Hindawi
Journal of Nanomaterials
Volume 2023, Article ID 9270064, 15 pages
https://doi.org/10.1155/2023/9270064

Review Article

The Development of Eco-Friendly Biopolymers for Use in Tissue Engineering and Drug Delivery

Md. Zobair Al Mahmud, Md. Didarul Islam, and Md Hosne Mobarak

Department of Mechanical Engineering, IUBAT-International University of Business Agriculture and Technology, Dhaka, Bangladesh

Correspondence should be addressed to Md. Zobair Al Mahmud; 20107009@iubat.edu

Received 12 July 2023; Revised 5 August 2023; Accepted 14 October 2023; Published 31 October 2023

Academic Editor: Dong Kee Yi

Tissue engineering and drug delivery have emerged as promising fields that hold the potential to revolutionize modern healthcare. The widespread use of synthetic polymers in these applications raises concerns about their environmental impact and biocompatibility. In response, researchers have shifted their focus toward the development of eco-friendly biopolymers as viable alternatives. This review paper aims to comprehensively analyze the progress made in the utilization of biopolymers for tissue engineering and drug delivery, with an emphasis on their ecological advantages and biomedical performance. The review begins by exploring the diverse sources of biopolymers, such as proteins, polysaccharides, and nucleic acids, derived from renewable resources, agricultural waste, etc. The discussion then delves into the unique properties of these biopolymers, including their biodegradability, nontoxic nature, and potential for controlled drug release. The incorporation of biopolymers in tissue engineering scaffolds is critically examined. The review also explores the role of biopolymers in the drug delivery systems, with a focus on nanoparticles, microparticles, hydrogels, and films. The capability of biopolymers to encapsulate and protect therapeutic agents, as well as their controlled release, is discussed in the context of targeted drug delivery and improved therapeutic outcomes. This paper highlights the challenges and future perspectives in the field of eco-friendly biopolymers for tissue engineering and drug delivery. Promising advancements in biofabrication techniques, nanotechnology, and personalized medicine are identified as key drivers for the rapid translation of these materials into the clinical applications. The development of eco-friendly biopolymers offers a sustainable and bio-safe alternative to the traditional synthetic polymers in tissue engineering and drug delivery. This comprehensive review underscores the crucial role of biopolymers in fostering advancements in regenerative medicine and therapeutic interventions while prioritizing environmental preservation and human health.

1. Introduction

Green biopolymers have emerged as a potential alternative in the fields of tissue engineering and medication delivery, providing ecologically friendly and sustainable solutions [1]. Because of the growing demand for biocompatible materials, the development of biopolymers generated from renewable resources has received a lot of attention. These green biopolymers are not only biocompatible, but also have favorable mechanical qualities, making them appropriate for a variety of biomedical applications [2]. Furthermore, their synthesis and processing procedures use environmentally friendly methods, reducing the environmental effect. The purpose of this paper is to investigate the synthesis of green biopolymers for tissue engineering and drug delivery applications, emphasizing their advantages over conventional synthetic polymers and emphasizing the potential of these sustainable biomaterials in advancing regenerative medicine and targeted drug delivery systems.

Tissue engineering has made considerable advances in recent years, with the goal of generating functional and biocompatible materials that can replicate the natural extracellular matrix (ECM) and assist tissue regeneration [3]. Traditional synthetic polymers, such as polyethylene glycol (PEG) and poly (lactic-co-glycolic acid) (PLGA), are widely utilized; nevertheless, their synthesis requires the use of nonrenewable resources and frequently results in the development of harmful byproducts [4]. Green biopolymers derived from natural sources, including polysaccharides like chitosan, cellulose,

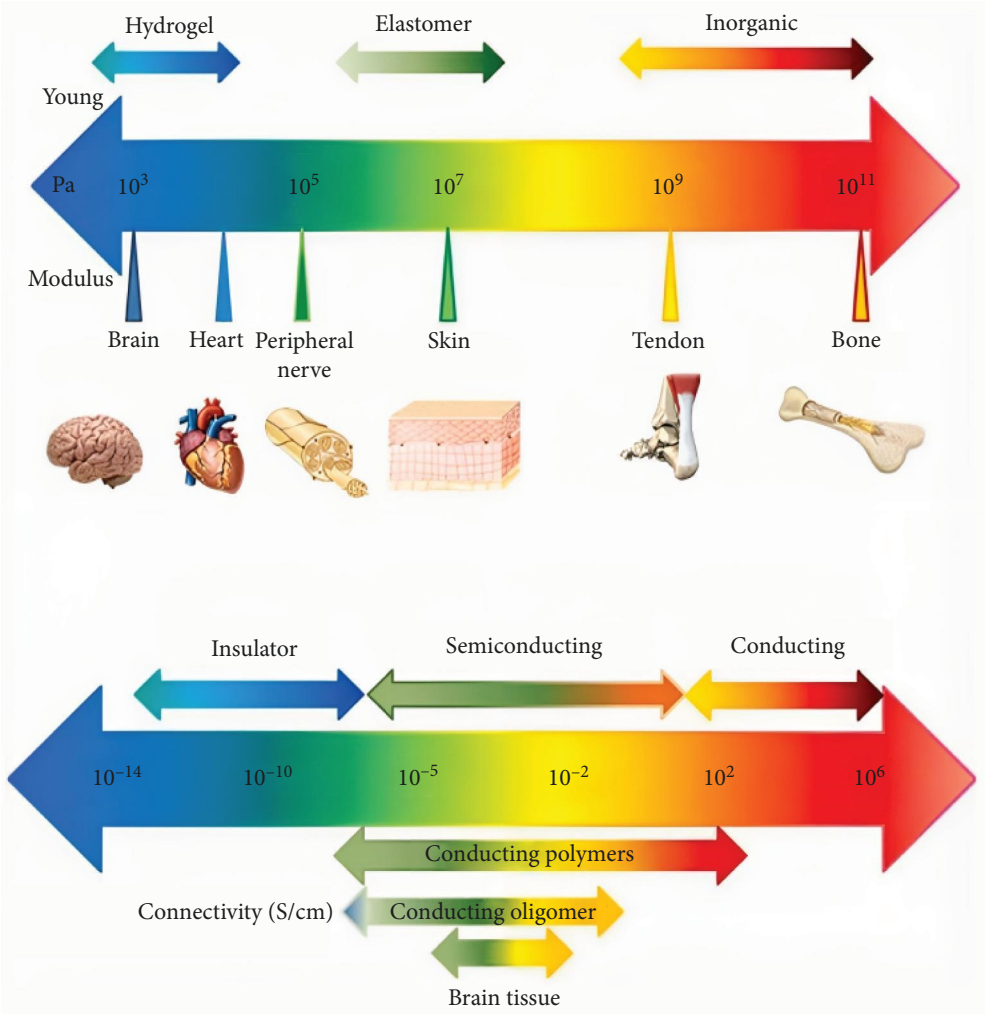


Figure 1: Comparison of behavior of tissue as a function of the type of biomaterial [12].

and alginate, as well as proteins such as collagen and silk fibroin, offer a sustainable alternative [5]. These biopolymers may be derived from plentiful and renewable sources such as plants, animals, and microbes, reducing dependency on fossil fuels and lowering carbon footprint.

Green biopolymer synthesis is a potential option for tissue engineering and drug delivery applications. Because of their long-term viability, high biocompatibility, and programable qualities, they are attractive candidates for producing functional biomaterials that stimulate tissue regeneration and allow controlled drug release. Furthermore, the environmentally friendly synthesis and processing procedures associated with green biopolymers help to reduce the ecological imprint of biomedical research and pave the way for a more sustainable future in regenerative medicine and tailored treatments [6]. Polymers should be altered to provide an acceptable amount of regeneration in order to replicate the behavior of a tissue. By utilizing synthetic polymers, various types of additives, and nanoparticles to create biocomposites, new functions may be added to the biopolymers [7, 8]. To imitate the architecture and characteristics of bone, hydroxyapatite has been introduced to biopolymer-based scaffolds [9, 10]. To induce stimulation and regulated medication release, magnetic nanoparticles have also been added to chitosan [11]. In order to create a scaffold that can imitate the behavior of the targeted tissue, it is important to understand the targeted tissue properties. Evidently, conductive substrates are favored for engineering brain tissue, but conductive elastomers would be a superior option for an engineering cardiac tissue [7]. The conductivity and mechanical characteristics of tissue are shown in Figure 1.

For example, brain is a soft tissue, whereas the bone is best known as a hard tissue. Biomaterials selection for such opposed tissues should be considered in terms of mechanical strength of biomaterials. From conductivity point of view, brain has conductivity similar to that of semiconducting materials. The chemistry of the utilized biomaterial should also be considered carefully, to make it able to resemble native extracellular matrix (ECM) needed for required level of tissue mimicking performance [12].

The primary tissue-specific regeneration processes that underlie the effectiveness of biopolymers in tissue engineering are also typically covered. To emphasize the performance window and other information related to functional biopolymers,

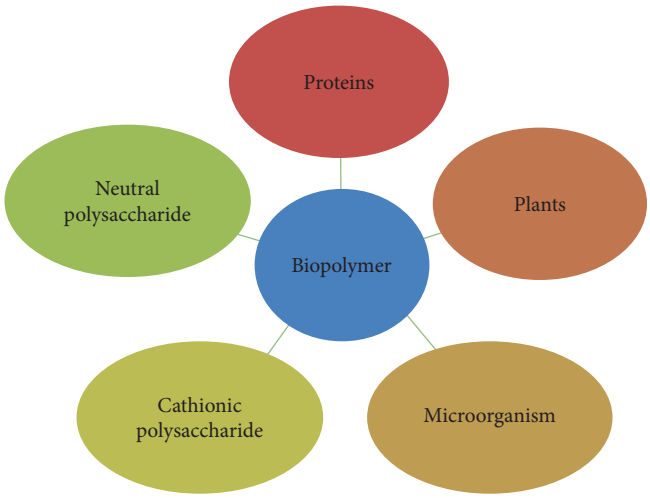


Figure 2: Demonstrate a number of different sources of natural renewable biopolymers.

biopolymers produced for various tissue scaffolds, such as neural, cardiac, skin, and bone, is individually examined. Biocomposites crafted from natural polymers are of particular concern, especially in the context of eco-friendly biopolymers used for tissue engineering and drug delivery.

