**, *6*:291–300.
184. Ghorbani, M.; Hamishehkar, H.; Tabibiazar, M.; BSA/chitosan polyelectrolyte complex: a platform for enhancing the loading and cancer cell-uptake of resveratrol, *Macromol. Res*. **2018**, *26*: 808–813.
185. Loughney, J.W.; Lancaster, C.; Ha, S.; Rustandi, R.R.; Residual bovine serum albumin (BSA) quantitation in vaccines using automated Capillary Western technology, *Anal. Biochem*. **2014**, *461*:49–56.
186. Jahanban-Esfahlan, A.; Ostadrahimi, A.; Jahanban-Esfahlan, R.; Roufegarinejad, L.; Tabibiazar, M.; Amarowicz, R.; Recent developments in the detection of bovine serum albumin, *Int. J. Biol. Macromol*. **2019**,*138*:602–617.
187. Uzun, L., Turner, A.P., Molecularly-imprinted polymer sensors: realizing their potential, *Biosens. Bioelectron*. **2016**, *76*:131–144.
188. Yang, Y.-Q.; He, X.-W.; Wang, Y.-Z.; Li, W.-Y.; Zhang, Y.-K.; Epitope imprinted polymer coating CdTe quantum dots for specific recognition and direct fluorescent quantification of the target protein bovine serum albumin, Biosens. Bioelectron. **2014**, *54*:266–272.
189. Boysen, R.I.; Advances in the development of molecularly imprinted polymers for the separation and analysis of proteins with liquid chromatography, *J. Sep. Sci*. **2019**, *42*:51–71.

190. Cieplak, M.; Kutner, W.; Artificial biosensors: how can molecular imprinting mimic biorecognition? *Trends Biotechnol*. **2016**, *34*:922–941.
191. Erdőssy, J.; Horváth, V.; Yarman, A.; Scheller, F.W.; Gyurcsányi, R.E.; Electrosynthesized molecularly imprinted polymers for protein recognition, *Trends Anal. Chem*. **2016**, *79*:179–190.
192. Krishnamoorthy, S.; Nanostructured sensors for biomedical applications - a current perspective, Curr. Opin. Biotechnol. **2015**,*34*:118–124.
193. Sanginario, A.; Cauda, V.; Bonanno, A.; Bejtka, K.; Sapienza, S.; Demarchi, D.; An electronic platform for real-time detection of bovine serum albumin by means of amine-functionalized zinc oxide microwires, *RSC Adv*. **2016**, *6*: 891–897.
194. Jahanban-Esfahlan, A.; Panahi-Azar, V.; Sajedi, S.; Spectroscopic and molecular docking studies on the interaction between N-acetyl cysteine and bovine serum albumin, *Biopolymers* **2015**, *103*:638–645.
195. Jahanban-Esfahlan, A.; Davaran, S.; Moosavi-Movahedi, A.A.; Dastmalchi, S.; Investigating the interaction of juglone (5-hydroxy-1, 4-naphthoquinone) with serum albumins using spectroscopic and in silico methods, *J. Iran. Chem. Soc*. **2017**, *14*:1527–1540.
196. Elzoghby, A.O.; Samy, W.M.; Elgindy, N.A.; Albumin-based nanoparticles as potential controlled release drug delivery systems, *J. Control. Release* **2012**,*157*:168–182.
197. Jahanban-Esfahlan, A.; Dastmalchi, S.; Davaran, S.; A simple improved desolvation method for the rapid preparation of albumin nanoparticles, Int. J. Biol. Macromol. **2016**, *91*:703–709.
198. Roufegarinejad, L.; Amarowicz, R.; Jahanban-Esfahlan, A.; Characterizing the interaction between pyrogallol and human serum albumin by spectroscopic and molecular docking methods, *J. Biomol. Struct. Dyn*. **2018**, *37*:2766–2775.
199. Çakir, P.; Cutivet, A.; Resmini, M.; Bui, B.T.S.; Haupt, K.; Protein-size molecularly imprinted polymer nanogels as synthetic antibodies, by localized polymerization with multi-initiators, *Adv. Mater.* **2013**, *25*:1048–1051.
200. Xiong, X.; Song, F.; Sun, S.; Fan, J.; Peng, X.; Red-emissive fluorescein derivatives and detection of bovine serum albumin, *Asian. J. Org. Chem*. **2013**, *2*:145–149.
201. Indyk, H.E.; Gill, B.D.; Woollard, D.C.; An optical biosensor-based immunoassay for the determination of bovine serum albumin in milk and milk products, *Int. Dairy J.* **2015**, *47*:72–78.
202. Whitcombe, M.J.; Chianella, I.; Larcombe, L.; Piletsky, S.A.; Noble, J.; Porter, R.; Horgan, A.; The rational development of molecularly imprinted polymer-based sensors for protein detection, *Chem. Soc. Rev*. **2011**, *40*:1547–1571.
203. Jahanban-Esfahlan, A.; Roufegarinejad, L.; Jahanban-Esfahlan, R.; Tabibiazar, M.; Amarowicz, R.; Latest developments in the detection and separation of bovine serum albumin using molecularly imprinted polymers. *Talanta*. **2020**, *207*:120317.
204. Gao, R.; Kong, X.; Wang, X.; He, X.; Chen, L.; Zhang, Y.; Preparation and characterization of uniformly sized molecularly imprinted polymers functionalized with core–shell magnetic nanoparticles for the recognition and enrichment of protein, *J. Mater. Chem.* **2011**, *21*:17863–17871.
205. Ansari, S.; Application of magnetic molecularly imprinted polymer as a versatile and highly selective tool in food and environmental analysis: recent developments and trends, *Trends Anal. Chem*. **2017**, *90*:89–106.
206. Sood, A.; Arora, V.; Shah, J.; Kotnala, R.; Jain, T.K.; Multifunctional gold-coated iron oxide core-shell nanoparticles stabilized using thiolated sodium alginate for biomedical applications, *Mater. Sci. Eng. C* **2017**, *80*: 274–281.

207. Chen, H.-J.; Zhang, Z.-H.; Luo, L.-J.; Yao, S.-Z.; Surface-imprinted chitosan-coated magnetic nanoparticles modified multi-walled carbon nanotubes biosensor for detection of bovine serum albumin, *Sens. Actuators B Chem.* **2012**,*163*:76–83.
208. Gai, Q.-Q.; Qu, F.; Zhang, T.; Zhang, Y.-K.; The preparation of bovine serum albumin surface-imprinted superparamagnetic polymer with the assistance of basic functional monomer and its application for protein separation, *J. Chromatogr. A* **2011**, *1218*:3489–3495.
