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Review Article

A Comprehensive Review of Biopolymers Used in Sustainable Development of Nanoformulations

Ruchi Tiwari[1], Priyanka Shukla[1], Gaurav Tiwari[1], Mahesh Kumar Posa[2], Mallikarjun Mugli[3,*], Anurag Mishra[4]

[1]PSIT-Pranveer Singh Institute of Technology (Pharmacy), Kalpi Road, Bhauti, Kanpur, Uttar Pradesh, INDIA.
[2]Department of Pharmacology, School of Pharmaceutical Sciences, Jaipur National University, Jagatpura, Jaipur, Rajasthan, INDIA.
[3]Department of Pharmaceutics, Karnataka M. H. Goel College of Pharmacy (Affiliated to RGUHS, Bangalore), Bidar, Karnataka, INDIA.
[4]Department of Pharmacology, Shree Krishna College of Pharmacy, Sitapur, Uttar Pradesh, INDIA.

ABSTRACT
A biopolymer is a naturally derived polymer, obtained from living organisms like plants, animals and various microorganism. The biopolymer is made up of various monomer units which are linked together with each other through biological process. This review article provides a detailed overview on biopolymer-based nano-formulation. The unique properties of biopolymer like biodegradability, biocompatibility, make it a perfect candidate and non-toxicity makes it a perfect candidate for developing various advance drug delivery systems. This review mainly highlights different types of biopolymers like polysaccharides, proteins, nucleic acids, Polyhydroxyalkanoates (PHAs), synthetic biopolymers. This review also explores the recent advancement of biopolymer-based nano-formulation, application of biopolymer in drug delivery system. The future prospective of biopolymer-based nano-formulation are also addressed in this article, concluding the need for future research to optimize their performance and clinical translation.

Keywords: Biopolymers, Environment sustainable polymers, Types, Nano formulation applications.

Correspondence:
Mr. Mallikarjun Mugli
Associate Professor, Department of Pharmaceutics, Karnataka M. H. Goel College of Pharmacy (Affiliated RGUHS, Bangalore), Bidar-585401, Karnataka, INDIA.
Email: msgmugli@gmail.com

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INTRODUCTION

Biological polymers are naturally produced by various organisms in land and water, often forming biofilms, with their material properties depending on monomer composition and high molecular weight (Gulati *et al*., 2024). Biopolymers represent a flexible family of chemicals obtained or manufactured via biological substances. Biopolymers, as polymers made from other substances, consist of repeating units called subunits that are joined collectively (Aggarwal *et al*., 2024). In the stages of biodegradation, polymers disintegrate by producing carbon dioxide, fluid, plant matter, polymeric macromolecular material (humic matter), and other naturally occurring chemicals. Thus, bio-polymers are substances that are spontaneously regenerated via biological mechanisms (Gulati *et al*., 2024). Biopolymers have several benefits, including reduced carbon emissions, sustainability, biocompatibility, as well as cost (Kumar *et al*., 2023). It is established that biological polymers are safe, non-thrombogenic, non-carcinogenic, and simple to separate (Patel and Desai *et al*., 2023). The dimensions of a nano-formulation can range between 10 to 100 nm, while it may break down, bind, wrap, or bind itself to the medication's vehicle (Singh and Kaur, 2022). Numerous studies have indicated that choosing the right way to prepare is crucial to producing the nanoformulations have the right characteristics for a certain medication delivering applications (Choudhary and Mehta, 2021). Various and varied complications, toxicities, inconsistency, limited accessibility, short delivery of drugs, and quick breakdown are the main issues with medication distribution (Verma and Gupta, 2020). Various applications of biopolymers have been successfully realized recently, with the advantage of environmentally benign deterioration (Sharma and Kumar, 2019) (Figure 1). The viability of using biopolymers in various fields is dependent on their performance, which is dependent on a number of factors including the type and quantity of solvent used, the intended use of the chosen biopolymer (e.g., gelation, viscosity-forming bulk structure, emulsion and foam surface activity), the structure-developing process, and its interaction with other developed substance (Rao and Singh, 2018). The creation of DDSs that utilize biopolymers has seen encouraging research to date because of these polymers' many benefits (Jesus *et al*., 2021) (Table 1).

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Biopolymer used in nano-formulation

Alginate, a polysaccharide, consists of mannuronic and guluronic acid units, forming a gel-like matrix upon ion exchange, often with calcium ions. Hyaluronic acid, a glycosaminoglycan, comprises repeating disaccharide units of N-acetylglucosamine and glucuronic acid, widely used for its biocompatibility and hydrophilicity. Proteins like gelatin and albumin, characterized by polypeptide chains with diverse amino acid sequences, provide functional groups for surface modifications. Synthetic biopolymers, such as Polylactic-Co-Glycolic Acid (PLGA), exhibit ester linkages in their backbone, allowing controlled degradation and drug release (Figure 2). These biopolymers collectively enable the design of nano-formulations with tailored properties for drug delivery, tissue engineering, and diagnostic applications. Nano-formulations range in diameter from 10 to 100 nm. The medicine is dispersed, enslaved enclosed, or connected with a carrier (Verma and Gupta, 2020; Sharma and Kumar, 2019; Turner *et al*., 2023).