2. Green Biopolymer Resources

Green biopolymers, which provide environmentally friendly substitutes for conventional petroleum-based plastics, are produced by a variety of plants and other natural sources [13]. Through processing, PLA and other biodegradable polymers may be made from maize [14]. To lessen dependency on fossil fuels, sugarcane is also used to produce biopolymers such poly hydroxyl alkanets (PHA) and bio-based polyethylene (PE) [15]. Chitin, a biopolymer with several uses in the domains of packaging and biomedicine, may be produced from the exoskeletons of crustaceans such as shrimp and crab, which is another noteworthy source [16]. A plentiful and renewable source of biopolymers is cellulose, an essential component of plant cell walls. It may be produced from materials like cellulose acetate and cellulose-based polymers as well as sources including wood pulp, cotton, hemp, and bamboo [17]. Due to their quick growth and low-resource needs, algae, and seaweed are gaining popularity as sustainable biopolymer sources. These marine creatures may be processed to produce biopolymers like agar, carrageenan, and alginate that are used in food packaging, medications, and biomedical equipment [18, 19]. In addition, some bacteria, such the strain *Escherichia coli*, may be genetically altered to make biopolymers like poly-3-hydroxybutyrate (PHB), which aids in the creation of bio-based plastics.

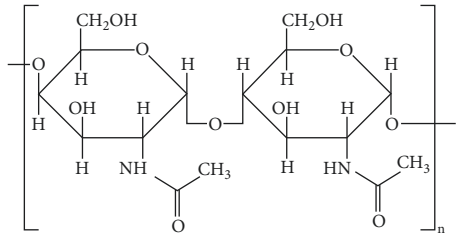
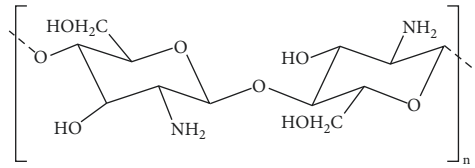
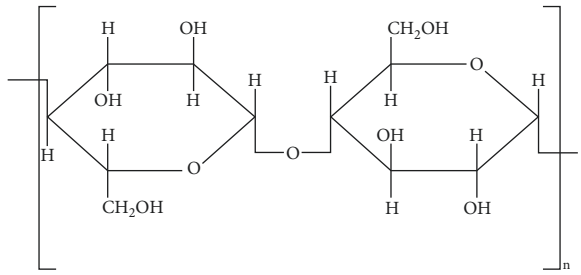
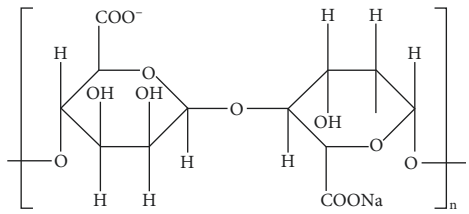
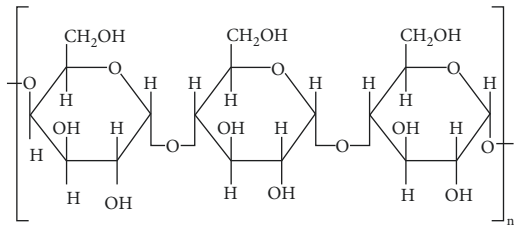
Figure 2 shows proteins, neutral polysaccharides, cationic polysaccharides, microbes, and plants are just a few of the many sources from which natural renewable biopolymers are produced. Proteins can be obtained from a variety of sources, including plant seeds, microbes, and animal byproducts [20]. Cell walls of plants and arthropod exoskeletons are both rich in neutral polysaccharides like cellulose and chitin [21]. These polysaccharides can be isolated and used in a variety of ways. On the other hand, cationic polysaccharides have positive charges because they include amino or ammonium groups [22]. They are derived from plants, microbes, and marine creatures and employed in the food, pharmaceutical, and cosmetic sectors [23]. Biopolymers with distinct characteristics can also be produced by microorganisms like bacteria and fungus [24]. For instance, several bacterial species generate bacterial cellulose, which is used in tissue engineering and wound treatments [25]. Table 1 indicates that biopolymers are formed from renewable sources, such as chitin, which is present in the exoskeletons of insects and crustaceans and is a precursor to chitosan. Plants have a lot of cellulose, which serves as structural support. Alginate is derived from seaweed and has gelling characteristics [26]. Plants use the starch they acquire from grains and tubers as a kind of energy storage and due to their biodegradability, biocompatibility, and nontoxicity, these biopolymers are suitable for a wide range of applications [27]. They are being used more often in a variety of industries, from biomedical gadgets to sustainable packaging, helping to create a greener and more ecologically friendly future.

3. Biopolymers Characterization Process

These characterization procedures are critical in understanding and optimizing the characteristics of biopolymers for use in a variety of sectors, including packaging, textiles, biomedical, and others. The process of determining the physical, chemical, and structural characteristics of biopolymers comprises a variety of methodologies and approaches. Fourier Transform Infrared Spectroscopy (FTIR) is a regularly used method that examines the molecular vibrations and functional groups present in the biopolymer, providing information on its chemical makeup [35]. The crystalline structure of biopolymers is studied using X-ray diffraction (XRD), which provides information on their molecular order and packing [36]. Scanning electron microscopy (SEM) and Rheology are used to examine the physical and structural properties of the biopolymers further [37]. Mechanical testing is important in the characterization of biopolymers which entails submitting biopolymer samples to various stresses and evaluating their responses in order to determine their mechanical characteristics [38]. Tensile testing, compression testing, bending testing, and shear testing are some popular mechanical testing methodologies for biopolymers. Tensile testing assesses the material's response to stretching pressures, whereas compression testing assesses its response to the compressive forces. Bending testing evaluates the biopolymer's resistance to flexural stress, whereas shear testing evaluates its resistance to forces applied parallel to its surface. These mechanical tests give useful information on the biopolymer's strength, stiffness, elasticity, and other mechanical characteristics, which aids in characterization and understanding of its possible uses.

Table 2 clearly illustrates the origin of various polysaccharide sources by listing their structural characteristics. Polysaccharides have been extensively utilized in the production of nano and microparticles due to their unique

Table 1: Biopolymers with their origins and chemical structures [28–34].

Biopolymer	Sources	Structure
Chitin	Corals, horseshoe worms, lamp shells, sponges, squid, cuttlefish, and clams are examples of aquatic species	
Chitosan	Fungi, mollusks, algae, crustaceans, and insects	
Cellulose	Agricultural trashes, such as Seaweed, rice husk, and sugarcane bagasse. Plant sources like wood, bamboo, sugarbeet, banana rachis, potato tubers, cotton, fique, kapok, agave, jute, kenaf, flax, hemp, vine, sisal, coconut, grass, wheat, rice, and barley	
Alginate	Seaweed	
Starch	Potatoes, maize, cassava, rice, sorghum, banana, wheat, and yams	

properties. Chitosan, a derivative of chitin, is a widely studied polysaccharide known for its biocompatibility and biodegradability. It has been employed in the formulation of nanoparticles for drug delivery systems, gene therapy, and wound healing applications. Table 3 presents biocomposite films and their properties, alongside corresponding analytical methods employed for the characterization.

Analytical techniques are essential for identifying the properties of biocomposite. Mechanical characteristics are evaluated using tensile and flexural testing, and their thermal stability and degradation behavior are better understood through thermal analysis (DSC and TGA). The morphology and fiber-polymer interfacial bonding can be better understood by SEM. Using FTIR, chemical interactions inside the biocomposite are investigated. Tests for biodegradability determine how they affect the environment. Life cycle assessment (LCA), makes it possible to measure the ecological footprint.

4. Application

Biopolymers play a vital role in tissue engineering and drug delivery due to their biocompatibility, biodegradability, and versatility as shown in Figure 3. Biopolymers can be utilized as scaffolds in tissue engineering to facilitate cell development and tissue regeneration. In order to encourage cell adhesion, proliferation, and differentiation, they offer a three-dimensional framework that resembles the natural extracellular matrix. In

Table 2: Examples of polysaccharides formerly used to make nano and microparticles [39–63].

Polysaccharide	Source	Structure
Agar	Gelidium and gracilarioid species of seaweed	Alternate β-1,3-linked-D-galactose and α-1-4-linked 3, 6-anhydro-L-galactose
Alginate	Brown algae and kelp	(1-4)-linked β-D-mannuronic acid and α-L-glucuronic acid
Carrageenan	Red seaweeds of the rhodophyceae class	No well-defined structure, consists of a group of linear galactan polysaccharides containing alternating (1-3) and (1-4)-β-glycosidic bonds
Cellulose	Plants	β-(1-4)-linked glucose
Chitosan	Hydrolyzed chitin of shells, crabs, shrimp, and krill	β-(1-4)-linked D-glucosamine and N-acetyl-D-glucosamine
Dextran	Bacteria (pseudomonas elodea or Sphingomonas elodea)	α-(1-6)-linked D-glucose
Gellan gum	Bacteria (sphingomonas elodea)	Tetrasaccharide repeating unit of rhamnose, glucuronic acid, and two glucose units
Inulin	Plants	β-(2-1)-linked D-fructose
Pectin	Plants (vegetables)	α-(1-4)-linked galacturonic acid residues which can be methoxylated
Pullulan	Fungus (aureobasidium pullulans)	α-(1-6)-linked maltotriose units
Starch, maltodextrins	Plants	α-(1-4)-and α-(1-6)-linked α-glucose

Table 3: Biocomposite characteristics and analytical methods for determining them [64–70].