209. Xu, Z.; Gao, H.; Zhang, L.; Chen, X.; Qiao, X.; The biomimetic immunoassay based on molecularly imprinted polymer: a comprehensive review of recent progress and future prospects, *J. Food Sci.* **2011**, *76*:69–75.
210. Guoning, C.; Pengqi, G.; Yan, W.; Lu, W.; Hua, S.; et.al.; Preparation of molecularly imprinted polymers and application in a biomimetic biotin-avidin-ELISA for the detection of bovine serum albumin, *Talanta* **2019**, *198*:55–62.
211. Bera, D.; Qian, L.; Tseng, T.-K.; Holloway, P.H.; Quantum dots and their multimodal applications: a review, Materials **2010**, *3*:2260–2345.
212. Zhang, W.; He, X.-W.; Chen, Y.; Li, W.-Y.; Zhang, Y.-K.; Molecularly imprinted polymer anchored on the surface of denatured bovine serum albumin modified CdTe quantum dots as fluorescent artificial receptor for recognition of target protein, Biosens. Bioelectron. **2012**, *31*:84–89.
213. Xu, L.; Huang, Y.-A.; Zhu, Q.-J.; Ye, C.; Chitosan in molecularly-imprinted polymers: current and future prospects, Int. J. Mol. Sci. **2015**, *16*:18328–18347.
214. Muthusankar, E.; Ragupathy, D.; Chitosan based nanocomposite biosensors: a recent review, *Sens. Lett.* **2018**, *16* :81–91.
215. Prasad, B.B.; Prasad, A.; Tiwari, M.P.; Multiwalled carbon nanotubes-ceramic electrode modified with substrate-selective imprinted polymer for ultra-trace detection of bovine serum albumin, *Biosens. Bioelectron*. **2013**, *39*:236–243.
216. Zhang, M.; Huang, J.; Yu, P.; Chen, X.; Preparation and characteristics of protein molecularly imprinted membranes on the surface of multiwalled carbon nanotubes, *Talanta* **2010**, *81*:162–166.
217. Yang, Z.; Xu, J.; Wang, J.; Zhang, Q.; Zhang, B.; Design and preparation of self-driven BSA surface imprinted tubular carbon nanofibers and their specific adsorption performance, *Chem. Eng. J.* **2019**, *373*:923–934.
218. Nishino, H.; Huang, C.S.; K.J. Shea, Selective protein capture by epitope imprinting, *Angew. Chem*., Int. Ed. Engl. **2006**, *118*:2452–2456.
219. Chen, L.; Xu, S.; Li, J.; Recent advances in molecular imprinting technology: current status, challenges and highlighted applications, *Chem. Soc. Rev.* **2011**, *40*:2922–2942.
220. Ertürk, G.; Berillo, D.; Hedström, M.; Mattiasson, B.; Microcontact-BSA imprinted capacitive biosensor for real-time, sensitive and selective detection of BSA, *Biotechnol. Rep*. **2014**, *3*:65–72.
221. Kryscio, D.R.; Peppas, N.A.; Surface imprinted thin polymer film systems with selective recognition for bovine serum albumin, *Anal. Chim. Acta* **2012**, *718*:109–115.
222. Xia, J.; Cao, X.; Wang, Z.; Yang, M.; Zhang, F.; Lu, B.; Li, F.; Xia, L.; Li, Y.; Xia, Y.; Molecularly imprinted electrochemical biosensor based on chitosan/ionic liquid–graphene composites modified electrode for determination of bovine serum albumin, *Sens. Actuators B Chem*. **2016**, *225*:305–311.
223. Wang, Y.; Han, M.; Liu, G.; Hou, X.; Huang, Y.; Wu, K.; Li, C.; Molecularly imprinted electrochemical sensing interface based on in-situ-polymerization of amino-functionalized ionic liquid for specific recognition of bovine serum albumin, *Biosens. Bioelectron*. **2015**, *74*:792–798.

224. Zhao, K.; Lin, B.; Cui, W.; Feng, L.; Chen, T.; Wei, J.; Preparation and adsorption of bovine serum albumin-imprinted polyacrylamide hydrogel membrane grafted on non-woven polypropylene, *Talanta* **2014**, *121*:256–262.
225. Ran, D.; Wang, Y.; Jia, X.; Nie, C.; Bovine serum albumin recognition via thermosensitive molecular imprinted macroporous hydrogels prepared at two different temperatures, *Anal. Chim. Acta* **2012**, *723*:45–53.
226. Pawar, S.N.; Edgar, K.J.; Alginate derivatization: a review of chemistry, properties and applications, *Biomaterials* **2012**, *33*:3279–3305.
227. Herrero, E.P.; Martín Del Valle, E.M.; Peppas, N.A.; Protein imprinting by means of alginate-based polymer microcapsules, *Ind. Eng. Chem. Res*. **2010**, *49*:9811–9814.
228. Zhao, K.; Chen, T.; Lin, B.; Cui, W.; Kan, B.; N. Yang, X. Zhou, X. Zhang, J. Wei, Adsorption and recognition of protein molecular imprinted calcium alginate/polyacrylamide hydrogel film with good regeneration performance and high toughness, *React. Funct. Polym*. **2015**, *87*:7–14.
229. Qi, M.; Zhao, K.; Bao, Q.; Pan, P.; Zhao, Y.; Yang, Z.; Wang, H.; Wei, J.; Adsorption and electrochemical detection of bovine serum albumin imprinted calcium alginate hydrogel membrane, *Polymers* **2019**,11:622.
230. Kan, B.; Lin, B.; Zhao, K.; Zhang, X.; Feng, L.; Wei, J.; Fan, Y.; Imprinting of bovine serum albumin in a nonwoven polypropylene membrane supported polyacrylamide/calcium alginate interpenetrating polymer network hydrogel, *RSC Adv*. **2014**, *4*:55846–55852.
231. Liu, D.; Zhao, K.; Qi, M.; Li, S.; Xu, G.; Wei, J.; He, X.; Preparation of protein molecular imprinted polysiloxane membrane using calcium alginate film as matrix and its application for cell culture, Polymers **2018**,*10*:170.
232. Zhou, J.; Wang, Y.; Ma, Y.; B. Zhang, Q. Zhang, Surface molecularly imprinted thermo-sensitive polymers based on light-weight hollow magnetic microspheres for specific recognition of BSA, *Appl. Surf. Sci.* **2019**, *486*:265–273.
233. Frangville, C.; Rutkevičius, M.; Richter, A.P.; Velev, O.D.; Stoyanov, S.D.; Paunov, V.N.; Fabrication of environmentally biodegradable lignin nanoparticles. *ChemPhysChem* **2012**, *13*:4235–4243.
