Polymers and Polysaccharides for Pharmaceuticals

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Edited by

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TABLE OF CONTENTS

PREFACE

POLYMERS AND POLYSACCHARIDES FOR PHARMACEUTICALS is an edited book, where eleven authors contributed their knowledge in nine chapters. Chapters are Exploring Polymers: Dawn to Dusk (Chapter-1), Natural Polymer and Their Utility (Chapter–2), Properties of Polymers (Chapter-3), Review on the Chemistry and Toxicity of Polymers used in Pharmaceutical Formulation (Chapter-4), Properties of Polysaccharides (Chapter–5), Chemistry of Polysaccharides (Chapter-6), Application of Polysaccharides and Future Aspects (Chapter – 7), ***Common Features of Natural Polysaccharides and Polymers (Chapter-8)*** and Research Review about the use of Polysaccharides as Polymers (Chapter-9). Editors of this book are also the authors of chapters and so extreme revision of all the chapters carried out. Few lines from different chapters are quoted for smooth entry into the book. Polymers have been fundamental components of life since its description, forming the essential building blocks of all living organisms. Polymers are crucial to the structure and function of all living organisms encompassing polysaccharides, proteins, and nucleic acids. Humans have been using natural polymers since ages: for the fulfillment of various survival needs as well as for recreational purposes, for instance fur, wood, silk, wool, horn, cotton, flax, resins, and gum. Even today many natural polymers find their use in our day-to-day life.In basic terms, polymers are generated by chemically combining small molecules or substances to form macromolecules. Polymers can be classified into 3 major types as natural, semi-synthetic and synthetic polymers. Polymerization is a technique by which monomers unite to form polymers. In simple terms, the features of polymers depend on their chemical setup and how their molecular mass is spread out. Over the course of the last several years, the pharmaceutical industry has paid a significant amount of attention to goods formed from polymers. Recent advances in medicine are essentially tied to research on the efficacy of bioactive or pharmacological substances, as well as appropriate synthetic or hybrid polymers that are important to a wide variety of biomedical and pharmaceutical fields. Polysaccharides, called glycans, are polymers made of 10 or more monosaccharide molecules. Glycosidic connections link these monosaccharide fragments. Polysaccharides made up of a single kind of monosaccharide units are termed homopolysaccharides, while polysaccharides formed from multiple kinds of carbohydrates are called heteropolysaccharides. Numerous commercial applicability of these polysaccharides is owing to their vast variety of functional qualities, which are unique in their chemical structure. The words "carbohydrate" and "saccharide" are closely connected, with "saccharide" deriving from the term for table sugar in various languages, such as sarkara in Sanskrit and saccharum in Latin. Polysaccharides, which have a place with the third significant category of biopolymers (carbohydrates), assume essential parts in a wide range of physiological cycles and growth metastasis**.** They can likewise give structure, assurance, attachment, and boosts responsiveness, and they additionally play significant parts in the resistant framework, blood thickening, fertilization, pathogenesis avoidance, and therapeutic activity**. *Natural polysaccharides are polymeric in nature whereas polymers are class of natural or synthetic substances composed of very large molecule that are composed of simple chemical unit called monomers. Thus, natural polysaccharides are long chain macromolecule polymer. Physical and chemical properties of polymer is closely resembled with the physical and chemical properties of natural polysaccharides.*** The intricate connection between natural polysaccharides and polymers has been thoroughly examined, highlighting their shared physical, chemical, and functional characteristics. These biopolymers, sourced from nature, exhibit exceptional versatility due to variations in molecular weight, rheological behavior, and solubility features. Biopolymers, made up of macromolecules derived from monomer units, have attracted considerable interest because of their distinctive characteristics that make them ideal for diverse biological applications. Especially in biomedical uses, their benefits like biodegradability, biocompatibility, and minimal toxicity reduce the potential dangers of negative reactions and side effects in patients. As renewable resources, these biopolymers not only offer substantial functional advantages but also align with ecological imperatives, fostering opportunities for progress in green technologies and environmentally responsible industrial practices. This book may be a book to earn complete knowledge on Polymers and Polysaccharides to help the students, researchers, educators, manufacturers in different field such as chemical sciences, pharmaceutical sciences, medical sciences, biological sciences etc.

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CHAPTER 1

EXPLORING POLYMERS: DAWN TO DUSK

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Introduction

Polymers have been fundamental components of life since its description, forming the essential building blocks of all living organisms. Animals and plants alike are composed of polymers.