Bio-composite material	Film property	Analytical methods
Chitosan/HNT/clove essential oil	Reduced water vapour permeability, moisture content, and water adsorption	Gravimetric analysis, weight and contact angle measurements
Chitosan/bentonite/poplar extract	Reduced oxygen permeability	Gas permeability according to the testing standard GB/T1038- 2000
Soy protein isolate/MMT/tannic acid	Increased tensile strength and young's modulus. Slight improvement of the elongation property. Successfully coating and better dispersion state of clay-hybrids in solution.	ISO527-3:1995(E) standard for mechanical properties, ATR-FTIR, XPS, XRD, FESEM and TEM
WPI/MMT/citric acid; cellulose acetate butyrate/OMMT	Improved thermal stability	TGA and DSC analyses
Gelatin/LDH/p- hydroxybenzoic acid; Chitosan/HNT/clove essential oil	Controlled released of the bioactive compound	UV-vis spectrophotometric analysis; GC-FID analysis
Pectin/HNT/cucurbit-6-uril/peppermint essential oil	Controlled released of menthone at 4°C	HPLC analysis

controlled drug delivery systems, biopolymers also act as drug carriers, allowing therapeutic substances to release slowly over time. Their capacity to enclose and safeguard medications while enabling their focused distribution improves therapeutic effectiveness and reduces negative effects. Biopolymers have transformed medication delivery and tissue engineering, providing innovative approaches to personalized and regenerative healthcare. Figure 3 depicts the various applications of biopolymers.

4.1. Tissue Engineering. An interdisciplinary field of study called tissue engineering uses chemistry, material science, engineering, and medicine to replace and repair organs and tissues [71]. The three major components of tissue engineering methodologies are scaffold, differentiated, or undifferentiated cells, and biological signaling molecules like growth factors (GFs) [72]. Recent developments in a variety of biodegradable natural polymer hydrogels, such as those made of chitosan, hyaluronic acid, alginate, and agarose, as well as proteins (collagen, gelatin, fibroin, and fibrin), and polysaccharides (chitosan, fibroin, and fibrin), are detailed here. These natural biopolymers exhibit distinctive physicochemical characteristics that are rooted in their chemical structures. These characteristics specify the advantages and limitations of each hydrogel material for applications in cartilage tissue engineering, such as cell adhesion, scaffold degradation kinetics, and mechanical strength [73]. Alginate hydrogels are frequently utilized as scaffolds for neural tissue engineering, drug, protein/enzyme, and cell delivery, protein immobilization, bone, and cartilage tissue engineering, and protein immobilization [74–77]. A variety of alginate materials have been created to satisfy distinct application-specific criteria. Alginate and its derivatives' chemistry, characteristics, and biological uses have recently been thoroughly reviewed in reviews [78].

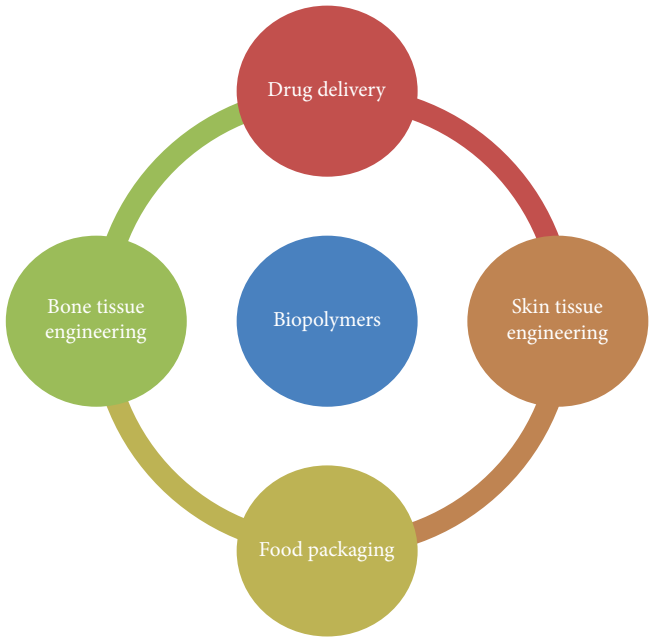


Figure 3: Shows the different uses of biopolymers.

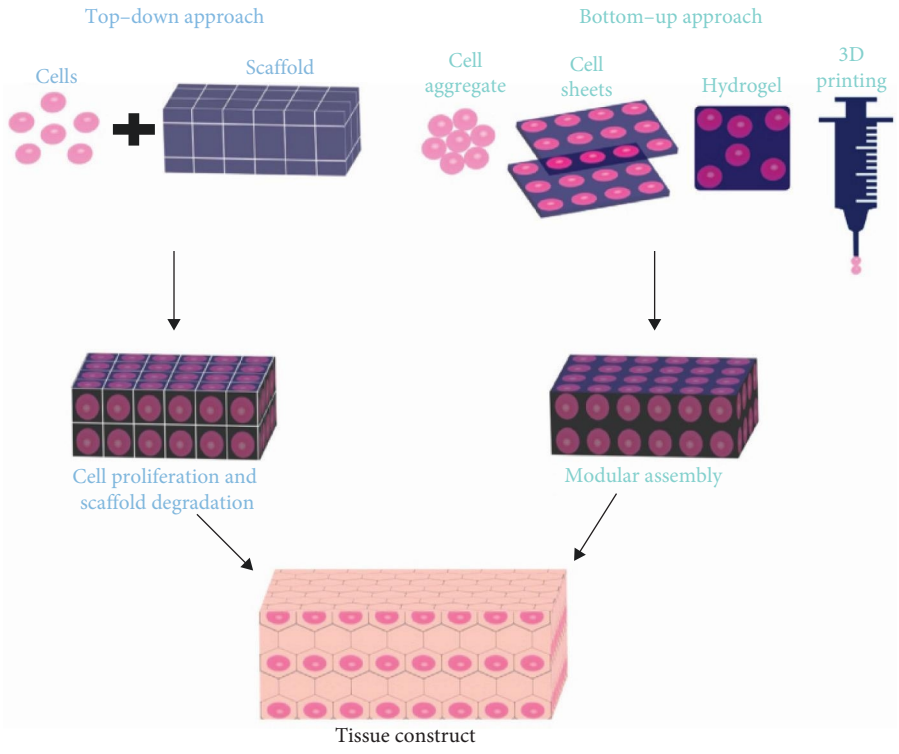


Figure 4: Top–down and bottom–up approaches of tissue engineering [81].

Tissue engineering employs top–down methods, manipulating existing tissues, and bottom–up techniques, creating tissues from cells and biomaterials, to develop innovative regenerative therapies, addressing diverse medical challenges [79]. Top–down tissue engineering entails creating new tissue constructions by dissecting an existing tissue into smaller pieces first. These elements are altered and arranged into desired structures using biomaterials. Building tissues from single cells or cell aggregates that are seeded onto biomaterial scaffolds to promote tissue development and organization is the focus of bottom–up tissue engineering [80]. Figure 4 depicts the methods used to solve diverse tissue engineering difficulties and produce viable tissue constructions for regenerative medicine and organ replacement.

Here is a list of some important biopolymers used in tissue engineering:

(1) Collagen: collagen is the most abundant protein in the ECM and is a critical component of various tissues, such as skin, bones, and cartilage. It provides structural support and promotes cell adhesion and migration. Collagen-based scaffolds are widely used in tissue engineering applications due to their excellent biocompatibility and biodegradability [82].
(2) Hyaluronic acid (HA): HA is a natural polysaccharide found in the ECM of many tissues, including skin and cartilage. It possesses excellent water retention properties and contributes to tissue hydration and lubrication. HA-based hydrogels are used to create scaffolds for tissue engineering applications, especially in cartilage repair and wound healing [83].
(3) Chitosan: chitosan is derived from chitin, a polysaccharide found in the exoskeletons of crustaceans. It has antimicrobial properties and promotes cell attachment and proliferation. Chitosan-based scaffolds are used in tissue engineering for applications like bone regeneration and wound healing [84].
(4) Fibrin: fibrin is a protein involved in the blood clotting process and is commonly used as a scaffold material in tissue engineering. It can be easily cross-linked to form hydrogels, providing a three-dimensional environment for cell growth and tissue regeneration [85].
(5) Silk fibroin: silk fibroin is derived from silk, a natural protein produced by silkworms. It has good mechanical properties and biocompatibility. Silk-based scaffolds are utilized in tissue engineering for various applications, including nerve regeneration and bone tissue engineering [86].
(6) Alginate: alginate is a polysaccharide extracted from brown algae. It forms hydrogels in the presence of divalent cations, making it suitable for encapsulating cells and promoting tissue growth in various tissue engineering applications [87].

Table 4 list biopolymers that may be combined or used singly to make scaffolds, hydrogels, and other structures that offer the right conditions for cells to develop, differentiate, and regenerate tissues. Due to their biological relevance and capacity to direct tissue formation and repair, they have a great deal of potential for use in tissue engineering and regenerative medicine. However, to improve tissue engineering outcomes and solve the unique difficulties related to different tissue types, researchers are still investigating novel techniques and biopolymer combinations.

Bio-inks play a vital role in tissue engineering, serving as printable materials for 3D bio-printing. Alginate-based bio-inks offer biocompatibility and structural support. Gelatin-based bio-inks promote cell adhesion and proliferation. Fibrin-based bio-inks facilitate tissue regeneration with the natural extracellular matrix components. Chitosan-based bio-inks possess antimicrobial properties and promote tissue integration. Each bio-ink's unique properties cater to diverse tissue engineering applications, from cartilage and bone to skin and vascular constructs.

4.2. Drug Delivery. Due to their distinctive qualities and possible uses, biopolymers have become recognized as promising materials in the field of medication delivery [99]. In terms of biocompatibility, biodegradability, and low immunogenicity, these naturally produced polymers—such as proteins, polysaccharides, and nucleic acids—offer significant benefits over synthetic polymers [100]. The pharmaceutical industry is very interested in their capacity to encapsulate and distribute therapeutic substances to specified target locations in a regulated manner.