234. Dai, L.; Liu, R.; Hu, L.-Q.; Zou, Z.-F.; Si, C.-L. Lignin nanoparticle as a novel green carrier for the efficient delivery of resveratrol. *ACS Sustain. Chem. Eng*. **2017**, *5*:8241–8249.
235. Terzioğlu, P.; Parın, F.N.; Sıcak, Y.; Lignin composites for biomedical applications: Status, challenges and perspectives. In Lignin: Biosynthesis Transformation for Industrial Applications; Springer: Berlin/Heidelberg, Germany, **2020**; pp. 253–273.
236. Iravani, S.; Biomedical applications of lignin-based nanoparticles. In Nanoparticles their Biomedical Applications; Springer: Berlin/Heidelberg, Germany, **2020**; pp. 217–224.
237. Ulasan, M.; Yavuz, E.; Bagriacik, E.U.; Cengeloglu, Y.; Yavuz, M.S.; Biocompatible thermoresponsive PEGMA nanoparticles crosslinked with cleavable disulfide-based crosslinker for dual drug release. *J. Biomed. Mater. Res. A* **2015**, *103*:243–251.
238. Reddy, N.; Reddy, R.; Jiang, Q. Crosslinking biopolymers for biomedical applications. *Trends Biotechnol*. **2015**, 33:362–369.
239. Oryan, A.; Kamali, A.; Moshiri, A.; Baharvand, H.; Daemi, H.; Chemical crosslinking of biopolymeric scaffolds: current knowledge and future directions of crosslinked engineered bone scaffolds. *Int. J. Biol. Macromol*. **2018**, *107*:678–688.
240. Lin, M.; Dai, Y.; Xia, F.; Zhang, X. Advances in non-covalent crosslinked polymer micelles for biomedical applications. *Mater. Sci. Eng. C* **2021**, *119*: 111626–111635.

241. Khunmanee, S.; Jeong, Y.; Park, H. Crosslinking method of hyaluronic-based hydrogel for biomedical applications. *J. Tissue Eng*. **2017**, *8*: 2041731417726464.
242. Van Bochove, B.; Grijpma, D.W.; Photo-crosslinked synthetic biodegradable polymer networks for biomedical applications. *J. Biomater. Sci. Polym. Ed.* **2019**, *30*:77–106.
243. Tincu, C.E.; Bouhadiba, B.; Atanase, L.I.; Stan, C.S.; Popa, M.; Ochiuz, L. An accessible method to improve the stability and reusability of porcine pancreatic α-amylase via immobilization in gellan-based hydrogel particles obtained by ionic cross-linking with Mg^{2+} ions. *Molecules* **2023**, *28*:4695.
244. Iurciuc-Tincu, C.E.; Atanase, L.I.; Ochiuz, L.; Jérôm, C.; Sol, V.; Martin, P.; Popa, M. Curcumin-loaded polysaccharides-based complex particles obtained by polyelectrolyte complexation and ionic gelation. I-Particles obtaining and characterization. *Int. J. Biol. Macromol.* **2020**, *147*:629–642.
245. Suflet, D.M.; Popescu, I.; Pelin, I.M.; Ichim, D.L.; Daraba, O.M.; Constantin, M.; Fundueanu, G.; Dual Cross-linked chitosan/PVA hydrogels containing silver nanoparticles with antimicrobial properties. *Pharmaceutics* **2021**, *13:* 1461.
246. Dellali, K.Z.; Dellali, M.; Raţă, D.M.; Cadinoiu, A.N.; Atanase, L.I.; Popa, M.; et.al.; Assessment of physicochemical and in vivo biological properties of polymeric nanocapsules based on chitosan and poly(N-vinyl pyrrolidone-alt-itaconic anhydride). *Polymers* **2022**, *14*:1811.
247. Talelli, M.; Barz, M.; Rijcken, C.J.; Kiessling, F.; Hennink, W.E.; Lammers, T. Core-crosslinked polymeric micelles: principles, preparation, biomedical applications and clinical translation. *Nano Today* **2015**, *10*: 93–117.
248. Van Nostrum, C.F. Covalently cross-linked amphiphilic block copolymer micelles. *Soft Matter* **2011**, *7*:3246–3259.
249. Fan, W.; Zhang, L.; Li, Y.; Wu, H. Recent progress of crosslinking strategies for polymeric micelles with enhanced drug delivery in cancer therapy. *Curr. Med. Chem*. **2019**, *26*:2356–2376.
250. Tian, H.; Tang, Z.; Zhuang, X.; Chen, X.; Jing, X. Biodegradable synthetic polymers: preparation functionalization and biomedical application. *Prog. Polym. Sci.* **2012**, *37*:237–280.
251. Rossi, F.; Van Griensven, M.; Polymer functionalization as a powerful tool to improve scaffold performances. *Tissue Eng. Part A* **2014**, *20*:15–16.
252. Xiao, Y.; Chinoy, Z.S.; Pecastaings, G.; Bathany, K.; Garanger, E.; Lecommandoux, S. Design of polysaccharide-b-elastin-like polypeptide bioconjugates and their thermoresponsive self-assembly. *Biomacromolecules* **2019**, *21*:114–125.
253. Thakor, P.; Bhavana, V.; Sharma, R.; Srivastava, S.; Singh, S.B.; Mehra, N.K. Polymer–drug conjugates: Recent advances and future perspectives. *Drug Discov. Today* **2020**, *25*:1718–1726.
254. Zhou, T.; Zhu, Y.; Li, X.; Liu, X.; Yeung, K.W.; Wu, S.; Wang, X.; Cui, Z.; Yang, X.; Chu, P.K. Surface functionalization of biomaterials by radical polymerization. *Prog. Mater. Sci*. **2016**, *83*:191–235.
255. Schatz, C.; Lecommandoux, S. Polysaccharide-containing block copolymers: Synthesis, properties and applications of an emerging family of glycoconjugates. *Macromol. Rapid Commun*. **2010**, *31*:1664–1684.
256. Farooq, U.; Teuwen, J.; Dransfeld, C.; Toughening of epoxy systems with interpenetrating polymer network (IPN): A review. *Polymers* **2020**, *12*:1908.
257. Pescosolido, L.; Vermonden, T.; Malda, J.; Censi, R.; Dhert, W.J.; Alhaique, F.; Hennink, W.E.; Matricardi, P. In situ forming IPN hydrogels of calcium alginate and dextran-HEMA for biomedical applications. *Acta Biomater.* **2011**, *7*:1627–1633.