Polysaccharide

Chitosan/Chitin

Because of exceptional biological qualities, chitin has become increasingly important in a variety of medicinal and biological uses, such as delivering medications, cell and transferring genes, etc. Biological attributes encompass non-toxicity, secure, breakdown, and biocompatibility (Rodriguez *et al*., 2019). In addition, it has anticarcinogenic, spermicidal, fungicide, antibacterial, and hemostatic properties (White *et al*., 2018) (Figures 3 and 4). Chitosan facilitates the creation of gels with molecules negative ions like polyphosphates and sulfur compounds. This enables numerous applications, which include facilitating the capture of biochemical substances like plants embryos, entire the cells, and phytoplankton in gels, and for the exterior coating of dietary and medicinal items (Marshall *et al*., 2020).

Chitosan is resistant with liquids and solvents made from organic compounds but accessible in slightly alkaline mixtures. acids dissolving chitin can be efficiently employed for Drug Delivery Systems (DDS) and altered chitin, such as partly deacetylated a-chitin tiny fibers, to make spontaneous hydrogels (Hardy *et al*., 2022). Chitin can be mixed into different substances, such as collagen, various polymers, hydroxyapatite, etc., to increase its rigidity and replicate the cell's nanostructure (Moore *et al*., 2018). The bodily breakdown of chitin during its use as a pharmaceutical carrier is another significant aspect. Enzymes breakdowns are necessary for chitin with an especially significant molecular size. The number of molecules and level of acetylation of the polymers determine the rate of breakdown. The kidneys and hepatic could be the location of deterioration. Several of the chitin enzyme were identified by Funkhouser *et al*., as having chitin degrade capability (Herrera *et al*., 2021). Marcel Jakubowski *et al*., developed Chitosan hydrogel modified with lanthanum as a drug delivery system for epigallocatechin gallate. The hydrogels were developed to confirm the successful retention of EGCG on the hydrogel surface. Based on the EDS mapping, it was possible to confirm the even distribution of the lanthanum ions. The hydrogels were created for the use of implantable hydrogel or coating (Delgado *et al*., 2022).

Starch

Numerous studies and conjectures have been made regarding the composition of starches. Starch is a combination of a couple distinct polysaccharides arranged in a granule-like fashion, which makes determining its distinctive shape extremely difficult (Sherman *et al*., 2024). Amylose as well as amylopectin are constituent polymers that lack identification indications, making it impossible to determine the composition of these materials unambiguously using chemical techniques (Shepard *et al*., 2019). Thomas and colleagues used a sustainable technique to create starch-modified alginate nanostructures for medication distribution. Bovine serum albumin and theophylline served as prototype medicines to assess the possibilities in regulated medication delivery systems (Howkins *et al*., 2020). Reserved starches are primarily employed for agriculture and industrial use because it is typically present in much larger quantities of each plant than assimilatory starches (Bowen *et al*., 2018). A long-standing method for producing a variety of conventional meals is the mixing of multiple kinds of grains and/or starches. The manufacturing of customized starch-based pharmaceuticals can be achieved through the application of basic ternary mixes of starch along with additional biopolymers (such hydrocolloids and protein), that are the subject of ongoing research. Obani *et al*., demonstrated that starch blends may be made to act like chemically altered starches, especially in terms of gluing tendency (Ball *et al*., 2022). Max Jelkmann *et al*., was to develop a novel mucoadhesive cationic polymer by introducing primary amino groups to the polymeric backbone of starch. Mucoadhesiveness was investigated by rotating cylinder, tensile studies and rheological measurements.

Primary amino groups were successfully attached to the polymer, proven by zeta potential measurements and UV-spectroscopy. The result concluded that the cationic starch derivatives seem to be promising excipients for mucosal drug delivery with superior properties compared to chitosan, the most examined cationic polymer (Mccormick *et al*., 2024). Jinchuan Xu *et al*., developed Starch/microcrystalline cellulose hybrid gels as gastric-floating drug delivery systems. The result demonstrated the excellent gastric-floating ability and sustainable drug release behavior of the starch/cellulose hybrid gels (Gulati *et al*., 2024).

Alginate

Brown algae's matrix of cells, which serves as a framework, is usually the source of alginate. *Macrocystis pyrifera, Ascophyllum nodosum*, and *Laminaria hyperborea* are the main sources of phytoplankton. Smidsrød and Skåk-Braek (1990) identified Laminaria, which digitata and *Laminaria japonica* as one another, less commonly utilized sources for alginates' genesis

(Idrees *et al.*, 2020). These are attributed to its beneficial physical features, including dissolution, thickness, the cross linkage, sol-gel alteration, and beneficial biological attributes, including biocompatibility, decomposition, adhesiveness, and immune system function (Sreena *et al.*, 2023). In recent years, Hadas and Simcha published the results of their fascinating investigation into the structure and characterization of calcium and sodium alginate. Alginate's various qualities and uses were additionally examined (Tripathi *et al.*, 2024).

Deepa Thomas *et al.*, developed Starch modified alginate nanoparticles for drug delivery applications. The developed starch-modified alginate nanoparticles using a green facile technique for drug delivery application (Vallim *et al.*, 2022). The preliminary investigation suggests the developed nanoparticle is a promising candidate for drug delivery application (Li *et al.*, 2022). Line Aanerud Omtvedt *et al.*, developed Alginate hydrogels functionalized with β-cyclodextrin as a local paclitaxel delivery system. In result demonstrated that indicate that functionalized alginate with β-CyDs has potential as a material for drug delivery systems (Kumari *et al.*, 2022).