A variety of medications, including small molecules, peptides, and proteins, can be encapsulated in biodegradable and biocompatible biopolymers that can be formed into nanoparticles or microparticles [101]. These particles can strengthen the drug's stability and solubility while also preventing it from degrading, which will increase the drug's therapeutic potency. Additionally, biopolymer-based nanoparticles' surface characteristics can be changed to provide precise targeting to sick tissues or cells, increasing medication delivery effectiveness while minimizing side effects [102]. Biopolymers can be used to improve the stability and delivery of pharmaceuticals made from nucleic acids like DNA or RNA [103]. These biomacromolecules have a low-cellular uptake and are extremely susceptible to enzymatic breakdown. Nucleic acids can be better protected from enzymatic degradation and given to target cells more easily by complexing with biopolymers. Gene therapy and vaccines based on nucleic acids may be made possible by biopolymer-based formulations that preserve nucleic acids and enhance their intracellular delivery [100].

According to Tables 5–7 biopolymers are great candidates for the creation of efficient and targeted drug delivery systems because of their biocompatibility, biodegradability, and ability to encapsulate and release therapeutic compounds in a controlled manner. The topic of medication delivery has great potential for the biopolymers. Further research and development in this field will enable the use of biopolymers in improving medicine delivery and revolutionizing the pharmaceutical business, ultimately benefiting patients throughout the world. Current research on the use of cellulose and its derivatives in medication administration is summarized in Table 5.

By modifying cellulose through chemical derivatization, its properties can be tailored to achieve controlled drug release, improved stability, and targeted delivery, making it a promising candidate for efficient and safe drug delivery systems in the pharmaceutical industry [113]. Table 6 outlines current research on chitosan's potential in drug delivery applications.

Chitosan, a natural biopolymer derived from chitin, exhibits biocompatibility, biodegradability, and low toxicity, making it an ideal candidate for encapsulating drugs and targeting specific sites in the body. Its unique properties offer potential

Table 4: Typical uses for various bio-inks [88–98].

Bioink	Composition	Study performed and potential application
Agarose based	Agarose, collagen (0.2%–0.5% each) + fibrinogen (1.25%)	(i) Bioink was evaluated for compatibility with human umbilical vein endothelial cells and human dermal fibroblast using by immunohistology and two photon laser scanning microscopy (ii) Formed bioink was readily printable in 3D manner and stimulated angiogenesis in prepared scaffold studied
Alginate based	Alginate (5% w/v) + honey (0%–10% w/v)	(i) Printed scaffolds (~10 × 10 mm, 100 μm thickness) were compatible with 3T3 fibroblast cells (ii) Utilization of honey (1%–2% w/v) in bioprinted scaffolds compromised mechanical strength however enhancement in cellular proliferation was noted without alteration in printability
Chitosan based	Chitosan + catechol (1% w/v each)	(i) Writable bioink made-up of catechol and chitosan were easily formed under serum culture media without external intervention and found compatible with L929 cells (ii) Incorporation of vanadium was found essential to enhance mechanical strength of formed scaffold
Clay based	Sodium montmorillonite + alginate (4% w/v each) + carboxymethyl cellulose (0%–3% w/v)	(i) Hybrid clay hydrogel was constructed to provide cell friendly environment and pre- requisite mechanical strength (ii) BxPC3 cells were easily encapsulated the hybrid material prepared with cell viability of around 84% after 7 day incubation (iii) Carboxymethyl cellulose and Montmorrilonite served as excellent fillers for the hydrogel system to tackle hurdles related to mechanical strength and shape fidelity
Collagen-alginate bio-ink	Sodium alginate and collagen (in ratio 3 : 1) and 4 : 1)	(i) 3D constructs formed strengthening treatment with 10% CaCl2and 0.1% FBS were suitable for cartilage tissue engineering (ii) Sodium alginate and collagen scaffolds helped preserve phenotype of the chondrocyte cells studied
Guar gum	Gelatin (1.5% *w/v*) and guar gum (1%, 2.5%, 5%, 10% *w/v*)	(i) Formed scaffolds were found biocompatible to be Kerationcytes cells (ii) Physical parameters, like contact angle and surface roughness of the optimized scaffold were favourable for soft tissue engineering
Gelatin hyaluronic acid based bioink	2-Hydroxyethyl acrylate (HEA) grafted hyaluronic scid and gelatin appx. 1 : 1 ratio	(i) Hybrid composite bioink exhibited excellent gel printing processability also supporting growth of MC3T3 bone cells (ii) Sustained release of dimethyloxalylglycine (a potent modulator of bone stem cells) was obtained from the matrix
Hydroxyapatite-modified hydrogel	Methacrylated hyaluronic acid and hydroxyapatite in 5% by weight of bioink produced	(i) Incorporation of hydroxyapatite provided required structural integrity to the bioink (ii) Further encapsulated cells promoted secretion of matrix components collagen 1, fibronectin, alkaline phosphatase and osteopontin as proven using staining techniques by staining of bone matrix components
Alginate/methyl cellulose hydrogel	Bioink was composed of alginic acid and methyl cellulose in different ratios of 3 : 1, 3 : 3, and 3 : 9	(i) Alginate and methyl cellulose with ratio of 3 : 9 displayed excellent thixotropic property, extrudability (ii) Trisodium citrate greatly improved the stackability aiding printing of upto 150 layers with high bio-compatibility toward mouse fibroblast L929 cell lines
Nanocellulose based	Oxidized nanocellulose fiber (0.25% w/w) + alginate (4% w/w) + gelatine(5% w/w) + bio-active glass(1% w/w)	(i) Human mesenchymal stem cells (from bone marrow) and Saos-2 cells were easily printable using the formed hybrid bioink (ii) Inclusion of bio-active glass in the bioink stimulated early secretion of ALP (an osteogenic marker)
Silk fibroin (SF) based	Silk fibrion was methacrylated to produce hydrogel	(i) Outstanding rheological and mechanical properties were reported for methacrylated silk fibrion which would be fine tuned with modulation of the extent of methacrylation performed (ii) Highly complex structures like heart, vessel, brain, trachea etc were easily printed

Table 5: Recent studies on the utilization of cellulose and its derivatives for use in medication delivery [104–112].

Cellulose and cellulose based drug delivery systems	Drug(s)
Matrix tablets made of alginate, HPMC, and microcrystalline cellulose	Bisoprolol fumarate
In situ crosslinked alginate matrix tablets for sustained release prepared using microcrystalline cellulose	Salbutamol sulfate
Chitosan-HPMC matrices for hydrodynamically balanced capsules	Moxifloxacin HCl
Floating capsules containing alginate-HPMC-based beads	Salbutamol sulfate
Ethyl cellulose microparticles	Metformin HCl
Alginate-HPMC and alginate-sodium CMC buccal patches	Atenolol
Alginate-methyl cellulose mucoadhesive microcapsules	Gliclazide
Alginate/HPMC-based in situ gelling ophthalmic system	Gatifloxacin
CMC/graphene oxide bio-nanocomposite buccal hydrogel beads	Doxorubicin

Table 6: Recent researches on the uses of chitosan for drug delivery applications [114–121].

Chitosan-based drug delivery system	Drug(s)
Chitosan succinate and chitosan phthalate microspheres for oral delivery	Insulin
Chitosan-gelatin films	Tyrosol and ferulic acid
Chitosan-HPMC matrices as carriers for hydrodynamically balanced capsules	Moxifloxacin HCl
Chitosan-tamarind seed polysaccharide interpenetrating polymeric network microparticles	Aceclofenac
Photoresponsive chitosan conjugated 5-fluorouracil prodrug nanocarrier	5-Fluorouracil
Chitosan-egg albumin nanoparticles for oral Alprazolam drug delivery	Alprazolam
Carbopol gel containing chitosan-egg albumin nanoparticles for transdermal delivery	Aceclofenac
Polysorbate 80 coated crosslinked chitosan nanoparticles for brain targeting	Ropinirole HCI
On-chip made chitosan nanoparticles for cancer therapeutics	Paclitaxel
Magnetic stimuli-responsive chitosan-based vancomycin drug delivery biocomposite for multiple triggered release	Vancomycin

Table 7: Recent researches on the uses of gelatin in drug delivery applications [123–130].

Gelatin-based drug delivery systems	Drug(s)
Semi-interpenetrating hydrogels from carboxymethyl guar gum and gelatin	Ciprofloxacin
Chitosan-gelatin films	Tyrosol and ferulic acid
Liposomes entrapped in chitosan-gelatin hydrogels	Calcein
Gum arabic aldehyde-gelatin nanogels for breast cancer therapy	Curcumin
Mucoadhesive buccal tablets based on chitosan-gelatin microparticles	Propranolol HCI
Gelatin nanoparticles for ocular delivery	Moxifloxacin
Gelatin liposomes for HIV therapy	Stavudine
Gelatin conjugate microparticles for the treatment of tuberculosis	Isoniazid and rifampicin
EGFR-targeted gelatin nanoparticles for systemic administration in an orthotopic pancreatic cancer model	Gemcitabine

advancements in targeted therapies and sustained drug release systems [122]. Table 7 summarizes current studies on gelatin's usage in drug delivery applications.

Gelatin finds versatile applications in drug delivery, serving as a biocompatible and biodegradable material. Its encapsulation properties aid in controlled release of pharmaceuticals, enhancing drug stability and targeting specific sites. Additionally, it enables the creation of various drug carriers like nanoparticles, microparticles, and hydrogels, fostering advancements in personalized medicine [131].