Polymers are crucial to the structure and function of all living organisms encompassing polysaccharides, proteins, and nucleic acids. They play a diverse range of roles from maintaining cellular integrity through substances like chitin and cellulose for providing biological protection as seen with lysozyme and a lot more (Kaufman and Falcetta, 1977; Marvel 1981).

The history of polymers extends far back in time. The earliest known application can be traced back to the rubber industry in Pre-Columbian Mexico (Hosler et al., 1999). The Mesoamericans skilfully combined latex from the rubber trees with juice extracted from the morning glory plant in varying proportions to create rubber with different properties, suitable for producing items such as bouncing balls, sandals, rubber bands and various essential products (Hosler and Tarkanian, 2011).

The advent of modern polymer science begun with the work of Henri Braconnot in the 1830s. Braconnot, along with Chrishcian Schonbein and others, developed derivatives of the natural polymer cellulose, leading to the creation of new semi synthetic materials like celluloid and cellulose acetate (Lambert *et al*., 2010).

The term 'polymer' itself was coined in1833 by John Jackob Berzelius, although his contribution to what we now consider polymer science was minimal (Jensen, 2008).

In the 1840s, Friedrich Ludersdorf and Nathaniel Hayward independently discovered that adding sulphur to raw natural rubber by a process known as vulcanization, significantly enhanced its properties. The year before, Thomas Hancock had already received a patent for the same process in the UK. Vulcanization strengthened natural rubber and preventing it from melting under heat while maintaining its flexibility. This advancement made practical products such as waterproofed articles possible (Bargah, 2024).

The advancement in the practical manufacture of rubberized materials was marked by the development of Vulcanized rubber, heralded as the first commercially successful product of polymer research. In 1884 Hilaire de Chardonnet founded the first plant to produce artificial fibre (plant-based) on regenerated cellulose, known as viscose rayon, as an alternative of silk, though it was notably flammable (Basit *et al*., 2018). The first synthetic polymer emerged in 1907 with LEO Baekeland's invention of Bakelite, a thermosetting phenol–formaldehyde resin (Tickell, 1965).

However, the molecular nature of polymers was not clearly understood until Hermann Staudinger's pivotal work in 1922 (Staudinger, 1920). Before Staudinger's work, polymers were thought to be aggregates of small molecules connected by an unknown intermolecular force, a theory proposed by Thomas Graham in 1861. Hermann Staudinger was the first to propose that polymers are long chains of atoms held together by covalent bond (Staudinger, 1920).

Staudinger's revolutionary idea took over a decade to gain wide acceptance within the scientific community, he was awarded the Nobel Prize in 1953 for this work (Mülhaupt, 2004). The polymer industry saw significant growth during World War II, driven by the necessity to replace the limited natural materials like silk and rubber with synthetic alternatives such as nylon and synthetic rubber (Graves, 2007). Since then, the development of advanced polymer like Kevlar and Teflon has continued to propel the industry forward, contributing to a wide range of applications and innovations (Kumar and Gupta, 2003).

In 1946, Herman Mark established the Polymer Research Institute at Brooklyn Polytechnic, the first research facility in the United States dedicated to polymer research and recognized as a pioneer in establishing curriculum and pedagogy for the field of polymer science (Hargittai, 2022).

The diverse origin coined with versatile composition of the natural polymers along with its other features like easy availability, economical aspect and environment friendliness that has helped them to gain position which is of keen human interest (Silva *et al.*, 2022).

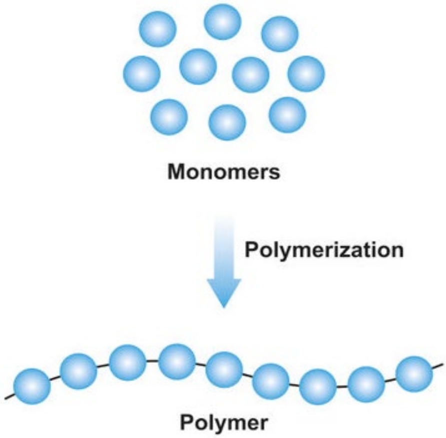
Humans have been using natural polymers since ages: for the fulfilment of various survival needs as well as for recreational purposes, for instance fur, wood, silk, wool, horn, cotton, flax, resins, and gum (Elias, 1997; Karak, 2009). Even today many natural polymers find their use in our day-to-day life as an integral part like wood, cotton, fur, wool, silk, starch, leather, paper, rubber, and a variety of resins, glues, and coatings (Chanda and Roy, 2008; Namazi, 2017).