258. Boppana, R.; Kulkarni, R.V.; Mutalik, S.S.; Setty, C.M.; Sa, B. Interpenetrating network hydrogel beads of carboxymethylcellulose and egg albumin for controlled release of lipid lowering drug. *J. Microencapsul*. **2010**, *27*: 337–344.

259. Kumar, G.A.; Wadood, S.A.; Maurya, S.D.; Ramchand, D.; Interpenetrating polymeric network hydrogel for stomach-specific drug delivery of clarithromycin: preparation and evaluation. *Asian J. Pharm.* **2010**, *4*:179–184.
260. Shivashankar, M.; Mandal, B.K.; A review on interpenetrating polymer network. *Int. J. Phram. Phram. Sci.* **2012**, *4*:1–7.
261. Kaity, S.; Isaac, J.; Ghosh, A. Interpenetrating polymer network of locust bean gum-poly (vinyl alcohol) for controlled release drug delivery. *Carbohydr. Polym*. **2013**, *94*:456–467.
262. Kaczmarek, H.; Vuković-Kwiatkowska, I. Preparation and characterization of interpenetrating networks based on polyacrylates and poly (lactic acid). *Express Polym. Lett*. **2012**, *6*:78–94.
263. Matricardi, P.; Di Meo, C.; Coviello, T.; Hennink, W.E.; Alhaique, F. Interpenetrating polymer networks polysaccharide hydrogels for drug delivery and tissue engineering. *Adv. Drug Deliv. Rev*. **2013**, *65*:1172–1187.
264. Lohani, A.; Singh, G.; Bhattacharya, S.S.; Verma, A.; Interpenetrating polymer networks as innovative drug delivery systems. *J. Drug Deliv.* **2014**, *2014*:583612.
265. Aminabhavi, T.M.; Nadagouda, M.; More, U.A.; Joshi, S.D.; Kulkarni, V.H.; et.al.; Controlled release of therapeutics using interpenetrating polymeric networks. *Expert. Opin. Drug Deliv*. **2015**, *12*:669–688.
266. Zoratto, N.; Matricardi, P. Semi-IPNs and IPN-based hydrogels. *Polym. Gels* **2018**, *4*:91–124.
267. Sperling, L.H.; Hu, R. Interpenetrating polymer networks. In Polymer Blends Handbook; Springer: Berlin/Heidelberg, Germany, **2014**; vol 2, pp. 677–724.
268. Roland, C. Interpenetrating Polymer Networks (IPN Q1): Structure and Mechanical Behavior. In Encyclopedia of Polymeric Nanomaterials; Springer: Berlin/Heidelberg, Germany, **2013**.
269. Dragan, E.S. Design and applications of interpenetrating polymer network hydrogels. A review. *Chem. Eng. J.* **2014**, *243*:572–590.
270. Ganguly, S.; Maity, P.P.; Mondal, S.; Das, P.; Bhawal, P.; Dhara, S.; Das, N.C. Polysaccharide and poly (methacrylic acid) based biodegradable elastomeric biocompatible semi-IPN hydrogel for controlled drug delivery. *Mater. Sci. Eng. C* **2018**, *92*:34–51.
271. Zou, Z.; Zhang, B.; Nie, X.; Cheng, Y.; Hu, Z.; Liao, M.; A sodium alginate-based sustained-release IPN hydrogel and its applications. *RSC Adv.* **2020**, *10*:39722–39730.
272. Cumpstey, I.; Chemical modification of polysaccharides. *Int. Sch. Res. Not.* **2013**, *2013*:417672.
273. Cheng, H.; Gu, Q.-M.; Enzyme-catalyzed modifications of polysaccharides and poly (ethylene glycol). *Polymers* **2012**, *4*:1311–1330.
274. Thakur, V.K.; Biopolymer Grafting: Synthesis and Properties; Elsevier: Amsterdam, The Netherlands, **2017**; ISBN 9780128104613.
275. Hu, Y.; Li, Y.; Xu, F.-J. Versatile functionalization of polysaccharides via polymer grafts: From design to biomedical applications. *Acc. Chem. Res*. **2017**, *50*:281–292.
276. Nishimura, T.; Shishi, S.; Sasaki, Y.; Akiyoshi, K. Thermoresponsive polysaccharide graft polymer vesicles with tunable size and structural memory. *J. Am. Chem. Soc.* **2020**, *142*:11784–11790.
277. Yao, H.; Wei, D.; Che, X.; Cai, L.; Tao, L.; Liu, L.; Wu, L.; Chen, G.Q. Comb-like temperature-responsive polyhydroxyalkanoate-graft-poly (2-dimethylamino-ethylmethacrylate) for controllable protein adsorption. *Polym. Chem.* **2016**, *7*:5957–5965.
278. Noreen, A.; Zia, K.M.; Tabasum, S.; Khalid, S.; Shareef, R. A review on grafting of hydroxyethylcellulose for versatile applications. *Int. J. Biol. Macromol.* **2020**, *150*:289–303.
279. Segneanu, A.E.; Macarie, C.; Ungureanu, M.; Gherman, V.; Grozescu, I.; Comparative study on enzymatic hydrolysis of cellulose. Digest Journal of Nanomaterials and Biostructures, **2013**,8(3):1061-106.

280. Carvalho, L.T.; Moraes, R.M.; Alves, G.M.; Lacerda, T.M.; Santos, J.C.; Santos, A.M.; Medeiros, S.F. Synthesis of amphiphilic pullulan-graft-poly (ε-caprolactone) via click chemistry. *Int. J. Biol. Macromol.* **2020**, *145*:701–711.
281. Aly, A.A.; El-Bisi, M.K. Grafting of polysaccharides: Recent advances. In Biopolymer Grafting; Elsevier: Amsterdam, The Netherlands, **2018**; pp. 469–519.
282. Atanase, L.I.; Winninger, J.; Delaite, C.; Riess, G. Reversible addition-fragmentation chain transfer synthesis and micellar characteristics of biocompatible amphiphilic poly(vinyl acetate)-graft-poly(N-vinyl-2-pyrrolidone) copolymers. *Eur. Poly. J*. **2014**, *53*:109–117.
283. Kumar, D.; Gihar, S.; Shrivash, M.K.; Kumar, P.; Kundu, P.P. A review on the synthesis of graft copolymers of chitosan and their potential applications. *Int. J. Biol. Macromol*. **2020**, *163*:2097–2112.
284. Liu, J.; Yong, H.; Liu, Y.; Bai, R. Recent advances in the preparation, structural characteristics, biological properties and applications of gallic acid grafted polysaccharides. *Int. J. Biol. Macromol.* **2020**, *156:*1539–1555.