5. Future Prospects and Challenges

Biopolymers have bright futures since they provide a sustainable and eco-friendly alternative to synthetic polymers that are often used in the industry [113]. Biopolymers, which are made from renewable resources including plants, microorganisms, and algae, provide a solution to the difficulties of plastic pollution and the depletion of fossil fuels. Applications for biopolymers include the packaging, textiles, and automotive, building, and biomedical sectors [114]. They are a desirable alternative for lowering waste and carbon impact because of their biodegradability and compatibility with the current manufacturing techniques. Additionally, biopolymers have the ability to display distinctive qualities and functions, enabling the creation of novel materials with improved performance. For biopolymers to be widely used, a number of issues must be resolved. These include enhancing its cost-effectiveness, scalability of production, mechanical strength, and thermal stability. This review paper has highlighted

the significant progress made in this field, showcasing the potential of biopolymers as a promising alternative to conventional synthetic materials. Looking ahead, several future prospects can be envisioned to drive this research area toward greater success. The ability to tailor the biodegradability of biopolymers opens up exciting possibilities for tissue engineering and drug delivery. By controlling the degradation rates, researchers can develop biopolymer-based scaffolds that provide mechanical support during tissue regeneration and gradually degrade as new tissue forms, eliminating the need for invasive removal procedures. The incorporation of bioactive molecules, such as growth factors and cytokines, into biopolymer matrices can enhance tissue regeneration and drug delivery applications. Future prospects include optimizing the release kinetics of these bioactive molecules to mimic the natural healing process, thereby accelerating tissue repair and reducing the need for repeated administrations. The primary challenges lies in establishing standardized production processes for biopolymer-based materials. Large-scale manufacturing with consistent quality is essential for their widespread adoption in tissue engineering and drug delivery, and this requires addressing variability in source materials, extraction techniques, and processing methods. While biopolymers offer inherent biocompatibility, some variations may still trigger immune responses in certain individuals. Understanding and minimizing immunogenicity is critical to ensure successful clinical translation. Additionally, achieving optimal biodegradation kinetics remains challenging, as it varies with tissue type and environmental conditions. As with any emerging technology, the cost-effectiveness of biopolymer-based solutions will influence their widespread adoption. Developing efficient and economical production methods and scaling up manufacturing processes are vital to make these materials accessible to a broader population. Despite the positive outlook for biopolymers, these issues must be resolved if they are to reach their full potential as a sustainable alternative to synthetic polymers [115]. The development of eco-friendly biopolymers for tissue engineering and drug delivery is an exciting area of research with enormous potential for transforming biomedical applications. With continued innovation and concerted efforts to overcome existing challenges, these biopolymers can pave the way for sustainable, personalized, and highly effective medical treatments in the future. Embracing these prospects and addressing the challenges will drive this field toward a greener and healthier future.

6. Conclusion

The development of eco-friendly biopolymers for use in tissue engineering and drug delivery holds tremendous promise as a sustainable and innovative approach to revolutionize the biomedical field. This comprehensive review highlights the remarkable progress achieved in recent years, emphasizing the significant advantages that biopolymers offer over traditional synthetic polymers. The utilization of natural, renewable resources for biopolymer production not only reduces the dependence on fossil fuels but also mitigates the environmental impact associated with nonbiodegradable materials. The biocompatibility and biodegradability of these biopolymers make them ideal candidates for a wide range of applications, including tissue engineering, drug delivery, and regenerative medicine. One of the key takeaways from this review is the vast array of sources available for biopolymer extraction, such as polysaccharides (e.g., chitosan, cellulose, and starch), proteins (e.g., collagen, gelatin, and silk fibroin), and nucleic acids (e.g., DNA and RNA). These diverse sources present researchers with an ever-expanding toolkit, allowing for tailoring biopolymers with specific properties to meet the unique requirements of different applications. Furthermore, advances in the processing techniques, such as electrospinning, 3D bioprinting, and microfluidics, have facilitated the fabrication of intricate structures, mimicking native tissues and organs more accurately. This has paved the way for the development of patient-specific implants and drug delivery systems that enhance the therapeutic efficacy while minimizing adverse effects.

However, despite these remarkable achievements, several challenges still lie ahead in the field of eco-friendly biopolymers. Standardization of production methods and quality control protocols remains a priority to ensure consistency and reproducibility across different biopolymer types. Additionally, the long-term stability and degradation rates of these materials need further investigation to optimize their performance in various biomedical applications. Addressing these challenges will not only enhance the reliability of biopolymer-based products but also facilitate their regulatory approval and widespread clinical adoption. The integration of biopolymers with advanced biomaterials, such as nanoparticles and hydrogels, presents an exciting avenue for the next generation of tissue engineering and drug delivery systems. These hybrid approaches could potentially offer enhanced therapeutic capabilities, targeted drug release, and better control over cellular responses. Furthermore, combining biopolymers with bioactive molecules, growth factors, or stem cells can unlock new possibilities in tissue regeneration, organ transplantation, and personalized medicine. As the field continues to evolve, collaboration between researchers, clinicians, and industry stakeholders will be crucial to propel eco-friendly biopolymer technologies into the mainstream. Government support, funding initiatives, and public awareness campaigns will also play pivotal roles in driving the adoption of sustainable biomaterials in the healthcare sector. By capitalizing on interdisciplinary expertise and embracing innovative approaches, we can accelerate the translation of biopolymer-based advancements from the laboratory to the clinical practice. In summary, this review highlights the immense potential of eco-friendly biopolymers in tissue engineering and drug delivery, emphasizing their sustainable nature, biocompatibility, and versatility. The strides made in biopolymer research have paved the way for a greener, more ethical approach to biomedical applications, shaping the future of regenerative medicine and patient care. With continued dedication, research, and collaborative efforts, eco-friendly biopolymers are poised to revolutionize the biomedical landscape and usher in a new era of therapeutic

solutions that are not only effective but also environmentally responsible.

Data Availability

The data used in this review article are derived from publicly available scientific literature and research papers obtained from reputable databases such as PubMed, Scopus, and Web of Science. The specific references for the data used in this review are cited appropriately in the reference list. No primary data or experimental results were generated for this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Md. Zobair Al Mahmud specializes in writing, while Md. Didarul Islam is proficient in data management and revision. Meanwhile, Md Hosne Mobarak excels in conceptualization and revision.

References

[1] D. Gnanasekaran, *Green Biopolymers and their Nanocomposites*, Springer, Singapore, 2019.

[2] A. Mahmood, D. Patel, B. Hickson, J. DesRochers, and X. Hu, "Recent progress in biopolymer-based hydrogel materials for biomedical applications," *International Journal of Molecular Sciences*, vol. 23, no. 3, Article ID 1415, 2022.

[3] M. Martina and D. W. Hutmacher, "Biodegradable polymers applied in tissue engineering research: a review," *Polymer International*, vol. 56, no. 2, pp. 145–157, 2007.

[4] C. Mukherjee, D. Varghese, J. S. Krishna et al., "Recent advances in biodegradable polymersproperties, applications and future prospects," *European Polymer Journal*, vol. 192, Article ID 112068, 2023.

[5] J. Jacob, J. T. Haponiuk, S. Thomas, and S. Gopi, "Biopolymer based nanomaterials in drug delivery systems: a review," *Materials Today Chemistry*, vol. 9, pp. 43–55, 2018.

[6] N. K. Singh, J. Baranwal, S. Pati, B. Barse, R. H. Khan, and A. Kumar, "Application of plant products in the synthesis and functionalisation of biopolymers," *International Journal of Biological Macromolecules*, vol. 237, Article ID 124174, 2023.

[7] C. Zhang, H. Wang, W. Zeng, and Q. Zhou, "High biobased carbon content polyurethane dispersions synthesized from fatty acid-based isocyanate," *Industrial & Engineering Chemistry Research*, vol. 58, no. 13, pp. 5195–5201, 2019.

[8] C. Zhang, H. Wang, and Q. Zhou, "Waterborne isocyanate-free polyurethane epoxy hybrid coatings synthesized from sustainable fatty acid diamine," *Green Chemistry*, vol. 22, no. 4, pp. 1329–1337, 2020.

[9] B. T. Reves, J. A. Jennings, J. D. Bumgardner, and W. O. Haggard, "Preparation and functional assessment of composite chitosan-nano-hydroxyapatite scaffolds for bone regeneration," *Journal of Functional Biomaterials*, vol. 3, no. 1, pp. 114–130, 2012.

[10] B. T. Reves, J. A. Jennings, J. D. Bumgardner, and W. O. Haggard, "Osteoinductivity assessment of BMP-2 loaded composite chitosan-nano-hydroxyapatite scaffolds in a rat muscle pouch," *Materials*, vol. 4, no. 8, pp. 1360–1374, 2011.

[11] A. Mohapatra, M. A. Harris, M. Ghimire et al., "Chitosan microbeads with MNP on printed electrodes for electric stimulus responsive drug delivery," in *2017 IEEE International Symposium on Medical Measurements and Applications (MeMeA)*, pp. 464–469, IEEE, 2017.

[12] M. Nourbakhsh, P. Zarrintaj, S. H. Jafari et al., "Fabricating an electroactive injectable hydrogel based on pluronic–chitosan/aniline–pentamer containing angiogenic factor for functional repair of the hippocampus ischemia rat model," *Materials Science and Engineering: C*, vol. 117, Article ID 111328, 2020.

[13] R. L. Reddy, V. S. Reddy, and G. A. Gupta, "Study of bioplastics as green and sustainable alternative to plastics," *International Journal of Emerging Technology and Advanced Engineering*, vol. 3, no. 5, pp. 76–81, 2013.

[14] K. Moraczewski, R. Malinowski, D. Łączny, and M. Macko, "Surface modification of maize stem with polydopamine and tannic acid coatings," *Surfaces and Interfaces*, vol. 26, Article ID 101319, 2021.

[15] U. E. Erdogan, *Success and failure factors for the adoption of bio-based packaging*, M.S. ThesisStockholm, Sweden, 2013.

[16] N. Morin-Crini, E. Lichtfouse, G. Torri, and G. Crini, *Fundamentals and Applications of Chitosan. Sustainable Agriculture Reviews 35. Chitin and Chitosan: History, Fundamentals and Innovations, 35*, pp. 49–123, Springer International Publishing AG, 2019.

[17] K. Molenveld and T. M. Slaghek, "Recent developments in biodegradable cellulose-based plastics," in *Biodegradable Polymers in the Circular Plastics Economy*, pp. 273–298, 2022.