Basic Concepts

The term “polymer” comes from the classical Greek words “poly,” meaning “many,” and “meres,” meaning “parts.” Therefore, a polymer is a large molecule, or macromolecule, composed of repeated small chemical units. These units, or monomers, are linked together to form long chains, resulting in the creation of polymers (Billmeyer, 1971).

Due to their potential size, often consisting of hundreds of thousands of atoms, polymers are also known as macromolecules. Imagine each monomer as a bead; when these beads are connected, they form a necklace, representing the polymer.

Let’s assume it is like a bead (monomer) that is connected to each other to form a necklace (polymer).



Thus, polymer may be defined as a macromolecule built up by the repetitive combining with other molecules of the same or different type known as monomers and the process of formation of polymers from monomers is called polymerization (Ali *et al*., 2005).

Natural Polymers are Organic as well as Inorganic

Natural polymers can be both organic and inorganic. Organic polymers include the hard parts of plants, such as lignin, cellulose, and resins. Cellulose, for instance, is a polymer made from sugar molecules (Satchanska *et al*., 2024). Inorganic natural polymers include substances like diamond and graphite. In graphite, carbon atoms are arranged in planes, making it useful as a lubricant and in pencils. The hardness of diamonds is due to the three-dimensional network of carbon atoms (Brown *et al*., 2014).

Natural polymers and their derivatives are widely used in paper and textile manufacturing, as food additives, in nutraceuticals, the biomedical field, and drug delivery (Aravamudhan *et al*., 2014; Rajeswari, 2017; Puertas-Bartolomé, 2021). Recent environmental concerns have renewed interest in using natural polymers due to their renewability and low carbon footprint. Their abundance in nature makes them a cost-effective alternative for developing new materials such as films, membranes, coatings, hydrogels, and micro- and nanoparticle systems (Ibrahim *et al*., 2019; Tongdeesoontorn and Rawdkuen, 2019; Graca *et al*., 2020; Mansoori *et al*., 2020; Nechita and Roman, 2020; Priyadarshi and Rhim 2020; Song *et al*., 2020; Bennacef *et al*., 2021; Carvalho *et al*., 2021; Vedula and Yadav, 2021)

The present section provides an overview of applications of natural polymers-based materials:

Cellulose-Based Materials

Cellulose is considered the most abundant biopolymer on the planet, being a constituent of most green plants and algae, such as *Valonia* and *Microdicyon*, and naturally secreted in its pure form by some strains of non-pathogenic bacteria (e.g., *Komagataeibacter*, *Acetobacter*) (Hess *et al.,* 1928; Ross *et al*., 1991; Pérez and Mazeau, 2004; Balart *et al*., 2021) and marine animals of the Ascite family (Pérez and Mazeau, 2004). This polysaccharide is an eminent feedstock for materials development and can be employed in its native state (Vilela *et al*., 2010; Valente *et al*., 2021) as cellulose derivatives, or in the form of cellulose nanofibrils (CNFs) (Martins *et al*., 2012; Moreirinha *et al*., 2020; Silva *et al*., 2020; Bastante *et al*., 2021), nanorods cellulose nanocrystals (CNCs) (Pinto *et al*., 2021), or three-dimensional hydrogel pellicles bacterial nanocellulose (BNC) (Trovatti *et al*., 2012; Gadim *et al*., 2014; Figueiredo *et al*., 2015; Vilela *et al*, 2019; Carvalho *et al*., 2020; Chantereau *et al*., 2020; Vilela *et al*., 2020; Silva *et al*., 2020; Fonseca *et al*., 2021) to manufacture a wide range of materials.

Owing to their excellent mechanical properties and good thermal stability, cellulose (nano) fibers have been employed as green reinforcing agents for the design of sustainable composites with poly (lactic acid) (PLA) (Tomé *et al*., 2011; Valente *et al*., 2021), poly(“-caprolactone) (PCL) (Figueiredo *et al*., 2015; Vilela *et al*., 2019) and poly(hydroxybutyrates) (PHB) (Valente *et al*., 2021) matrices. An interesting issue is that the inclusion of cellulosic fibers, apart from enhancing the mechanical performance of the thermoplastic matrices, may also quicken the degradation rate of the composite materials. As an illustrative example, the deterioration of the surface of latex-modified CNFs/PCL composites (Vilela *et al*., 2019) under enzymatic conditions was more pronounced when compared to the neat polymer, highlighting the enhancement of its degradation behavior.