285. Garcia-Valdez, O.; Champagne, P.; Cunningham, M.F.; Graft modification of natural polysaccharides via reversible deactivation radical polymerization. *Prog. Polym. Sci*. **2018**, *76*:151–173.
286. Kumar, D.; Pandey, J.; Raj, V.; Kumar, P. A review on the modification of polysaccharide through graft copolymerization for various potential applications. *Open J. Med. Chem*. **2017**, *11*:109–126.
287. Singh, V.; Kumar, P.; Sanghi, R. Use of microwave irradiation in the grafting modification of the polysaccharides—a review. *Prog. Polym. Sci.* **2012**, *37*:340–364.
288. Omagari, Y.; Kaneko, Y.; Kadokawa, J.-I.; Chemoenzymatic synthesis of amylose-grafted alginate and its formation of enzymatic disintegratable beads. *Carbohydr. Polym.* **2010**, *82*: 394–400.
289. Kadokawa, J.-I.; Arimura, T.; Takemoto, Y.; Yamamoto, K.; Self-assembly of amylose-grafted carboxymethyl cellulose. *Carbohydr. Polym*. **2012**, *90*:1371–1377.
290. Maia, A.M.; Silva, H.V.; Curti, P.S.; Balaban, R.C.; Study of the reaction of grafting acrylamide onto xanthan gum. *Carbohydr. Polym*. **2012**, *90*:778–783.
291. Sun, J.; Li, Z. Polyion complexes via electrostatic interaction of oppositely charged block copolymers. *Macromolecules* **2020**, *53*:8737–8740.
292. Zhang, Q.; Ko, N.R.; Oh, J.K. Recent advances in stimuli-responsive degradable block copolymer micelles: Synthesis and controlled drug delivery applications. Chem. Commun. 2012, 48, 7542–7552.
293. Soni, V.; Pandey, V.; Asati, S.; Gour, V.; Tekade, R.K. Biodegradable block copolymers and their applications for drug delivery. In Basic Fundamentals of Drug Delivery; Academic Press: Cambridge, MA, USA, **2019**; pp. 401–447.
294. Luo, Y.; Wang, Q. Recent development of chitosan-based polyelectrolyte complexes with natural polysaccharides for drug delivery. *Int. J. Biol. Macromol*. **2014**, *64*:353–367.
295. Costa, R.R.; Mano, J.F. Polyelectrolyte multilayered assemblies in biomedical technologies. *Chem. Soc. Rev*. **2014**, *43*:3453–3479.
296. Kulkarni, A.D.; Vanjari, Y.H.; Sancheti, K.H.; Patel, H.M.; Belgamwar, V.S.; Surana, S.J.; Pardeshi, C.V. Polyelectrolyte complexes: mechanisms, critical experimental aspects, and applications. *Artif. Cells Nanomed. Biotechnol*. **2016**, *44*:1615–1625.
297. Ishihara, M.; Kishimoto, S.; Nakamura, S.; Sato, Y.; Hattori, H. Polyelectrolyte complexes of natural polymers and their biomedical applications. *Polymers* **2019**, *11*:672.
298. Wu, D.; Zhu, L.; Li, Y.; Zhang, X.; Xu, S.; Yang, G.; Delair, T.; Chitosan-based colloidal polyelectrolyte complexes for drug delivery: A review. *Carbohydr. Polym*. **2020**, *238*:116126–116129.

299. Zhao, L.; Skwarczynski, M.; Toth, I.; Polyelectrolyte-based platforms for the delivery of peptides and proteins. *ACS Biomater. Sci. Eng*. **2019**, *5*:4937–4950.
300. Timilsena, Y.P.; Akanbi, T.O.; Khalid, N.; Adhikari, B.; Barrow, C.J. Complex coacervation: Principles, mechanisms and applications in microencapsulation. *Int. J. Biol. Macromol*. **2019**, *121*:1276–1286.
301. Shariatinia, Z. Biopolymeric nanocomposites in drug delivery. In Advanced Biopolymeric Systems for Drug Delivery; Springer: Berlin/Heidelberg, Germany, **2020**; pp. 233–290.
302. Hamad, K.; Kaseem, M.; Ko, Y.G.; Deri, F. Biodegradable polymer blends and composites: an overview. *Polym. Sci. Ser. A* **2014**, *56*:812–829.
303. Goonoo, N.; Bhaw-Luximon, A.; Jhurry, D.; Biodegradable polymer blends: miscibility, physicochemical properties and biological response of scaffolds. *Polym. Int*. **2015**, *64*:1289–1302.
304. Girdhar, M.; Mohan, A.; Sharma, A. Blending strategies of natural polymers: A review. *Trends Biomater. Artif. Organs*. **2016**, *30*:61–76.
305. Ghadi, R.; Muntimadugu, E.; Domb, A.; Khan, W.; Zhang, X. Synthetic biodegradable medical polymer: Polyanhydrides. In Science and Principles of Biodegradable and Bioresorbable Medical Polymers; Woodhead Publishing: Sawston, UK, **2017**; pp. 153–188.
306. Nofar, M.; Sacligil, D.; Carreau, P.J.; Kamal, M.R.; Heuzey, M.-C. Poly (lactic acid) blends: Processing, properties and applications. *Int. J. Biol. Macromol*. **2019**, *125*: 307–360.
307. Saini, P.; Arora, M.; Kumar, M.R. Poly (lactic acid) blends in biomedical applications. *Adv. Drug Deliv. Rev*. **2016**, *107*:47–59.
308. Hamad, K.; Kaseem, M.; Ayyoob, M.; Joo, J.; Deri, F.; Polylactic acid blends: the future of green, light and tough. *Prog. Polym. Sci*. **2018**, *85*: 83–127.
309. Raza, Z.A.; Khalil, S.; Abid, S. Recent progress in development and chemical modification of poly (hydroxybutyrate)-based blends for potential medical applications. *Int. J. Biol. Macromol.* **2020**, *160*:77–100.
310. Zafar, R.; Zia, K.M.; Tabasum, S.; Jabeen, F.; Noreen, A.; Zuber, M. Polysaccharide based bionanocomposites, properties and applications: A review. *Int. J. Biol. Macromol.* **2016**, 92:1012–1024.
311. Ali, A.; Ahmed, S. A review on chitosan and its nanocomposites in drug delivery. *Int. J. Biol. Macromol*. **2018**, *109*:273–286.
312. Armentano, I.; Puglia, D.; Luzi, F.; Arciola, C.; Morena, F.; Martino, S.; Torre, L. Nanocomposites based on biodegradable polymers. *Materials* **2018**, *11*:795.