[18] T. H. Silva, A. Alves, B. M. Ferreira et al., "Materials of marine origin: a review on polymers and ceramics of biomedical interest," *International Materials Reviews*, vol. 57, no. 5, pp. 276–306, 2013.

[19] M. J. Cardoso, R. R. Costa, and J. F. Mano, "Marine origin polysaccharides in drug delivery systems," *Marine Drugs*, vol. 14, no. 2, p. 34, 2016.

[20] B. Bajić, D. Vučurović, Đ. Vasić, R. Jevtić-Mučibabić, and S. Dodić, "Biotechnological production of sustainable microbial proteins from agro-industrial residues and by-products," *Foods*, vol. 12, no. 1, p. 107, 2023.

[21] S. I. Ahmad, R. Ahmad, M. S. Khan et al., "Chitin and its derivatives: structural properties and biomedical applications," *International Journal of Biological Macromolecules*, vol. 164, pp. 526–539, 2020.

[22] L. Ghimici and M. Nichifor, "Novel biodegradable flocculanting agents based on cationic amphiphilic polysaccharides," *Bioresource Technology*, vol. 101, no. 22, pp. 8549–8554, 2010.

[23] A. Leandro, L. Pereira, and A. M. M. Gonçalves, "Diverse applications of marine macroalgae," *Marine Drugs*, vol. 18, no. 1, Article ID 17, 2020.

[24] T. Khan, J. K. Park, and J.-H. Kwon, "Functional biopolymers produced by biochemical technology considering applications in food engineering," *Korean Journal of Chemical Engineering*, vol. 24, no. 5, pp. 816–826, 2007.

[25] T. Carvalho, G. Guedes, F. L. Sousa, C. S. Freire, and H. A. Santos, "Latest advances on bacterial cellulose-based materials for wound healing, delivery systems, and tissue engineering," *Biotechnology Journal*, vol. 14, no. 12, Article ID 1900059, 2019.

[26] S. Pradhan, A. K. Brooks, and V. K. Yadavalli, "Nature-derived materials for the fabrication of functional

biodevices," *Materials Today Bio*, vol. 7, Article ID 100065, 2020.

[27] G. Gopinath, S. Ayyasamy, P. Shanmugaraj, R. Swaminathan, K. Subbiah, and S. Kandasamy, "Effects of biopolymers in energy storage applications: a state-of-the-art review," *Journal of Energy Storage*, vol. 70, Article ID 108065, 2023.

[28] G. P. Udayakumar, S. Muthusamy, B. Selvaganesh et al., "Ecofriendly biopolymers and composites: preparation and their applications in water-treatment," *Biotechnology Advances*, vol. 52, Article ID 107815, 2021.

[29] D. Elieh-Ali-Komi and M. R. Hamblin, "Chitin and chitosan: production and application of versatile biomedical nanomaterials," *International Journal of Advanced Research*, vol. 4, pp. 411–427, 2016.

[30] S. Satitsri and C. Muanprasat, "Chitin and chitosan derivatives as biomaterial resources for biological and biomedical applications," *Molecules*, vol. 25, no. 24, Article ID 5961, 2020.

[31] I. Aranaz, A. R. Alcántara, M. C. Civera et al., "An overview of its properties and applications," *Polymers*, vol. 13, no. 19, Article ID 3256, 2021.

[32] A. Farooq, M. K. Patoary, M. Zhang et al., "Cellulose from sources to nanocellulose and an overview of synthesis and properties of nanocellulose/zinc oxide nanocomposite materials," *International Journal of Biological Macromolecules*, vol. 154, pp. 1050–1073, 2020.

[33] K. Y. Lee and D. J. Mooney, "Alginate: properties and biomedical applications," *Progress in Polymer Science*, vol. 37, no. 1, pp. 106–126, 2012.

[34] A. J. F. Carvalho, "Starch: major sources, properties and applications as thermoplastic materials," in *Monomers, Polymers and Composites from Renewable Resources*, pp. 321–342, Elsevier, Amsterdam, The Netherlands, 2008.

[35] Z. Movasaghi, S. Rehman, and D. I. ur Rehman, "Fourier transform infrared (FTIR) spectroscopy of biological tissues," *Applied Spectroscopy Reviews*, vol. 43, no. 2, pp. 134–179, 2008.

[36] R. K. Ramakrishnan, S. Wacławek, M. Černík, and V. V. Padil, "Biomacromolecule assembly based on gum kondagogu–sodium alginate composites and their expediency in flexible packaging films," *International Journal of Biological Macromolecules*, vol. 177, pp. 526–534, 2021.

[37] M. Ghasemlou, F. Khodaiyan, and A. Oromiehie, "Rheological and structural characterisation of film-forming solutions and biodegradable edible film made from kefiran as affected by various plasticizer types," *International Journal of Biological Macromolecules*, vol. 49, no. 4, pp. 814–821, 2011.

[38] E. H. Arias-Nava, D. J. Valles-Rosales, and B. P. Sullivan, "Biopolymer non-parametric analysis: a degradation study under accelerated destructive tests," *Polymers*, vol. 15, no. 3, Article ID 620, 2023.

[39] P. de Vos, M. M. Faas, M. Spasojevic, and J. Sikkema, "Encapsulation for preservation of functionality and targeted delivery of bioactive food components," *International Dairy Journal*, vol. 20, no. 4, pp. 292–302, 2010.

[40] P. Burey, B. R. Bhandari, T. Howes, and M. J. Gidley, "Hydrocolloid gel particles: formation, characterization, and application," *Critical Reviews in Food Science and Nutrition*, vol. 48, no. 5, pp. 361–377, 2008.

[41] R. Diab, C. Jaafar-Maalej, H. Fessi, and P. Maincent, "Engineered nanoparticulate drug delivery systems: the next frontier for oral administration?" *The AAPS Journal*, vol. 14, no. 4, pp. 688–702, 2012.

[42] C.-Y. Yu, X.-C. Zhang, F.-Z. Zhou, X.-Z. Zhang, S.-X. Cheng, and R.-X. Zhuo, "Sustained release of antineoplastic drugs from chitosan-reinforced alginate microparticle drug delivery systems," *International Journal of Pharmaceutics*, vol. 357, no. 1-2, pp. 15–21, 2008.

[43] K. Mladenovska, O. Cruaud, P. Richomme et al., "5-ASA loaded chitosan–Ca–alginate microparticles: preparation and physicochemical characterization," *International Journal of Pharmaceutics*, vol. 345, no. 1-2, pp. 59–69, 2007.

[44] A. J. Ribeiro, C. Silva, D. Ferreira, and F. Veiga, "Chitosan-reinforced alginate microspheres obtained through the emulsification/internal gelation technique," *European Journal of Pharmaceutical Sciences*, vol. 25, no. 1, pp. 31–40, 2005.

[45] T. Huq, A. Khan, R. A. Khan, B. Riedl, and M. Lacroix, "Encapsulation of probiotic bacteria in biopolymeric system," *Critical Reviews in Food Science and Nutrition*, vol. 53, no. 9, pp. 909–916, 2013.

[46] A. Hanafi, N. Nograles, S. Abdullah, M. N. Shamsudin, and R. Rosli, "Cellulose acetate phthalate microencapsulation and delivery of plasmid DNA to the intestines," *Journal of Pharmaceutical Sciences*, vol. 102, no. 2, pp. 617–626, 2013.

[47] J. Tripathy and A. M. Raichur, "Designing carboxymethyl cellulose based layer-by-layer capsules as a carrier for protein delivery," *Colloids and Surfaces B: Biointerfaces*, vol. 101, pp. 487–492, 2013.

[48] O. Gunduz, Z. Ahmad, E. Stride, and M. Edirisinghe, "Continuous generation of ethyl cellulose drug delivery nanocarriers for microbubbles," *Pharmaceutical Research*, vol. 30, no. 1, pp. 225–237, 2013.

[49] A. Montes, M. D. Gordillo, C. Pereyra, and E. J. Martinez de la Ossa, "Co-precipitation of amoxicillin and ethyl cellulose microparticles by supercritical antisolvent process," *The Journal of Supercritical Fluids*, vol. 60, pp. 75–80, 2011.

[50] S. Suarez, G. N. Grover, R. L. Braden, K. L. Christman, and A. Almutairi, "Tunable protein release from acetalated dextran microparticles: a platform for delivery of protein therapeutics to the hear post-MI," *Biomacromolecules*, vol. 14, no. 11, pp. 3927–3935, 2013.

[51] H. Wang, S. Han, J. Sun, T. Fan, C. Tian, and Y. Wu, "Amphiphilic dextran derivatives nanoparticles for the delivery of mitoxantrone," *Journal of Applied Polymer Science*, vol. 126, no. S1, pp. E35–43, 2012.

[52] C. B. Fritzen-Freire, E. S. Prudêncio, S. S. Pinto, I. B. Muñoz, and R. D. M. C. Amboni, "Effect of microencapsulation on survival of Bifidobacterium BB-12 exposed to simulated gastrointestinal conditions and heat treatments," *LWT - Food Science and Technology*, vol. 50, no. 1, pp. 39–44, 2013.

[53] N. Poulain, I. Dez, C. Perrio, M.-C. Lasne, M.-P. Prud'homme, and E. Nakache, "Microspheres based on inulin for the controlled release of serine protease inhibitor: preparation, characterization and in vitro release," *Journal of Controlled Release*, vol. 92, no. 1-2, pp. 27–38, 2003.

[54] S. Beirão-da-Costa, C. Duarte, A. I. Bourbon et al., "Inulin potential for encapsulation and controlled delivery of oregano essential oil," *Food Hydrocolloids*, vol. 33, no. 2, pp. 199–206, 2013.

[55] P. Garcia, J. Vega, P. Jimenex, J. Santos, and P. Robert, "Alpha-tocopherol microspheres with cross-linked and acetylated inulin and their release profile in a hydrophilic model," *European Journal of Lipid Science and Technology*, vol. 115, no. 7, pp. 811–819, 2013.