Cellulose

A lengthy network of connected sugar atoms makes up the chemical substance known as cellulose (Xi *et al.*, 2022). Because synthesized glycopolymers involving sugar chains are attached to the polymeric framework or chains terminals can imitate the natural configurations and activities of glycoproteins that are via diverse reactions with lectins that they are particularly interesting. 35 A "cluster glycoside effect" is produced by the multivalent characteristics of glycopolymers including a significant amount of repeated carbohydrate units, and thus significantly improves carbohydrate-lectin link (Balaji *et al.*, 2022). Bacterial cellulose differs greatly from plants cellulose, but having the same chemical structure (Nitta and Numata, 2013).

The two main characteristics that distinguish bacterial cellulose are its high-water content of 90% or higher and its superior purity (no interaction with associated compounds such as hemicelluloses, lignin, or pectin) (Kumar and Kaur, 2019). Hanieh Mianehrow *et al.*, developed Graphene-oxide stabilization in electrolyte solutions using Hydroxyethyl Cellulose (HEC) for drug delivery application. The result demonstrated that the nanohybrid could be highly loaded by folic acid. Moreover, HEC content in the nanohybrid played an important role in final application to make it applicable either as a carrier for controllable drug release or as a folate-targeted drug carrier. In addition, according to cytotoxicity results, the nanohybrid showed good biocompatibility which indeed confirms its potential application as a drug carrier (Patel and Patel, 2020). Jinchuan Xu *et al.*, developed Starch/microcrystalline cellulose hybrid gels as gastric-floating drug delivery systems. In result demonstrated the excellent gastric-floating ability and sustainable drug release behaviour of the starch/cellulose hybrid gels (Singh and Sharma, 2021).

Proteins

Collagen

A highly prevalent protein in the vertebrate organism's collagen makes up over 25% of all proteins in vertebrates. Collagen is special because it can form straight-handed triple super-helical rods made from 3 nearly identical chains of polypeptide with insoluble fibers with a high degree of tensile strength. Initially collagen was originally extracted from the skin of land creatures like pigs and cows (Zhang and Li, 2022).

The most common kind of collagen utilized in medicines is type I, which is also the least prevalent type in mammals (Chen and Wang, 2023). Refined collagen is being added to numerous pharmacological and beauty products. Fish collagen exhibits lower gelling and temperature of melting but relatively greater viscosities than similar bovine forms, which is how collagen from mammals differs from fish collagen. These collagens derived from fish may find commercial usage in situations where highly viscous liquids without gel formation are necessary (Gupta and Kumar, 2024). Ecaterina Andronescu *et al.*, developed Collagen-hydroxyapatite/cisplatin drug delivery systems for locoregional treatment of bone cancer. The outcome demonstrated the possibility that the recently created COLL/HA-cisplatin drug delivery system might work well for locoregional treatment for bone cancer (Mills *et al.*, 2022). M Higaki *et al.*, developed Collagen minipellet as a controlled release delivery system for tetanus and diphtheria toxoid. Furthermore, the identical categories of antibodies generated by alum compositions were also produced by minipellet formulations. The outcome showed that a single dosage of minipellet formulations could potentially produce the best and longest-lasting reactions (Vasquez *et al.*, 2020).

Gelatin

Gelatin is a naturally occurring polymer derived from the hydrolytic degradation of collagen protein. Its unique amino acid composition confers many health advantages. Gelatin is typically found in pills, granules, or powdered substances, though it occasionally needs to be dissolved with water prior usage. In chemical terms, gelatin is composed of eighteen different types of complicated amino acids. The main constituents of this mixture are roughly 57% glycine, proline, and hydroxyproline, with the remainder, or 43%, consisting of additional notable amino acid groups like glutamic acid, alanine, arginine, and aspartic acid (Wood *et al.*, 2021). Gelatin is typically derived from the epidermis of cattle and pigs as well as demineralized bones and hooves. Consumers are nevertheless gravely concerned about consuming gelatin made from the bones and skins of pigs and cows for a number of factors. This is due to several issues, including social issues, religious concerns, and the disease mad cow (also known as BSE). Elements The BSE incidence and increasing requirements for non-mammalian gelatin have reignited the pursuit of finding substitute options for gelatin, including using freshwater and marine seafood and poultry as starting elements (Allen *et al.*, 2020).

Pleasant physical attributes, including tensile strength, elongation at break, puncture strength, tear strength, acid resistance, alkali resistance, moderate oxygen permeability, and oil permeability, are produced in films when gelatin is added to solutions made from water in a range of 4 to 8% (Morrow *et al.*, 2020). Agnes Cecheto Trindade *et al.*, demonstrated that gelatin nanoparticles via template polymerization for drug delivery system to photo process application in cells. The outcome showed that gelatin-poly (acrylic acid) nanoparticle-encapsulated ClAlPc is an effective delivery mechanism for enhancing photodynamic activities in the intended tissues (Andrade *et al.*, 2019). Yizhuo Ren *et al.*, developed Injectable hydrogel based on quaternized chitosan, gelatin and dopamine as localized drug delivery system to treat Parkinson's disease. The outcome demonstrated a novel and simple method for creating injectable dopamine-based substances that can be employed as both an anti-inflammatory medication and a long-term injectable sustained release system for dopamine in the treatment of Parkinson's disease (Booth *et al.*, 2022).