313. Kuperkar, K.; Atanase, L.I.; Bahadur, A.; Crivei, I.C.; Bahadur, P. Degradable polymeric bio(nano)materials and their biomedical applications: A comprehensive overview and recent updates. *Polymers* **2024**, *16*:206.
314. Sionkowska, A.; Current research on the blends of natural and synthetic polymers as new biomaterials: review, *Prog. Polym. Sci.* **2011**, *36*:1254–1276.
315. Bin Park, S.; Lih, E.; Park, K.S.; Joung, Y.K.; Han, D.K.; Biopolymer-based functional composites for medical applications, *Prog. Polym. Sci*. **2017**, *68*:77–105.
316. Yun, Y.H.; Lee, B.K.; Park, K. Controlled drug delivery: historical perspective for the next generation. *J. Control. Release* **2015**, 21:2–7.
317. Wen, P.; Ke, W.; Dirisala, A.; Toh, K.; Tanaka, M.; Li, J. Stealth and pseudo-stealth nanocarriers. *Adv. Drug Deliv. Rev.* **2023**, *198*:114895.
318. Singh, A.V.; Biopolymers in drug delivery: a review, *Pharmacol. Online* **2011**, *674*:666–674.
319. Gopi, S.; Amalraj, A.; Sukumaran, N.P.; Haponiuk, J.T.; Thomas, S.; Biopolymers and their composites for drug delivery: a brief review, *Macromol. Symp.* **2018**, *380*:1800114.

320. Müller, A.; Ni, Z.; Hessler, N.; Wesarg, F.; Müller, F.A.; Kralisch, D.; Fischer, D.; The biopolymer bacterial nanocellulose as drug delivery system: investigation of drug loading and release using the model protein albumin, *J. Pharm. Sci.* **2013**, *102*:579–592.
321. Das, D.; Pal, S.; Modified biopolymer-dextrin based crosslinked hydrogels: application in controlled drug delivery, *RSC Adv.* **2015**, *5*:25014–25050.
322. Ezike, T.C.; Okpala, U.S.; Onoja, U.L.; Nwike, C.P.; Ezeako, E.C.; Okpara, O.J.; Okoroafor, C.C.; et al. Advances in drug delivery systems, challenges and future directions. *Heliyon* **2023**, *9*: e17488.
323. Vargason, A.M.; Anselmo, A.C.; Mitragotri, S. The evolution of commercial drug delivery technologies. *Nat. Biomed. Eng*. **2021**, *5*: 951–967.
324. Adepu, S.; Ramakrishna, S.; Controlled drug delivery systems: current status and future directions. *Molecules* **2021**, *26*: 5905.
325. Mansour, A.; Romani, M.; Acharya, A.B.; Rahman, B.; Verron, E.; Badran, Z.; Drug delivery systems in regenerative medicine: an updated review. *Pharmaceutics* **2023**, *15*:695.
326. Jeong, W.Y.; Kwon, M.; Choi, H.E.; Kim, K.S. Recent advances in transdermal drug delivery systems: A review. *Biomater. Res*. **2021**, *25*: 24–32.
327. Liu, G.; Yang, L.; Chen, G.; Xu, F.; Yang, F.; Yu, H.; Li, L.; et al. A Review on drug delivery system for tumor therapy. *Front. Pharmacol.* **2021**, *12*:735446.
328. Wajid, A.; Taimur, K.; Imran, B.; Javed, I.; A comprehensive review on targeted drug delivery system. *Asian J. Pharm. Res.* **2022**, *12*:335–340.
329. Abasian, P.; Ghanavati, S.; Rahebi, S.; Khorasani, S.N.; Khalili, S. Polymeric nanocarriers in targeted drug delivery systems: A review. *Polym. Adv. Technol.* **2020**, *31*:2939–2954.
330. Prakash, S. Nano-based drug delivery system for therapeutics: A comprehensive review. *Biomed. Phys. Eng. Express* **2023**, *9*:052002.
331. Bakhrushina, E.O.; Demina, N.B. Implants as targeted drug delivery systems (Review). *Pharm. Chem. J.* **2022**, *56*: 396–402.
332. Duan, Y.; Dhar, A.; Patel, C.; Khimani, M.; Neogi, S.; Sharma, P.; Kumar, N.S.; Vekariya, R.L. A brief review on solid lipid nanoparticles: Part and parcel of contemporary drug delivery systems. *RSC Adv*. **2020**, *10*:26777–26791.
333. Mohammed, M.A.; Syeda, J.T.M.; Wasan, K.M.; Wasan, E.K. An overview of chitosan nanoparticles and its application in non-parenteral drug delivery. *Pharmaceutics* **2017**, *9*:53.
334. Kamaly, N.; Yameen, B.; Wu, J.; Farokhzad, O.C. Degradable controlled-release polymers and polymeric nanoparticles: Mechanisms of controlling drug release. *Chem. Rev*. **2016**, *116*, 2602–2663.
335. Binauld, S.; Stenzel, M.H. Acid-degradable polymers for drug delivery: A decade of innovation. *Chem. Commun*. **2013**, *49*:2082–2102.
336. Janssen, M.; Mihov, G.; Welting, T.; Thies, J.; Emans, P. Drugs and polymers for delivery systems in OA joints: clinical needs and opportunities. *Polymers* **2014**, *6*:799–819.
337. Doppalapudi, S.; Jain, A.; Domb, A.J.; Khan, W.; Biodegradable polymers for targeted delivery of anti-cancer drugs. *Expert. Opin. Drug Deliv*. **2016**, *13*:891–909.
338. Fortuni, B.; Inose, T.; Ricci, M.; Fujita, Y.; Van Zundert, I.; Masuhara, A.; et.al.; Polymeric engineering of nanoparticles for highly efficient multifunctional drug delivery systems. *Sci. Rep.* **2019**, *9*:2666–2678.
339. Kuperkar, K.; Patel, D.; Atanas, L.I.; Bahadur, P. Amphiphilic block copolymers: their structures, and self-assembly to polymeric micelles and polymersomes as drug delivery vehicles. *Polymers* **2022**, *14*:4702.

340. De, A.; Nayak, A.K.; Kundu, A.; Das, B.; Samanta, A. Gum arabic-based nanomaterials in drug delivery and biomedical applications. In Biopolymer-Based Nanomaterials in Drug Delivery and Biomedical Applications; Academic Press: Cambridge, MA, USA, **2021**; pp. 165–182.
341. Wei, M.; Gao, Y.; Li, X.; Serpe, M.J. Stimuli-responsive polymers and their applications. *Polym. Chem*. **2017**, *8*:127–143.
342. Bratek-Skicki, A.; Towards a new class of stimuli-responsive polymer-based materials–recent advances and challenges. *Appl. Surf. Sci. Adv.* **2021**, *4*:100068.