[56] A. M. Matalanis, *Fabrication, Characterization and Utilization of Filled Hydrogel Particles as Food Grade Delivery Systems*, University of Massachusetts, Amherst, 2012.

[57] A. Matalanis and D. J. McClements, "Hydrogel microspheres for encapsulation of lipophilic components: optimization of fabrication and performance," *Food Hydrocolloids*, vol. 31, no. 1, pp. 15–25, 2013.

[58] H. Kim and K. Na, "Evaluation of succinylated pullulan for long-term protein delivery in poly(lactide-co-glycolide) microspheres," *Macromolecular Research*, vol. 18, no. 8, pp. 812–819, 2010.

[59] D. Sun-Waterhouse, S. S. Wadhwa, and G. I. N. Waterhouse, "Spray-drying microencapsulation of polyphenol bioactives: a comparative study using different natural fibre polymers as encapsulants," *Food and Bioprocess Technology*, vol. 6, no. 9, pp. 2376–2388, 2013.

[60] C. Chranioti and C. Tzia, "Binary mixtures of modified starch, maltodextrin and chitosan as efficient encapsulating agents of fennel oleoresin," *Food and Bioprocess Technology*, vol. 6, no. 11, pp. 3238–3246, 2013.

[61] A. Lopez-Cordoba, L. Deladino, and M. Martino, "Release of yerba mate antioxidants from corn starch–alginate capsules as affected by structure," *Carbohydrate Polymers*, vol. 99, pp. 150–157, 2014.

[62] P. Zimet and Y. D. Livney, "Beta-lactoglobulin and its nanocomplexes with pectin as vehicles for omega-3 polyunsaturated fatty acids," *Food Hydrocolloids*, vol. 23, no. 4, pp. 1120–1126, 2009.

[63] B. Bigliardi and F. Galati, "Innovation trends in the food industry: the case of functional foods," *Trends in Food Science & Technology*, vol. 31, no. 2, pp. 118–129, 2013.

[64] M. H. Lee, S. Y. Kim, and H. J. Park, "Effect of halloysite nanoclay on the physical, mechanical, and antioxidant properties of chitosan films incorporated with clove essential oil," *Food Hydrocolloids*, vol. 84, pp. 58–67, 2018.

[65] M. Sun, N. Liu, S. Ni, H. Bian, Y. Fu, and X. Chen, "Poplar hot water extract enhances barrier and antioxidant properties of chitosan/bentonite composite film for packaging applications," *Polymers*, vol. 11, no. 10, Article ID 1614, 2019.

[66] Z. Wang, H. Kang, W. Zhang, S. Zhang, and J. Li, "Improvement of interfacial interactions using natural polyphenol-inspired tannic acid-coated nanoclay enhancement of soy protein isolate biofilms," *Applied Surface Science*, vol. 401, pp. 271–282, 2017.

[67] V. M. Azevedo, E. K. Silva, C. F. G. Pereira, J. M. G. da Costa, and S. V. Borges, "Whey protein isolate biodegradable films: influence of the citric acid and montmorillonite clay nanoparticles on the physical properties," *Food Hydrocolloids*, vol. 43, pp. 252–258, 2015.

[68] N. R. Saha, I. Roy, G. Sarkar et al., "Development of active packaging material based on cellulose acetate butyrate/polyethylene glycol/aryl ammonium cation modified clay," *Carbohydrate Polymers*, vol. 187, pp. 8–18, 2018.

[69] H.-M. Cheng, X.-W. Gao, K. Zhang et al., "A novel antimicrobial composite: ZnAl-hydrotalcite with *p*-hydroxybenzoic acid intercalation and its possible application as a food packaging material," *New Journal of Chemistry*, vol. 43, no. 48, pp. 19408–19414, 2019.

[70] G. Biddeci, G. Cavallaro, F. Di Blasi et al., "Halloysite nanotubes loaded with peppermint essential oil as filler for functional biopolymer film," *Carbohydrate Polymers*, vol. 152, pp. 548–557, 2016.

[71] W. Cui, Y. Zhou, and J. Chang, "Electrospun nanofibrous materials for tissueengineering and drug delivery," *Science and Technology of Advanced Materials*, vol. 11, Article ID 01410, 2010.

[72] H. Pereira, A. M. Frias, J. M. Oliveira, J. Esprequeira-Mendes, and R. L. Reis, "Tissue engineering and regenerative medicine strategies in meniscus lesions," *Arthroscopy*, vol. 27, no. 12, pp. 1706–1719, 2011.

[73] W. Zhao, X. Jin, Y. Cong, Y. Liu, and J. Fu, "Degradable natural polymer hydrogels for articular cartilage tissue engineering," *Journal of Chemical Technology & Biotechnology*, vol. 88, no. 3, pp. 327–339, 2013.

[74] C. C. Ribeiro, C. C. Barrias, and M. A. Barbosa, "Calcium phosphatealginate microspheres as enzyme delivery matrices," *Biomaterials*, vol. 25, no. 18, pp. 4363–4373, 2004.

[75] A. Martinsen, I. Storrø, and G. Skjåk-Braek, "Alginate as immobilization material: III. diffusional properties," *Biotechnology and Bioengineering*, vol. 39, no. 2, pp. 186–194, 1992.

[76] E. Alsberg, K. W. Anderson, A. Albeiruti, R. T. Franceschi, and D. J. Mooney, "Cell-interactive alginate hydrogels for bone tissue engineering," *Journal of Dental Research*, vol. 80, no. 11, pp. 2025–2029, 2001.

[77] E. Alsberg, K. W. Anderson, A. Albeiruti, J. A. Rowley, and D. J. Mooney, "Engineering growing tissues," *Proceedings of the National Academy of Sciences*, vol. 99, no. 19, pp. 12025–12030, 2002.

[78] S. N. Pawar and K. J. Edgar, "Alginate derivatization: a review of chemistry, properties and applications," *Biomaterials*, vol. 33, no. 11, pp. 3279–3305, 2012.

[79] V. Kesireddy and F. K. Kasper, "Approaches for building bioactive elements into synthetic scaffolds for bone tissue engineering," *Journal of Materials Chemistry B*, vol. 4, no. 42, pp. 6773–6786, 2016.

[80] A. Indurkar, A. Pandit, R. Jain, and P. Dandekar, "Plant-based biomaterials in tissue engineering," *Bioprinting*, vol. 21, Article ID e00127, 2021.

[81] J. W. Nichol and A. Khademhosseini, "Modular tissue engineering: engineering biological tissues from the bottom up," *Soft Matter*, vol. 5, no. 7, pp. 1312–1319, 2009.

[82] A. M. Salo and J. Myllyharju, "Prolyl and lysyl hydroxylases in collagen synthesis," *Experimental Dermatology*, vol. 30, no. 1, pp. 38–49, 2021.

[83] Y. W. Ding, X. W. Zhang, C. H. Mi, X. Y. Qi, J. Zhou, and D. X. Wei, "Recent advances in hyaluronic acid-based hydrogels for 3D bioprinting in tissue engineering applications," *Smart Materials in Medicine*, vol. 4, pp. 59–68, 2022.

[84] S. M. Ahsan, M. Thomas, K. K. Reddy, S. G. Sooraparaju, A. Asthana, and I. Bhatnagar, "Chitosan as biomaterial in drug delivery and tissue engineering," *International Journal of Biological Macromolecules*, vol. 110, pp. 97–109, 2018.

[85] P. De la Puente and D. Ludeña, "Cell culture in autologous fibrin scaffolds for applications in tissue engineering," *Experimental Cell Research*, vol. 322, no. 1, pp. 1–11, 2014.

[86] M. Farokhi, F. Mottaghitalab, Y. Fatahi et al., "Silk fibroin scaffolds for common cartilage injuries: possibilities for future clinical applications," *European Polymer Journal*, vol. 115, pp. 251–267, 2019.

[87] D. R. Sahoo and T. Biswal, "Alginate and its application to tissue engineering," *SN Applied Sciences*, vol. 3, no. 1, Article ID 30, 2021.

[88] F. Kreimendahl, M. Köpf, A. L. Thiebes et al., "Three-dimensional printing and angiogenesis: tailored agarose-type I collagen blends comprise threedimensional printability and angiogenesis potential for tissue-engineered substitutes," *Tissue Engineering Part C: Methods*, vol. 23, no. 10, pp. 604–615, 2017.

[89] S. Datta, R. Sarkar, V. Vyas et al., "Alginate-honey bioinks with improved cell responses for applications as bioprinted tissue engineered constructs," *Journal of Materials Research*, vol. 33, no. 14, pp. 2029–2039, 2018.

[90] D. Lee, J. P. Park, M.-Y. Koh et al., "Chitosan-catechol: a writable bioink under serum culture media," *Biomaterials Science*, vol. 6, no. 5, pp. 1040–1047, 2018.

[91] M. A. Habib and B. Khoda, "Development of clay based novel bio-ink for 3D bio-printing process," *Procedia Manufacturing*, vol. 26, pp. 846–856, 2018.

[92] X. Yang, Z. Lu, H. Wu, W. Li, L. Zheng, and J. Zhao, "Collagen-alginate as bioink for three-dimensional (3D) cell printing based cartilage tissue engineering," *Materials Science and Engineering: C*, vol. 83, pp. 195–201, 2018.

[93] A. Indurkar, P. Bangde, M. Gore, P. Reddy, R. Jain, and P. Dandekar, "Optimization of guar gum-gelatin bioink for 3D printing of mammalian cells," *Bioprinting*, vol. 20, Article ID e00101, 2020.

[94] I. Noh, N. Kim, H. N. Tran, J. Lee, and C. Lee, "3D printable hyaluronic acid-based hydrogel for its potential application as a bioink in tissue engineering," *Biomaterials Research*, vol. 23, no. 1, 2019.

[95] A. Wenz, K. Borchers, G. E. M. Tovar, and P. J. Kluger, "Bone matrix production in hydroxyapatite-modified hydrogels suitable for bone bioprinting," *Biofabrication*, vol. 9, no. 4, Article ID 044103, 2017.