Silk Fibroin (SF)

SF is a naturally occurring polymer made of 390 kDa of substantial chains and 26 kDa lighter chains connected by a disulfide, which is extracted from the silkworm *Bombyx mori*. Repeated Gly-Ala-Gly-Ala-Gly-Ser repetitions which may self-assemble into an a-sheet framework are present in the amino acid sequences of SF (Mullins *et al.*, 2019). SF has been used as a useful biological material because of its strong mechanical qualities, low immunological response, regulated biodegradation, and permeability to water. It is also highly biocompatible. Due to these variables, SF has been produced in a variety of forms for use in films, hydrogels, electrospun mats, sponges that are and nano- or tiny particles (Roberts *et al.*, 2018). Silk fibroin may play a significant role in biomedicine due to its ease of engineering and appropriateness as the foundation for cell attachment. The binding of proteins on fibroin film appeared to be somewhat loose; in specifically, there appeared to be a noticeable lack of activity when it comes to fibrin adsorb. On the other hand, it appears that the sheet additional structure gives the outermost layer of fiber a hydrophobicity, which increases serum protein binding (Reed *et al.*, 2024).

Similar bioprocessing procedures were used to create the silk fibroin and fibrin elements, but this time around, the materials were introduced into a specially designed cylindrical mold. In particular, the mold measured 5 cm in length, 1.2 cm in diameter, and 1 mm in walls thicknesses (Patel *et al.*, 2018). Fatemeh Rezaei *et al.*, developed a dual drug delivery system based on pH-sensitive silk fibroin/alginate nanoparticles entrapped in PNIPAM hydrogel for treating severe infected burn wound. The outcome demonstrated that the hybrid system under development could serve as a viable tool for treating serious infections of wounds (Smith *et al.*, 2020). Bano Subia *et al.*, demonstrated that Folate conjugated silk fibroin nanocarriers for targeted drug delivery. The creation of substances that are immune-compatible, recyclable, environmentally friendly, and have the ability of releasing macromolecules over an extended period is the focus of this work. According to the findings, silk

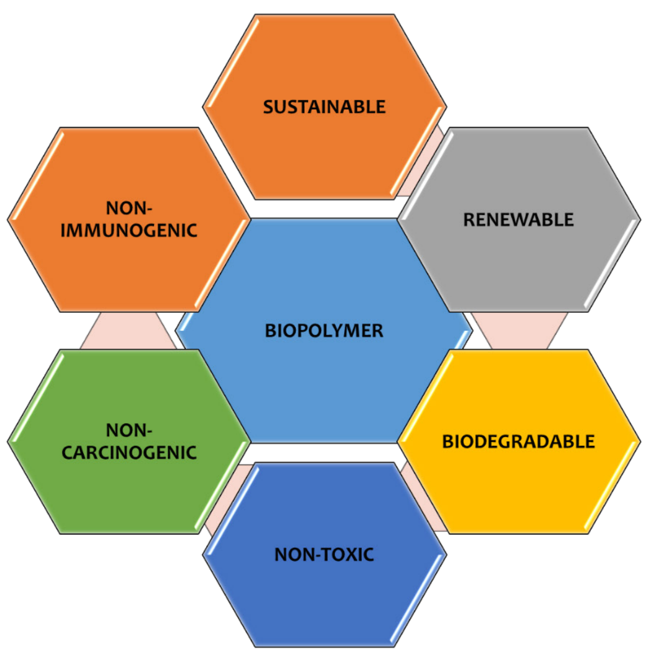

Figure 1: Applications of biopolymer.

Table 1: Biopolymer used in drug delivery systems.

Drug delivery system	Drug	Discussion	References
Hydrogel	Baicalin (Anti-infective)	Incorporating baicalin nanocrystals into 1% HA hydrogels significantly increased both drug content and penetration (20.65-fold, $p<0.01$) due to reduced particle size and HA's mucoadhesive properties.	(Hardy *et al.*, 2022)
	Latanoprost	HA-based hybrid hydrogels of latanoprost showed prolonged *in vitro* absorption compared to liposomal and synthetic polymer-based hydrogels.	
Nanoparticle	Lactoferrin (L), Chitosan (C), and Gellan (G)	Lactoferrin–chitosan–gellan nanoparticles created via electrostatic association showed enhanced antibacterial activity against *S. aureus* compared to individual biopolymers, making them promising natural food preservatives.	(Duarte *et al.*, 2022)
	Beta-Glucan	Beta-glucans from microbial cell walls, though less immunogenic than endotoxins, can activate immune responses and currently lack defined regulatory limits in nanomedicine products.	(Neun and Dobrovolskaia, 2024)
Nanofiber	Cellulose	Cellulose nanofiber solutions from bamboo and needle-leaved trees improved the surface wettability of denture base resins without affecting their flexural strength.	(Zou *et al.*, 2024)
	Polylactic Acid (PLA)	PLA scaffolds reinforced with cellulose nanofibers showed improved cell migration, biocompatibility, and reduced biodegradation over eight weeks, promoting wound healing.	(Revati *et al.*, 2021)
Microparticles	1) Poly(Lactic-Co-Glycolic Acid) (PLGA)	Double-layered PLGA and Ac-dextran microparticles showed pH-responsive degradation and sustained antioxidant and antibacterial release, extending shelf life in acidic products like pork broth.	(Smith *et al.*, 2023)
	1) Risperidone Atypical 2) (Antipsychotics), Buserelin (Harmone therapy drug) and 3) Octreotide acetate (*octapeptides)*	Microparticles provide effective delivery systems for poorly water-soluble drugs due to their tunable properties like size, porosity, and controlled release profiles, with some already in clinical use.	
Conjugate based	Alpha-interferon (Immunomodulator)	A method was proposed for conjugating alpha-interferon with hyaluronan or its polymer blends via divinyl sulfone chemistry, yielding stable intermediates for biomedical applications.	(Liu *et al.*, 2018)

fibroin-folate nanoparticles could be useful nanocarriers for a variety of cancer-related medicinal and nanotechnology uses (Smith *et al.*, 2019).