In the pharmaceutical industry, cellulose is commonly used as an excipient, serving as an anticaking agent, stabilizer, texture modifier, and suspending agent for other applications (Ciolacu *et al*., 2018; Pandey, 2021). It has excellent compressibility and is used in solid dosage forms, like tablets. Cellulose is commonly used in tablet formulations to provide bulk and improve compressibility. Different forms of cellulose, such as microcrystalline cellulose and cellulose ethers, are commonly used in tablet formulations due to their good binding, disintegration, and lubrication properties (Chaerunisaa *et al*., 2019).

Cellulose derivatives, such as hydroxypropyl methylcellulose, are used to form matrices that regulate the release of drugs over time. These matrices can be designed to release drugs at a controlled rate, providing sustained drug delivery and reducing the frequency of dosing (Sun et al., 2019).

Cellulose-based wound dressings have been developed as an alternative to traditional wound dressings. Cellulose-based dressings can provide an absorbent, non-adhesive, and non-irritating surface for wound healing, while also allowing for moisture regulation and gas exchange (Mensah *et al*., 2021; Zheng *et al*., 2020).

Cellulose derivatives, such as hydroxypropyl cellulose, are used to form capsule shells for oral drug delivery. These cellulose-based capsules provide an alternative to gelatin-based capsules, which may not be suitable for certain patient populations due to religious or dietary restrictions (Mariia *et al*., 2022).

Cellulose derivatives can be used as coating agents for tablets or capsules, protecting against moisture, light, and other environmental factors. Cellulose-based coatings can also be used to mask the taste or odor of certain drugs, improving patient compliance (Sganzerla *et al*., 2021.

A semipermeable cellulose membrane, with or without the use of immunosuppressive drugs having less antigenicity, is revolutionary in artificial kidney for hemodialysis (raju *et al*., 2011; Chen *et al*., 2022). Despite the increased use of cellulose in tablets as suitable excipients, there is ongoing research on the potential use of cellulose as a novel drug carrier in modern drug-loaded systems (Arca *et al*., 2018)].

Hemicellulose

Hemicellulose is the second most abundantly available organic biomaterial in nature after cellulose and is an important heteropolysaccharide component of grains and lignified plant cell walls. Xylose is the most common sugar found in hemicellulose, particularly in hardwoods. Mannose, a six-carbon sugar, is commonly found in mannans, a type of hemicellulose abundant in softwoods. Due to its amorphous, cross-linked structure, hemicellulose exhibits excellent biological and physical properties, making it a highly biocompatible, biodegradable, and low-cytotoxic biomaterial ideal for various medical and pharmaceutical applications (Niksa, 2022; Wang *et al*., 2016; Liu *et al*., 2019).

Hemicellulose can also be utilized in numerous industrial fields such as food packaging, biological devices, biological implants, and medicinal products (Liu *et al*., 2019; Huang *et al*., 2021; Qaseem *et al*., 2021; Chen *et al*., 2022). Arabinoxylan (AX), a hemicellulose derivative, is favoured as an excipient due to its properties as a binder, matrix former, emulsifier, and release modifier in pharmaceutical formulations (Robert *et al*., 2022). AX also imparts mucoadhesiveness in medicinal products, enhancing drug delivery systems. The drug release behaviour can be controlled by integrating AX-based biomaterials in a matrix system, with AX-based matrices designed to respond to pH and temperature changes, making them suitable for targeted medication delivery (George *et al*., 2019; He *et al*., 2021).

Recent advancements have expanded the use of hemicellulose in the production of bioplastics and biomaterials, emphasizing its potential in reducing plastic use and promoting sustainability (Nechita *et al*., 2021; Mathura *et al*., 2024). Hemicellulose's polysaccharide structure allows it to be hydrolysed to sugars, which can be used to produce biofuels and chemicals. Furthermore, its water solubility and flexible structure make it an excellent raw material for high-value purposes such as emulsifiers in food and cosmetic products, providing a renewable and environmentally friendly alternative (Kokabas *et al*., 2020; Rao *et al*., 2023; Mathura *et al*., 2024).

Alginate

Alginate, a naturally occurring polysaccharide derived from brown seaweed, is known for its unique colloidal properties, such as thickening, stabilizing, suspending, film-forming, gel-producing, and emulsion-stabilizing abilities (Lee & Mooney, 2012). Structurally, it is composed of unbranched binary copolymers of β-D-mannuronic acid and α-L-guluronic acid residues, forming polymer segments that include consecutive G residues, M residues, and alternating MG residues (George & Abraham, 2006). This configuration allows alginate to interact with metal cations, particularly calcium ions, resulting in the formation of strong gels or insoluble polymers, which are highly valuable in various applications (Tonnesen & Karlsen, 2002).