[96] H. Li, Y. J. Tan, K. F. Leong, and L. Li, "3D bioprinting of highly thixotropic alginate/methylcellulose hydrogel with strong interface bonding," *ACS Applied Materials & Interfaces*, vol. 9, no. 23, pp. 20086–20097, 2017.

[97] M. Ojansivu, A. Rashad, A. Ahlinder et al., "Wood-based nanocellulose and bioactive glass modified gelatin–alginate bioinks for 3D bioprinting of bone cells," *Biofabrication*, vol. 11, no. 3, Article ID 035010, 2019.

[98] H. Mokhtari, M. Kharaziha, F. Karimzadeh, and S. Tavakoli, "An injectable mechanically robust hydrogel of Kappa-carrageenan-dopamine functionalized graphene oxide for promoting cell growth," *Carbohydrate Polymers*, vol. 214, pp. 234–249, 2019.

[99] N. Desai, D. Rana, S. Salave et al., "Chitosan: a potential biopolymer in drug delivery and biomedical applications," *Pharmaceutics*, vol. 15, no. 4, Article ID 1313, 2023.

[100] S. K. Nitta and K. Numata, "Biopolymer-based nanoparticles for drug/gene delivery and tissue engineering," *International Journal of Molecular Sciences*, vol. 14, no. 1, pp. 1629–1654, 2013.

[101] M. L. Verma, B. S. Dhanya, Sukriti et al., "Carbohydrate and protein based biopolymeric nanoparticles: current status and biotechnological applications," *International Journal of Biological Macromolecules*, vol. 154, pp. 390–412, 2020.

[102] S. Gopi, A. Amalraj, N. P. Sukumaran, J. T. Haponiuk, and S. Thomas, "Biopolymers and their composites for drug delivery: a brief review," *Macromolecular Symposia*, vol. 380, no. 1, Article ID 1800114, 2018.

[103] W. Li and F. C. Szoka, "Lipid-based nanoparticles for nucleic acid delivery," *Pharmaceutical Research*, vol. 24, no. 3, pp. 438–449, 2007.

[104] A. K. Nayak, B. Das, and R. Maji, "Gastroretentive hydrodynamically balanced system of ofloxacin: formulation and in vitro evaluation," *Saudi Pharmaceutical Journal*, vol. 21, no. 1, pp. 113–117, 2013.

[105] R. Maji, S. Ray, B. Das, and A. K. Nayak, "Ethyl cellulose microparticles containing metformin HCl by emulsification-solvent evaporation technique: effect of formulation variables," *International Scholarly Research Notices*, vol. 2012, Article ID 801827, 7 pages, 2012.

[106] J. Malakar, K. Das, and A. K. Nayak, "In situ cross-linked matrix tablets for sustained salbutamol sulfate release—formulation development by statistical optimization," *Polymers in Medicine*, vol. 44, no. 4, pp. 221–230, 2014.

[107] A. Verma, J. Dubey, N. Verma, and A. K. Nayak, "Chitosan-hydroxypropyl methylcellulose matrices as carriers for hydrodynamically balanced capsules of moxifloxacin HCl," *Current Drug Delivery*, vol. 14, no. 1, pp. 83–90, 2017.

[108] J. Malakar, P. K. Datta, S. D. Purakayastha, S. Dey, and A. K. Nayak, "Floating capsules containing alginate-based beads of salbutamol sulfate: in vitro-in vivo evaluations," *International Journal of Biological Macromolecules*, vol. 64, pp. 181–189, 2014.

[109] S. N. R. Rath Adhikari, B. S. Nayak, A. K. Nayak, and B. Mohanty, "Formulation and evaluation of buccal patches for delivery of atenolol," *AAPS PharmSciTech*, vol. 11, no. 3, pp. 1038–1044, 2010.

[110] D. Pal and A. K. Nayak, "Development, optimization and anti-diabetic activity of gliclazideloaded alginate-methyl cellulose mucoadhesive microcapsules," *AAPS PharmSciTech*, vol. 12, no. 4, pp. 1431–1441, 2011.

[111] Z. Liu, J. Li, S. Nie, H. Liu, P. Ding, and W. Pan, "Study of an alginate/HPMC-based in situ gelling ophthalmic delivery system for gatifloxacin," *International Journal of Pharmaceutics*, vol. 315, no. 1-2, pp. 12–17, 2006.

[112] R. Monireh and N. Hassan, "Carboxymethyl cellulose/graphene oxide bio-nanocomposite hydrogel beads as anticancer drug carrier agent," *Carbohydrate Polymers*, vol. 168, pp. 320–326, 2017.

[113] H. Abou-Yousef, S. Dacrory, M. Hasanin, E. Saber, and S. Kamel, "Biocompatible hydrogel based on aldehyde-functionalized cellulose and chitosan for potential control drug release," *Sustainable Chemistry and Pharmacy*, vol. 21, Article ID 100419, 2021.

[114] U. Ubaidulla, R. K. Khar, F. J. Ahmad, and P. Tripathi, "Optimization of chitosan succinate and chitosan phthalate microspheres for oral delivery of insulin using response surface methodology," *Pharmaceutical Development and Technology*, vol. 14, no. 1, pp. 99–108, 2008.

[115] N. Benbettaïeb, A. Assifaoui, T. Karbowiak, F. Debeaufort, and O. Chambin, "Controlled release of tyrosol and ferulic acid encapsulated in chitosan–gelatin films after electron beam irradiation," *Radiation Physics and Chemistry*, vol. 118, pp. 81–86, 2016.

[116] H. Horo, S. Das, B. Mandal, and L. M. Kundu, "Development of a photoresponsive chitosan conjugated prodrug nano-carrier for controlled delivery of antitumor drug 5-fluorouracil," *International Journal of Biological Macromolecules*, vol. 121, pp. 1070–1076, 2019.

[117] S. Jana, N. Maji, A. K. Nayak, K. K. Sen, and S. K. Basu, "Development of chitosan-based nanoparticles through inter-polymeric complexation for oral drug delivery," *Carbohydrate Polymers*, vol. 98, no. 1, pp. 870–876, 2013.

[118] S. Jana, S. Manna, A. K. Nayak, K. K. Sen, and S. K. Basu, "Carbopol gel containing chitosan-egg albumin nanoparticles for transdermal aceclofenac delivery," *Colloids and Surfaces B: Biointerfaces*, vol. 114, pp. 36–44, 2014.

[119] S. Ray, P. Sinha, B. Laha, S. Maiti, U. K. Bhattacharyya, and A. K. Nayak, "Polysorbate 80 coated crosslinked chitosan nanoparticles of ropinirole hydrochloride for brain targeting,"

Journal of Drug Delivery Science and Technology, vol. 48, pp. 21–29, 2018.

[120] F. S. Majedi, M. M. Hasani-Sadrabadi, J. J. VanDersarl et al., "On-chip fabrication of paclitaxel-loaded chitosan nanoparticles for cancer therapeutics," *Advanced Functional Materials*, vol. 24, no. 4, pp. 432–441, 2014.

[121] M. Harris, H. Ahmed, B. Barr et al., "Magnetic stimuli-responsive chitosan-based drug delivery biocomposite for multiple triggered release," *International Journal of Biological Macromolecules*, vol. 104, pp. 1407–1414, 2017.

[122] A. Ali and S. Ahmed, "A review on chitosan and its nanocomposites in drug delivery," *International Journal of Biological Macromolecules*, vol. 109, pp. 273–286, 2018.

[123] P. R. Sarika and R. J. Nirmala, "Curcumin loaded gum arabic aldehyde–gelatin nanogels for breast cancer therapy," *Materials Science and Engineering: C*, vol. 65, pp. 331–337, 2016.

[124] S. K. Ghosh, A. Das, A. Basu et al., "Semi-interpenetrating hydrogels from carboxymethyl guar gum and gelatin for ciprofloxacin sustained release," *International Journal of Biological Macromolecules*, vol. 120, pp. 1823–1833, 2018.

[125] B. C. Ciobanu, A. N. Cadinoiu, M. Popa, J. Desbrieres, and C. A. Peptu, "Modulated release from liposomes entrapped in chitosan/gelatin hydrogels," *Materials Science and Engineering C*, vol. 43, pp. 383–391, 2014.

[126] A. Abruzzo, T. Cerchiara, F. Bigucci, M. C. Gallucci, and B. Luppi, "Mucoadhesive buccal tablets based on chitosan/gelatin microparticles for delivery of propranolol hydrochloride," *Journal of Pharmaceutical Sciences*, vol. 104, no. 12, pp. 4365–4372, 2015.

[127] A. Mahor, S. K. Prajapati, A. Verma, R. Gupta, A. K. Iyer, and P. Kesharwani, "Moxifloxacin loaded gelatin nanoparticles for ocular delivery: formulation and in-vitro, in-vivo evaluation," *Journal of Colloid and Interface Science*, vol. 483, pp. 132–138, 2016.

[128] D. Nayak, A. Boxi, S. Ashe, N. C. Thathapudi, and B. Nayak, "Stavudine loaded gelatin liposomes for HIV therapy: preparation, characterization and in vitro cytotoxic evaluation," *Materials Science & Engineering. C, Materials for Biological Applications*, vol. 73, pp. 406–416, 2017.

[129] M. L. Manca, R. Cassano, D. Valenti et al., "Isoniazid-gelatin conjugate microparticles containing rifampicin for the treatment of tuberculosis," *Journal of Pharmacy and Pharmacology*, vol. 65, no. 9, pp. 1302–1311, 2013.

[130] A. Singh, J. Xu, G. Mattheolabakis, and M. Amiji, "EGFR-targeted gelatin nanoparticles for systemic administration of gemcitabine in an orthotopic pancreatic cancer model," *Nanomedicine*, vol. 12, no. 3, pp. 589–600, 2016.

[131] M. Foox and M. Zilberman, "Drug delivery from gelatin-based systems," *Expert Opinion on Drug Delivery*, vol. 12, no. 9, pp. 1547–1563, 2015.