Albumin

Albumin also the most abundant protein in plasma, making up half of the total plasma proteins, which is essential to the functioning of the human body. To be more precise, albumin is an inner supply of amino acids. Additionally, it helps to maintain plasma's consistent osmotic pressure. When the pH is 7, albumin is up to 40% soluble in water. Consequently, albumin functions as a non-specific transport protein that can be coupled *in vivo* with a variety of stubborn chemical substances and inorganic ions to create accessible complexes. Albumin's biocompatibility, non-immunogenicity, and biodegradability are some of its beneficial qualities (Ivanov *et al.*, 2021). Nevertheless, there are presently few clinical uses for albumin-based therapy, despite its clear promise and the plethora of research studies supporting it. There aren't lots of goods in clinical use yet (Nguyen *et al.*, 2022). There has been a rise of studies recently on protein-based delivery systems utilizing albumin for utilization in ophthalmic treatments. However, since proteins are constantly vulnerable to enzymatic degradation, unique design approaches are needed for distribution at locations. It's important to note that charging bioactive substances can be adsorbed electrostatically onto highly charged proteins like albumin (Chen *et al.*, 2023). Lingqiao Hao *et al.*, developed albumin-binding prodrugs via reversible iminoboronate forming nanoparticles for cancer drug delivery.

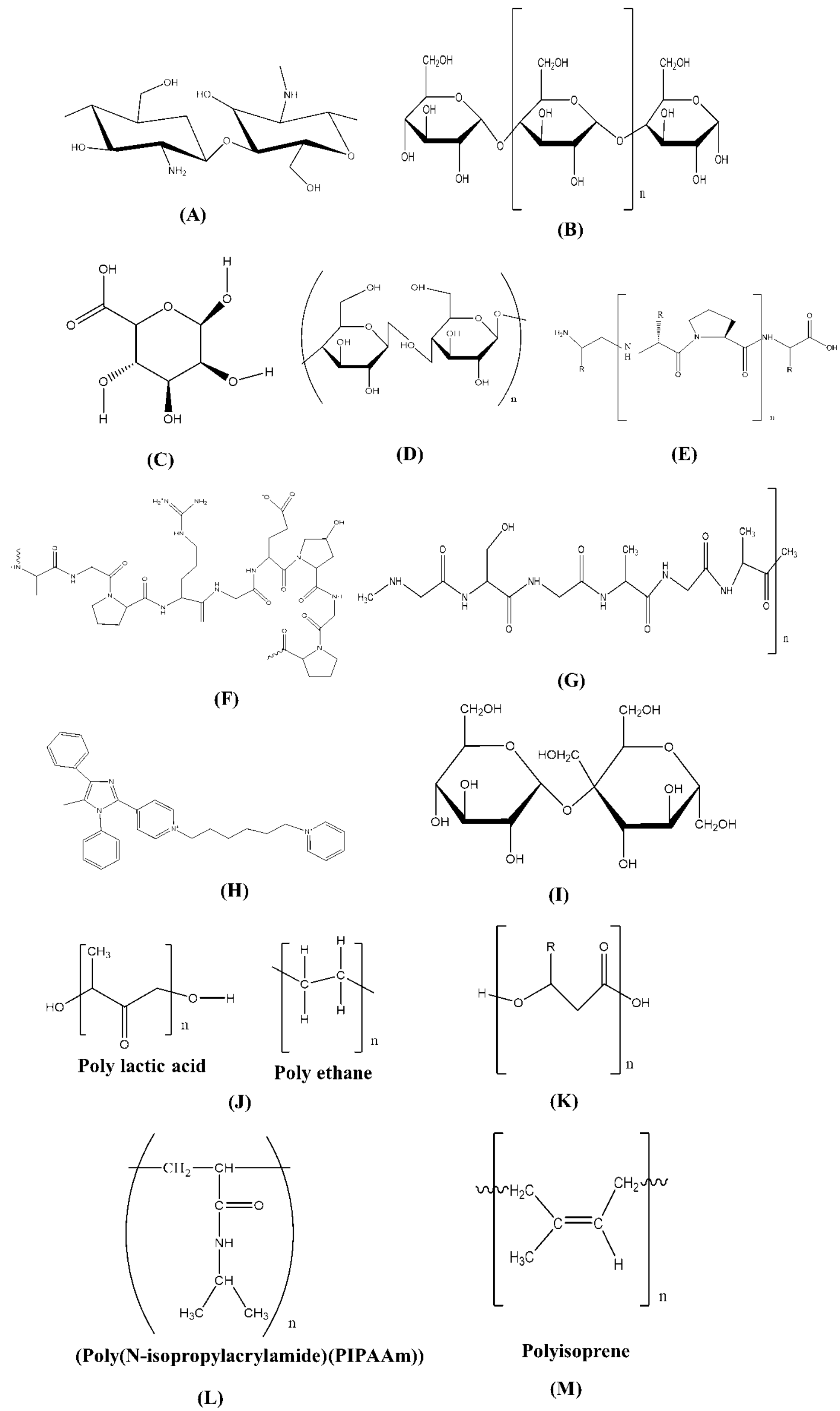

Figure 2: (A) Chitosan/ chitin; (B) Starch; (C) Alginate; (D) Cellulose; (E) Collagen; (F) Gelatin; (G) Silk fibroin; (H) Albumin; (I) Nucleic acid; (J) Bio-based polymer (i) Poly lactic acid (ii) Polyethylene); (K) Polyhydroxyalkanoates (PHAs); (L) Synthetic polymer (Poly(N-isopropylacrylamide (PIPAAm); (M) Natural rubber and latex (Polyisoprene).