In the biomedical field, alginate's biocompatibility and biodegradability make it an excellent material for wound dressings, controlled drug delivery, and tissue engineering (Draget & Taylor, 2011). For instance, alginate-based hydrogels loaded with cynaroside, a phytocompound with anti-inflammatory and anti-allergic properties, have shown high bioadhesion and viscosity. In vivo studies demonstrated a reduction in T cells, histiocytes, and mast cells in inflamed skin, or atopic dermatitis, in mouse models following the topical application of the hydrogels (Frontiers in Molecular Biosciences, 2021). Additionally, alginate-based hydrogels loaded with naringenin, known for its antioxidant, anti-inflammatory, and antibacterial activities, have shown positive effects in skin wound treatment (MDPI Polymers, 2020). Certain alginate dressings, such as Kaltostat®, can enhance wound healing by stimulating monocytes to produce elevated levels of cytokines, including interleukin-6 and tumor necrosis factor-α, which promote pro-inflammatory factors beneficial for wound healing (Mollah *et al.*, 2021).

The ability of sodium alginate gels to create a moist environment conducive to healing, through ion exchange between the wound exudate and the dressing, underscores their effectiveness as biomaterials for medical applications (Lee & Mooney, 2012). Alginate-based dressings also have hemostatic properties, which are crucial in controlling bleeding and promoting clot formation (Ruperez, 2002). Furthermore, alginate is utilized in the encapsulation of probiotics, protecting them from the acidic environment of the stomach and ensuring their release in the intestine, enhancing gut health (George & Abraham, 2006).

Beyond biomedical uses, alginate's versatility extends to industrial applications, such as food packaging and bioplastics, offering a sustainable alternative to synthetic polymers (Rinaudo, 2008). Alginate films have been developed with antimicrobial properties, extending the shelf life of food products and ensuring food safety (Puscaselu *et al.*, 2020). Additionally, alginate is used in water treatment processes to remove heavy metals and pollutants, demonstrating its environmental applications (Draget & Taylor, 2011).

Chitosan

Chitosan, a natural polymer derived from the deacetylation of chitin, is a linear nitrogen-containing polysaccharide composed of β-(1,4)-linked N-acetylglucosamine units. It ranks as the second most abundant natural polymer after cellulose (Rinaudo, 2009). Extracted from the exoskeletons of crustaceans, chitosan has garnered significant attention due to its unique combination of properties including biocompatibility, biodegradability, non-toxicity, and antimicrobial activity, which make it highly suitable for a wide range of innovative uses in both biomedical and environmental sectors (Acosta *et al.*, 1993; Meenakshi *et al.*, 2023).

In the biomedical sector, chitosan-based dressings have been shown to accelerate the healing process by promoting cell growth and collagen deposition while also reducing inflammation. Studies have highlighted the efficacy of chitosan dressings in treating chronic wounds, such as those associated with diabetes, demonstrating significant improvements in healing rates compared to conventional treatments (Jayakumar *et al.*, 2011; Zhang *et al.*, 2015). Additionally, chitosan's antimicrobial properties help prevent wound infections, further enhancing its suitability for wound care applications (Jayakumar *et al.*, 2011).

Chitosan is also widely researched for its potential in drug delivery systems. Its ability to form hydrogels and nanoparticles allows for the encapsulation and controlled release of various therapeutic agents, which is particularly beneficial for drugs with poor bioavailability or those requiring targeted delivery to specific sites in the body (Yedi *et al.*, 2022; Srinivasan *et al.*, 2020). Chitosan nanoparticles have been used to improve the stability and absorption of orally administered drugs, such as insulin, by protecting them from degradation in the gastrointestinal tract and facilitating their uptake (Akhgari *et al.*, 2013; Muzzarelli *et al.*, 2016). Furthermore, the mucoadhesive properties of chitosan enhance the residence time of drug formulations at mucosal surfaces, improving the efficacy of topical and nasal drug delivery systems (Sarmento *et al.*, 2006).

In the field of tissue engineering, chitosan's structural similarity to glycosaminoglycans in the extracellular matrix makes it an ideal scaffold material. It supports cell attachment, proliferation, and differentiation, which are crucial for tissue regeneration. Research has demonstrated the potential of chitosan scaffolds in cartilage tissue engineering, showing that they can support chondrocyte proliferation and matrix production, leading to the formation of functional cartilage tissue (Malafaya *et al.*, 2007; Kundu *et al.*, 2014). The versatility of chitosan allows it to be combined with other biomaterials to create composite scaffolds with enhanced mechanical properties and biological functionality (Sharma *et al.*, 2015).