343. Chatterjee, S.; Hui, P.C.-L.; Review of stimuli-responsive polymers in drug delivery and textile application. *Molecules* **2019**, *24*:2547.
344. Zhu, M.; Whittaker, A.K.; Han, F.Y.; Smith, M.T. Journey to the market: the evolution of biodegradable drug delivery systems. *Appl. Sci.* **2022**, *12*: 935.
345. Revia, R.A.; Stephen, Z.R.; Zhang, M. Theranostic nanoparticles for RNA-based cancer treatment. *Acc. Chem. Res*. **2019**, *52*:1496–1506.
346. Kim, H.J.; Kim, A.; Miyata, K.; Kataoka, K.; Recent progress in development of siRNA delivery vehicles for cancer therapy. *Adv. Drug Deliv. Rev*. **2016**, *104*:61–77.
347. Kim, K.; Chen, W.C.; Heo, Y.; Wang, Y. Polycations and their biomedical applications. *Prog. Polym. Sci.* **2016**, *60*: 18–50.
348. Dai, T.; Tanaka, M.; Huang, Y.-Y.; Hamblin, M.R.; Chitosan preparations for wounds and burns: antimicrobial and wound-healing effects. *Expert. Rev. Anti Infect. Ther.* **2011**, *9*: 857–879.
349. Zhu, T.; Mao, J.; Cheng, Y.; Liu, H.; Lv, L.; Ge, M.; Li, S.; Huang, J.; et al. Recent progress of polysaccharide-based hydrogel interfaces for wound healing and tissue engineering. *Adv. Mater. Interfaces* **2019**, *6*:1900761–1900782.
350. Mir, M.; Ali, M.N.; Barakullah, A.; Gulzar, A.; Arshad, M.; Fatima, S.; Asad, M.; Synthetic polymeric biomaterials for wound healing: A review. *Prog. Biomater.* **2018**, *7*:1–21.
351. Rajendran, N.K.; Kumar, S.S.D.; Houreld, N.N.; Abrahamse, H. A review on nanoparticle based treatment for wound healing. *J. Drug Deliv. Sci. Technol*. **2018**, *44*:421–430.
352. Ribeiro, D.M.L.; Carvalho Junior, A.R.; Vale de Macedo, G.H.R.; Chagas, V.L.; et.al.; Polysaccharide-based formulations for healing of skin-related wound infections: lessons from animal models and clinical trials. *Biomol. Ther*. **2019**, 10:63.
353. Andryukov, B.G.; Besednova, N.N.; Kuznetsova, T.A.; Zaporozhets, T.S.; et.al.; Sulfated polysaccharides from marine algae as a basis of modern biotechnologies for creating wound dressings: current achievements and future prospects. *Biomedicines* **2020**, *8*:301.
354. Debele, T.A.; Su, W.-P.; Polysaccharide and protein-based functional wound dressing materials and applications. Int. J. Polym. Mater. Polym. Biomater. **2022**, *71*:87–108.
355. Xu, R.; Fang, Y.; Zhang, Z.; Cao, Y.; Yan, Y.; Gan, L.; Xu, J.; Zhou, G. Recent advances in biodegradable and biocompatible synthetic polymers used in skin wound healing. *Materials* **2023**, *16*:5459.
356. Zhang, H.; Lin, X.; Cao, X.; Wang, Y.; Wang, J.; Zhao, Y. Developing natural polymers for skin wound healing. *Bioact. Mater*. **2024**, *33*:355–376.
357. Mahalakshmi, P.; Reshma, G.; Arthi, C.; Másson, M.; Rangasamy, J.; Biodegradable polymeric scaffolds and hydrogels in the treatment of chronic and infectious wound healing. *Eur. Polym. J.* **2023**, 198:112390–112405.
358. Prete, S.; Dattilo, M.; Patitucci, F.; Pezzi, G.; Parisi, O.I.; Puoci, F.; Natural and synthetic polymeric biomaterials for application in wound management. *J. Funct. Biomater.* **2023**, *14*:455.

359. Nguyen, H.M.; Le, T.T.N.; Nguyen, A.T.; Le, H.N.T.; Pham, T.T.; Biomedical materials for wound dressing: Recent advances and applications. *RSC Adv*. **2023**, *13*: 5509–5528.
360. Alven, S.; Peter, S.; Mbese, Z.; Aderibigbe, B.A.; Polymer-based wound dressing materials loaded with bioactive agents: potential materials for the treatment of diabetic wounds. *Polymers* **2022**, *14*:724.
361. Zhou, W.; Yu, X.; Zhang, Z.; Zou, X.; Song, H.; Zheng, W.; Preparation and evaluation of luteolin-loaded PLA-based shape memory gastroretentive drug delivery systems. *Int. J. Pharm*. **2023**, *650*:123670.
362. Bajracharya, R.; Song, J.G.; Patil, B.R.; Lee, S.H.; Noh, H.-M.; Kim, D.-H.; et.al.; Functional ligands for improving anticancer drug therapy: current status and applications to drug delivery systems. Drug Deliv. **2022**, *29*:1959–1970.
363. Wu, H.-Q.; Wang, C.-C. Biodegradable smart nanogels: A new platform for targeting drug delivery and biomedical diagnostics. *Langmuir* **2016**, *32*:6211–6225.
364. Marin, E.; Briceño, M.I.; Caballero-George, C. Critical evaluation of biodegradable polymers used in nanodrugs. *Int. J. Nanomed.* **2013**, *8*:3071–3091.
365. Kamaly, N.; Xiao, Z.; Valencia, P.M.; Radovic-Moreno, A.F.; Farokhzad, O.C. Targeted polymeric therapeutic nanoparticles: Design, development and clinical translation. *Chem. Soc. Rev*. **2012**, *41*:2971–3010.
366. Rață, D.M.; Cadinoiu, A.N.; Atanase, L.I.; Bacaita, S.E.; Mihalache, C.; Daraba, O.-M.; Gherghel, D.; Popa, M.; *In vitro* behaviour of aptamer-functionalized polymeric nanocapsules loaded with 5-fluorouracil for targeted therapy. *Mater. Sci. Eng. C* **2019**, *103*:109828–109838.
367. Rata, D.M.; Cadinoiu, A.N.; Atanase, L.I.; Popa, M.; Mihai, C.-T.; Solcan, C.; Ochiuz, L.; Vochita, G. Topical formulations containing aptamer-functionalized nanocapsules loaded with 5-fluorouracil-An innovative concept for the skin cancer therapy. *Mater. Sci. Eng. C* **2021**, *119*: 111591–111602.