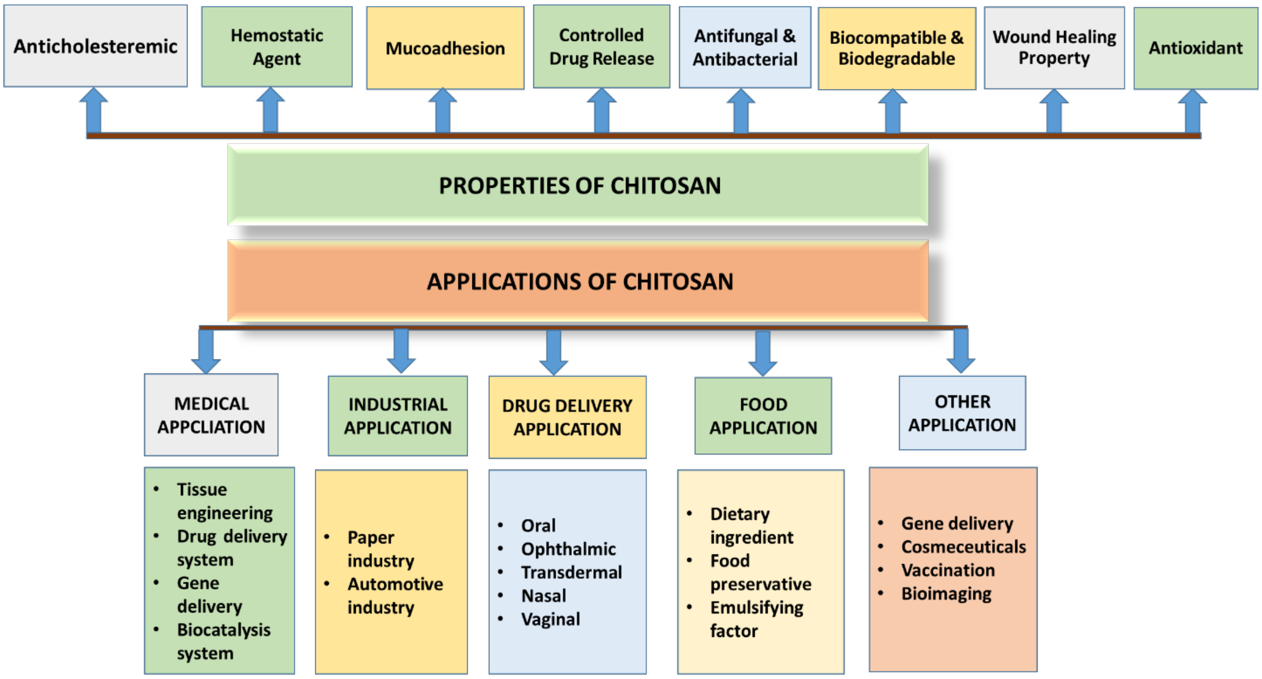

Figure 3: Applications and properties of chitosan.

The findings suggested the possibility of a flexible protein-binding prodrug substrate that may be used for conjugates of antibodies and drugs as well as protein-based medication compositions (Lee *et al*., 2019). Zhengxing Su *et al*., created a new docetaxel formulation that would have better water solubility and increased anti-tumor activity. The findings demonstrated significant promise for creating an innovative drug delivery method for cancer treatment by lowering toxicity and improving efficacy in clinical use of such albumin-bound docetaxel nanoparticles (Almeida *et al*., 2024).

Nucleic acid

Effective applications for macromolecular single- and double-stranded nucleic acids, which include plasmid DNA (pDNA), tiny interfering RNA (siRNA), and Antisense Oligonucleotide (AsON), are promising for treating a wide range of diseases, like tumors and inflaming, neural, heart disease, and metabolic problems (Gomez *et al*., 2021). Numerous clinical trials assessing the reliability and efficacy of nucleic acid therapies for various illnesses have been conducted over the last 20 years, which amply demonstrates this (Patel *et al*., 2020). A variety of buildings, including hydrogels, polymeric micelles, polymerosomes, and polyplexes-which are combinations of cationic polymers and nucleic acids-are included in polymeric-based nanotechnology (Hines *et al*., 2020). The result of polyplex creation, that is based on the entropy-driven ionic relationship that occurs between the polyanionic nucleic acid and the multivalent cationic polymers, is the creation of nanoparticles with the nucleic acid payloads in a compacted protective state (Stuart *et al*., 2023).

E Fattal *et al*., demonstrated that Gel and solid matrix systems for the controlled delivery of drug carrier-associated nucleic acids. This work created a novel delivery system concept that combines enhanced intracellular penetration with sustained release. Microspheres encapsulating pdT16/PEI complex improved intracellular absorption of released ODN when treated with HeLa cells. Microspheres and liposomes can both be used to distribute ODNs locally (Bailey *et al*., 2019).