Chitosan's antimicrobial activity is another key attribute that has been leveraged in various biomedical applications. Its mechanism of action involves the interaction with microbial cell membranes, increasing their permeability and leading to cell death. This property is particularly valuable in developing antimicrobial coatings for medical devices and implants, where infection prevention is critical. Chitosan-coated surfaces have been shown to reduce bacterial adhesion and biofilm formation, thereby lowering the risk of device-related infections (Rabea *et al.*, 2003; Li *et al.*, 2014).

In environmental applications, chitosan's high chelation capacity and flocculating properties make it highly effective in water purification. It can remove heavy metals, dyes, and other pollutants from water through adsorption and coagulation processes. Studies have demonstrated chitosan's ability to remove contaminants such as lead, cadmium, and arsenic from industrial wastewater, highlighting its potential as an eco-friendly alternative to conventional water treatment methods (Rinaudo, 2006; Lin *et al.*, 2010). The use of chitosan in water purification not only addresses environmental pollution but also contributes to the sustainable management of water resources (Feng *et al.*, 2018).

Chitosan's role in soil remediation has also been explored, with research showing its effectiveness in binding and immobilizing heavy metals in contaminated soils. By reducing the bioavailability and mobility of these metals, chitosan helps mitigate their toxic effects on plants and the environment (Kamari *et al*., 2011; Crini *et al*., 2019). This property is particularly useful in rehabilitating polluted agricultural lands and promoting sustainable farming practices. Chitosan amendments have been shown to decrease the uptake of heavy metals by crops, thereby reducing the risk of food chain contamination (Islam *et al*., 2020; Zhang *et al*., 2021).

In agriculture, chitosan has been applied as a biostimulant to enhance plant growth and protect against pathogens (El Hassni *et al*., 2004; Das *et al*., 2019). Its use has been associated with improved seed germination, increased plant vigor, and enhanced resistance to diseases. Studies have indicated that chitosan treatment can lead to higher crop yields and better-quality produce, making it a valuable tool for sustainable agriculture (El Hadrami *et al*., 2010; Denancé *et al*., 2013; Asgari-Targhi *et al*., 2018; Elsherbiny *et al*., 2022).

Despite its numerous benefits, several challenges must be addressed to fully realize the potential of chitosan. One of the primary challenges is the scalability of chitosan production. Current extraction methods from chitin are not cost-effective for large-scale production, limiting its commercial viability (Horst *et al*., 1993). Research into more efficient and sustainable extraction methods is essential to overcome this barrier. Additionally, the variability in the quality and properties of chitosan, depending on the source and extraction process, can affect its performance in different applications. Standardization of production processes is necessary to ensure consistent quality and reliability (Huq *et al*., 2022).

Regulatory approval for chitosan-based products, particularly in the biomedical field, can be a significant hurdle due to the stringent requirements for safety and efficacy. Comprehensive clinical trials and toxicological studies are needed to establish the safety profile of chitosan products. Furthermore, the environmental impact of chitosan disposal needs to be considered. Although chitosan is biodegradable, its degradation products and their effects on the environment should be thoroughly investigated (Pathak *et al*., 2023).

Carrageenan

Carrageenan, a natural polysaccharide extracted from red seaweeds, is renowned for its gelling, thickening, and stabilizing properties, making it a versatile ingredient in numerous biomedical and environmental applications (Necas & Bartosikova, 2013; Campo *et al*., 2009). Its unique properties arise from its sulfate content, which influences its solubility and interaction with other molecules (Campo *et al*., 2009; Liu *et al*., 2007; Van de Velde *et al*., 2002).

In the biomedical field, carrageenan's ability to form gels is exploited in drug delivery systems (Necas & Bartosikova, 2013; Prabaharan, 2008). Its capacity to encapsulate drugs and release them in a controlled manner enhances the efficacy of treatments while minimizing side effects (Tuvikene, 2013; Liu *et al*., 2007). Research has demonstrated that carrageenan-based hydrogels can deliver both hydrophilic and hydrophobic drugs effectively, providing sustained release and improved bioavailability (Tuvikene, 2013; Liu *et al*., 2007; Prabaharan, 2008). This property is particularly valuable in oral drug delivery, where carrageenan helps protect drugs from the acidic environment of the stomach, ensuring their release in the intestine (Liu *et al*., 2007; Prabaharan, 2008; Davidovich-Pinhas & Bianco-Peled, 2011).