368. Pescosolido, L.; Schuurman, W.; Malda, J.; Matricardi, P.; Alhaique, F.; Coviello, T.; van Weeren, et.al; Hyaluronic acid and dextran-based semi-IPN hydrogels as biomaterials for bioprinting. *Biomacromolecules* **2011**, *12*:1831–1838.
369. Guo, B.; Ma, P.X. Synthetic biodegradable functional polymers for tissue engineering: A brief review. *Sci. China Chem*. **2014**, *57*:490–500.
370. Deepthi, S.; Venkatesan, J.; Kim, S.-K.; Bumgardner, J.D.; Jayakumar, R. An overview of chitin or chitosan/nano ceramic composite scaffolds for bone tissue engineering. *Int. J. Biol. Macromol*. **2016**, *93*:1338–1353.
371. Patel, H.; Bonde, M.; Srinivasan, G. Biodegradable polymer scaffold for tissue engineering. *Trends Biomater. Artif*. **2011**, *25*:20–29.
372. Pedram Rad, Z.; Mokhtari, J.; Abbasi, M.; Biopolymer based three-dimensional biomimetic micro/nanofibers scaffolds with porous structures via tailored charge repulsions for skin tissue regeneration. *Polym. Adv. Technol*. **2021**, *32*:3535–3548.
373. Samiei, M.; Fathi, M.; Barar, J.; Fathi, N.; Amiryaghoubi, N.; Omidi, Y.; Bioactive hydrogel-based scaffolds for the regeneration of dental pulp tissue. *J. Drug. Deliv. Sci. Technol*. **2021**, *64*:102600–102611.
374. Gathani, K.M.; Raghavendra, S.S.; Scaffolds in regenerative endodontics: a review. *J. Dent. Res*. **2016**, *13*: 379–386.
375. Amini, A.R.; Laurencin, C.T.; Nukavarapu, S.P.; Bone tissue engineering: recent advances and challenges. *Crit. Rev. Biomed*. **2012**, *40*:363–408.
376. Lavanya, K.; Chandran, S.V.; Balagangadharan, K.; Selvamurugan, N.; Temperature-and pH-responsive chitosan-based injectable hydrogels for bone tissue engineering. *Mater. Sci. Eng. C* **2020**, *111*:110862–110873.

377. Tang, G.; Tan, Z.; Zeng, W.; Wang, X.; Shi, C.; Liu, Y.; He, H.; Chen, R.; Ye, X.; Recent advances of chitosan-based injectable hydrogels for bone and dental tissue regeneration. *Front. Bioeng. Biotechnol*. **2020**, *8*:587658–587672.
378. Rahmani, F.; Larbi Bouamrane, O.; Ben Bouabdallah, A.; Atanase, L.I.; Hellal, A.; Apintiliesei, A.N.; Biomimetic hydroxyapatite crystals growth on phosphorylated chitosan films by in vitro mineralization used as dental substitute materials. *Polymers* **2023**, *15*:2470.
379. Lim, J.; You, M.; Li, J.; Li, Z.; Emerging bone tissue engineering via polyhydroxyalkanoate (PHA)-based scaffolds. *Mater. Sci. Eng. C* **2017**, *79*: 917–929.
380. Suginta, W.; Khunkaewla, P.; Schulte, A.; Electrochemical biosensor applications of polysaccharides chitin and chitosan. *Chem. Rev*. **2013**, *113*:5458–5479.
381. Shan, D.; Gerhard, E.; Zhang, C.; Tierney, J.; Xie, D.; Liu, Z.; Yang, J. Polymeric biomaterials for biophotonic applications. *Bioact. Mater*. **2018**, *3*:434–445.
382. Mohankumar, P.; Ajayan, J.; Mohanraj, T.; Yasodharan, R. Recent developments in biosensors for healthcare and biomedical applications: A review. *Measurement* **2021**, *16*:108293–108361.
383. Gamboa, J.; Paulo-Mirasol, S.; Estrany, F.; Torres, J. Recent progress in biomedical sensors based on conducting polymer hydrogels. *ACS Appl. Bio Mater*. **2023**, *15*:1720–1741.
384. Jadoun, S.; Rathore, D.S. Polymer-based biosensors for medical applications. In Handbook of Polymers in Medicine; Woodhead Publishing: Sawston, UK, **2023**; pp. 635–652.
385. Rebelo, R.; Fernandes, M.; Fangueiro, R.; Biopolymers in medical implants: a brief review, *Procedia Eng*. **2017**, *200*:236–243.
386. Bonartsev, A.P.; Bonartseva, G.A.; Shaitan, K.V.; Kirpichnikov, M.P.; Poly (3- hydroxybutyrate) and poly (3-hydroxybutyrate)-based biopolymer systems, *Biochem. Suppl. Ser. B Biomed. Chem*. **2011**, *5*:10–21.
387. Tang, X.Z.; Kumar, P.; Alavi, S.; Sandeep, K.P.; Recent advances in biopolymers and biopolymer-based nanocomposites for food packaging materials, *Crit. Rev. Food Sci. Nutr*. **2012**, *52*:426–442.
388. Valdes, A.; Mellinas, A.C.; Ramos, M.; Garrigos, M.C.; Jimenez, A.; Natural additives and agricultural wastes in biopolymer formulations for food packaging, *Front. Chem*. **2014**, *2*:1–10.
389. Verma, M.L.; Dhanya, B.S.; Sukriti, V.; Rani, V.; Thakur, M.; et.al.; Carbohydrate and protein based biopolymeric nanoparticles: current status and biotechnological applications, *Int. J. Biol. Macromol*. **2020**, *154*: 390–412.
390. Calderon, L.A.; Iglesias, L.; Laca, A.; Herrero, M.; Díaz, M.; The utility of life cycle assessment in the ready meal food industry, *Resour. Conserv. Recycl*. 54 (2010) 1196–1207.
391. Pattanashetti, N.A.; Heggannavar, G.B.; Kariduraganavar, M.Y.; Smart biopolymers and their biomedical applications, *Procedia Manuf*. **2017**, *12*:263–279.
392. Wroblewska-Krepsztul, J.; Rydzkowski, T.; Michalska-Pozoga, I.; Thakur, V.K.; Biopolymers for biomedical and pharmaceutical applications: recent advances and overview of alginate electrospinning, *Nanomaterials* **2019**, *9*:404.
393. Freeman, R.; Boekhoven, J.; Dickerson, M.B.; Naik, R.R.; Stupp, S.I.; Biopolymers and supramolecular polymers as biomaterials for biomedical applications, *MRS Bull*. **2015**, *40*:1089–1101.