Bio-based polymer

Substances that are subjected to microorganisms, carbon dioxide (aerobic activities), methane (anaerobic activities), freshwater (aerobic and anaerobic processes), and various other activities that cause deterioration and full degradation are known as polymers that degrade. There are two types of bio-based polymers in the following biodegradable (like polylactic acid) and nondegradable (like biopolyhethylene). Only a small portion of the overall global plastic market is now occupied by bio-based polymers. Presently, fewer than one percent of all polymers are biopolymers (Moore *et al*., 2020). Corn and soybeans are examples of bio-based commodities that can be used to manufacture a variety of goods (Rangel *et al*., 2020). The sustainable development of bio-based polymers from "cradle to grave" is measured using the Life Cycle Assessment (LCA) technique. A review of LCAs and LCA databases offers direction to the polymers and scientific communities regarding the application of LCA in advancing the future viability of the use, creation, and dispose of bio-based polymers (Martinez *et al*., 2020). Paola Allavena *et al*., demonstrated that PLGA Based Nanoparticles for the Monocyte-Mediated Anti-tumor Drug Delivery System. This study described the effective internalization of PLGA-NPs by separated pure monocytes and observed their transport *in vivo* following intravenous injection in mice harbouring tumors (Allavena *et al.*, 2020). Compared to free PLGA-Cy7 NPs, macrophages containing the compound were more effective in reaching the location of the tumor, and the bio-distribution investigation verified that tumours were the more frequently contacted peripheral tissues. This work offers demonstrations of concept data supporting the use of monocytes in live cell-mediated drug delivery systems for the treatment of tumors (Patel *et al.*, 2022).

Polyhydroxyalkanoates (PHAs)

Developed in various quantities through fermented methods, Polyhydroxyalkanoates (PHA) are a class of biodegradable and biocompatible polyesters that are sustainable and kind to the environment (Nguyen *et al.*, 2018). PHA, or polyesters composed of various hydroxyalkanoates, are produced by a wide variety of gram-positive and gram-negative bacteria belonging to a minimum of 75 distinct genera. Under dietary stress, these polymers can aggregate within the cell to as much as 90% of the cell dry weight and become a store of carbon and energy (Zhou *et al.*, 2020). A biodegradable polymer called poly (3HB) possess piezoelectricity and being perfectly pure aid in the procedure of osteoinduction, which osteogenesis (Ahmed *et al.*, 2019). PHAs help anaerobic biological degradation in sedimentation by being inaccessible in water, resistant to UV rays, hydrolytic in nature attack, and sinking in water (Garcia *et al.*, 2021). PHA can be plastic materials, but they are also valuable as stereo regular molecules that may serve asymmetric precursors in the biological production of chemicals which are optically active (Fernandez *et al.*, 2017).

Alejandra Rodríguez-Contreras *et al.*, developed Antimicrobial PHAs coatings for solid and porous tantalum implants. The research revealed that polyhydroxyalkanoates (PHAs) might be used as matrices to convey an active concept in antimicrobial coatings for tantalum (Ta) implants (Rodríguez-Contreras *et al.*, 2019). Solid Ta discs have been effectively coated using the dip-coating them method. The outcome demonstrated that Ta would be protected versus bacterial infections for a certain amount of time by the drug's delivery mechanism (Bhatia *et al.*, 2022). Sasivimon Pramual *et al.*, demonstrated that Development and characterization of bio-derived polyhydroxyalkanoate nanoparticles as a delivery system for hydrophobic photodynamic therapy agents (Pramual *et al.*, 2016). The outcome highlighted the possibility of employing P(HB-HV) copolymers produced by microorganisms to deliver hydrophobic photosensitizer medication via nanoparticles and their possible use in photodynamic therapy (Fernandez *et al.*, 2017).

Synthetic biopolymer

Biodegradable artificial polymers have a wide range of medical uses, some of which include ortho anchoring devices including rods, screws, and sutures that can be reabsorbed, as well as systems to deliver drugs. A vast range of biodegradable polymers,