Moreover, carrageenan is widely used in wound healing applications due to its biocompatibility and non-toxic nature (Necas & Bartosikova, 2013; Campo *et al*., 2009). Carrageenan-based dressings maintain a moist environment that is conducive to wound healing, promoting faster tissue regeneration and reducing the risk of infection (Necas & Bartosikova, 2013; Campo *et al*., 2009). Studies have shown that incorporating antimicrobial agents into carrageenan-based dressings can further enhance their effectiveness, making them suitable for treating chronic and infected wounds (Necas & Bartosikova, 2013; Campo *et al*., 2009; Mihaila *et al*., 2012). Additionally, carrageenan's ability to form films and gels makes it ideal for creating barrier dressings that protect wounds from external contaminants (Necas & Bartosikova, 2013; Campo *et al*., 2009; Mihaila *et al*., 2012).

In tissue engineering, carrageenan is used to develop scaffolds that support cell growth and differentiation (Tuvikene, 2013; Liu *et al*., 2007). Its ability to mimic the extracellular matrix and provide a conducive environment for cell proliferation makes it a valuable material for regenerative medicine (Tuvikene, 2013; Liu *et al*., 2007; Campo *et al*., 2009). Research has highlighted the potential of carrageenan-based scaffolds in cartilage and bone tissue engineering, where they support the growth of chondrocytes and osteoblasts, leading to the formation of functional tissue (Tuvikene, 2013; Liu *et al*., 2007; Campo *et al*., 2009; He *et al*., 2008). Furthermore, carrageenan can be combined with other biopolymers to enhance the mechanical properties and biological functionality of scaffolds, providing better support for tissue regeneration (Tuvikene, 2013; Liu *et al.*, 2007; Campo *et al.*, 2009; He *et al.*, 2008).

In the environmental sector, carrageenan's biodegradable and non-toxic nature makes it an attractive option for water treatment (Tuvikene, 2013; Campo *et al.*, 2009; Liu *et al.*, 2007). It is used as a flocculant to remove suspended solids and contaminants from wastewater, where its ability to aggregate particles and facilitate their removal is well-documented (Campo *et al.*, 2009; Liu *et al.*, 2007; Van de Velde *et al.*, 2002). Studies have shown that carrageenan can effectively remove heavy metals and other pollutants from industrial effluents, highlighting its potential as an eco-friendly alternative to synthetic flocculants (Campo *et al.*, 2009; Liu *et al.*, 2007; Van de Velde *et al.*, 2002; Singh *et al.*, 2010). The use of carrageenan in water treatment not only improves water quality but also reduces the environmental impact associated with chemical flocculants (Campo *et al.*, 2009; Liu *et al.*, 2007; Singh *et al.*, 2010).

Carrageenan is also employed in soil stabilization and erosion control, where its ability to bind soil particles together improves soil structure and reduces erosion (Tuvikene, 2013; Campo *et al.*, 2009; Liu *et al.*, 2007). Research has demonstrated that the application of carrageenan to soil can significantly reduce soil loss due to wind and water erosion, promoting sustainable land management practices (Campo *et al.*, 2009; Liu *et al.*, 2007; Singh *et al.*, 2010; Amin *et al.*, 2011). Additionally, carrageenan enhances the soil's water retention capacity, which can be beneficial in arid regions where water conservation is critical (Campo *et al.*, 2009; Liu *et al.*, 2007; Amin *et al.*, 2011).

In agriculture, carrageenan is used as a biostimulant to improve plant growth and yield. Its ability to retain moisture and improve soil structure enhances seed germination and root development (Tahar *et al.*,2021). Research has indicated that carrageenan treatments can lead to increased crop yields and better-quality produce, making it a valuable tool for sustainable agriculture (Shukla *et al.*, 2016; Iqbal *et al.*, 2011; Amin *et al.*, 2011). Furthermore, carrageenan can be used to formulate biopesticides and biofertilizers, contributing to the reduction of chemical inputs in farming (Campo *et al.*, 2009; Liu *et al.*, 2007; Amin *et al.*, 2011; Davidovich-Pinhas & Bianco-Peled, 2011).

Despite its numerous benefits, there are challenges associated with the use of carrageenan. One of the primary challenges is the potential for carrageenan to cause gastrointestinal inflammation when consumed in large quantities (Borsani *et al.*, 2021; Amin *et al.*, 2011). While food-grade carrageenan is generally considered safe, concerns about its degradation into poligeenan, a substance with known harmful effects, have prompted further research into its safety (Saikh *et al*., 2024).