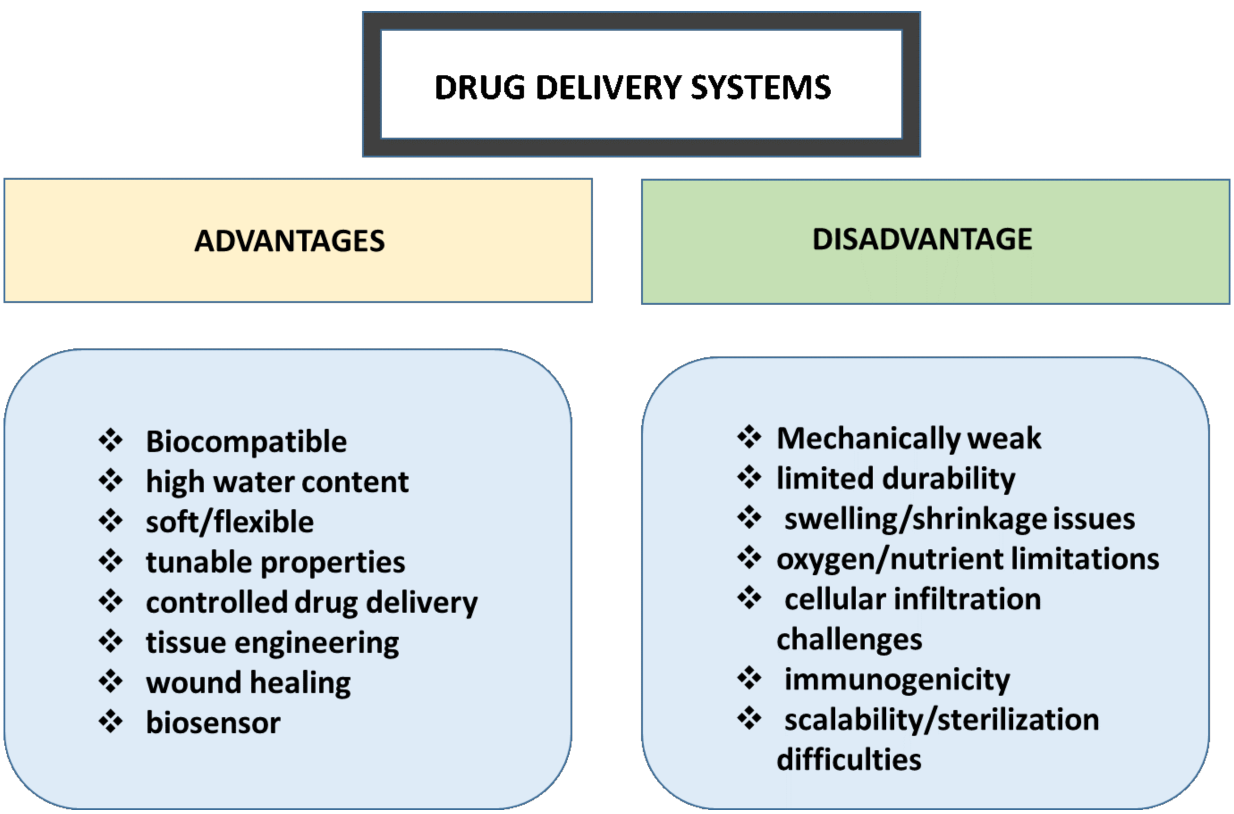

Figure 4: Advantages and disadvantages of drug delivery systems.

from flexible, elastic substances for regenerating soft tissue to rigid compounds that can be employed in load-bearing tissues like bone, are needed to construct scaffolding appropriate for various purposes. Apart from the mechanical characteristics, the polymer's degradation kinetics and, eventually, the scaffold (Moore *et al.*, 2020).

Hanieh Gholizadeh *et al.*, demonstrated the *in vitro* and *in vivo* applications of a universal and synthetic thermo-responsive drug delivery hydrogel platform. In this dissertation, an accessible carriers platforms for prolonged drug release are formulated using a synthetic and thermo-responsive polymer, poly (N-isopropylacrylamide)-co-(polylactide/2-hydroxy methacrylate)-co-oligo (ethylene glycol). The tremendous potential of the TP polymer systems as an enabled carrier was confirmed by *in vitro* and *in vivo* animal tests that demonstrated the released medications from the TP hydrogel matrix remained potent and bioactive (Stuart *et al.*, 2023).

Natural rubber and latex

Natural rubber and latex are renewable biopolymers derived from *Hevea brasiliensis*, valued for their elasticity, biocompatibility, and biodegradability. They are widely used in medical devices, coatings, and drug delivery systems. Their natural origin supports sustainable material development, making them eco-friendly alternatives to synthetic polymers in various industrial applications decomposition (Wood *et al.*, 2021; Fernandez *et al.*, 2017).

Llácer *et al.*, demonstrate that Adsorption-desorption of ondansetron on latex particles. It is primarily employed for alleviating postoperatively vomiting following gynaecological surgery and to manage nausea and vomiting brought on by cytotoxic chemotherapy and radiation (Llácer *et al.*, 2000; Morrow *et al.*, 2020). V J Tomazic *et al.*, demonstrated that cornstarch powder on latex products is an allergen carrier. This investigation assessed the limit protein's allergenic qualities and examined cornstarch powder's capacity to interact with latex proteins (Reed *et al.*, 2024).

CONCLUSION

In conclusion, biopolymers play a pivotal role in the sustainable development of nanoformulations due to their biodegradability, biocompatibility, and renewable nature. They offer a green alternative to synthetic polymers, enhancing drug delivery, stability, and targeted release in pharmaceutical and biomedical applications (Shepard *et al.*, 2019). The integration of biopolymers with nanotechnology promotes environmentally friendly innovations, reducing ecological footprints while maintaining therapeutic efficacy. Continued research into functionalization and optimization of biopolymer-based nanocarriers holds promise for advancing sustainable healthcare solutions (Patel *et al.*, 2022). Their potential to revolutionize nanomedicine aligns with global goals of eco-conscious development and offers a pathway toward safer, more effective, and sustainable therapeutic systems (Herrera *et al.*, 2021).

ABBREVIATIONS

APBA: Acetylphenylboronic acid; **AsON:** Antisense oligonucleotide; **BSA:** Bovine serum albumin; **ClAlPc:** Aluminium chloride phthalocyanine; **CNC:** Cellulose nanocrystals; **CNF:** Cellulose nanofibers; **DDSs:** Drug delivery systems; **DMSO:** Dimethyl sulfoxide; **DT:** Diphtheria toxoid; **DTX:** Docetaxel; **EGCG:** Epigallocatechin gallate; **FA:** Folic acid; **FTIR:** Fourier-transform infrared spectroscopy; **GO:** Graphene oxide; **HEC:** Hydroxyethyl cellulose; **miRNA:** MicroRNA; **MMT:** Montmorillonite; **NRL:** Natural rubber latex; **ODN:** Oligodeoxynucleotide; **pDNA:** Plasmid DNA; **PDT:** Photodynamic therapy; **PEI:** Polyethylenimine; **PHAs:** Polyhydroxyalkanoates; **PIPAAm:** Poly(N-isopropylacrylamide); **PLGA:** Polylactic-co-glycolic acid; **PNIPAM:** Poly(N-isopropylacrylamide); **PVA:** Poly(vinyl alcohol); **SEM:** Scanning electron microscopy; **siRNA:** Small interfering RNA; **TGA:** Thermogravimetric analysis; **TPP:** Tripolyphosphate; **TT:** Tetanus toxoid; **XRD:** X-ray diffraction.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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