Xanthan

Xanthan gum, a polysaccharide produced by the bacterium *Xanthomonas campestris*, has become a significant natural polymer due to its versatility and unique properties (Garcia-Ochoa *et al*., 2000). Known for its excellent thickening, stabilizing, and emulsifying capabilities, xanthan gum has found extensive use in both the biomedical and environmental fields (Sworn, 2009). This analysis explores the various applications of xanthan gum, highlighting its potential and the challenges associated with its use.

In the biomedical sector, xanthan gum's rheological properties make it an excellent candidate for drug delivery systems (Sharma *et al*., 2013). Its high viscosity at low concentrations and ability to form stable gels enable the controlled release of drugs (Rao *et al*., 2011). Research has demonstrated that xanthan gum-based hydrogels can encapsulate and release drugs in a sustained manner, improving therapeutic efficacy and patient compliance (Yadav *et al*., 2009). For instance, studies have shown that xanthan gum-based hydrogels enhance the delivery of poorly water-soluble drugs, providing a consistent release over an extended period. This property is particularly beneficial for the oral delivery of drugs, where controlled release can improve bioavailability and reduce dosing frequency (Abu Elella *et al*., 2021).

Xanthan gum's biocompatibility and non-toxic nature further enhance its suitability for biomedical applications (Garcia-Ochoa *et al*., 2000; Liu *et al*., 2008). It is used as a matrix in tissue engineering to create scaffolds that support cell growth and differentiation (Garcia *et al*., 2011; Ribeiro *et al*., 2017). Research has shown that xanthan gum can be combined with other biopolymers, such as alginate and chitosan, to develop composite scaffolds with improved mechanical properties and biological functionality (Ribeiro *et al*., 2017; Garcia *et al*., 2011; Liu *et al*., 2008). These scaffolds provide a conducive environment for cell attachment and proliferation, facilitating tissue regeneration (Liu *et al*., 2008; Ribeiro *et al*., 2017). For instance, xanthan gum-based scaffolds have been used in cartilage tissue engineering, where they support chondrocyte growth and matrix production, leading to the formation of functional cartilage tissue (Garcia *et al*., 2011; Ribeiro *et al*., 2017; Liu *et al*., 2008).

In wound healing, xanthan gum's hydrophilic nature and ability to form a gel make it an effective component in wound dressings (Patel *et al*., 2009; Lim *et al*., 2011). Xanthan gum-based dressings maintain a moist wound environment, which is crucial for optimal healing (Boateng *et al.*, 2013). They also provide a barrier against microbial invasion, reducing the risk of infection (Patel *et al.*, 2009; Lim *et al.*, 2011). Studies have highlighted the efficacy of xanthan gum in wound care, showing that it promotes faster healing and reduces scarring compared to traditional dressings (Patel *et al.*, 2009; Lim *et al.*, 2011; Boateng *et al.*, 2013). Additionally, the incorporation of antimicrobial agents into xanthan gum-based dressings can further enhance their protective effects, making them suitable for treating chronic and infected wounds (Patel *et al.*, 2009; Boateng *et al.*, 2013).

In the environmental sector, xanthan gum's ability to act as a flocculant and its biodegradable nature make it an attractive option for water treatment (Kalia *et al.*, 2011; Rani *et al.*, 2012). It is used to remove suspended solids and contaminants from wastewater through flocculation, where particles aggregate and settle out of the water (Singh *et al.*, 2010; Rani *et al.*, 2012). Research has demonstrated the effectiveness of xanthan gum in removing heavy metals and other pollutants from industrial effluents, highlighting its potential as an eco-friendly alternative to synthetic flocculants (Kalia *et al.*, 2011; Rani *et al.*, 2012; Singh *et al.*, 2010). The use of xanthan gum in water treatment not only improves water quality but also reduces the environmental impact associated with chemical flocculants (Singh *et al.*, 2010; Rani *et al.*, 2012).

Xanthan gum's role in soil stabilization and erosion control is another area of significant interest (Buhmann *et al.*, 2013; Lee *et al.*, 2011). Its ability to bind soil particles together improves soil structure and reduces erosion, particularly in agricultural and construction sites (Zhang *et al.*, 2012). Studies have shown that the application of xanthan gum to soil can significantly reduce soil loss due to wind and water erosion, promoting sustainable land management practices (Buhmann *et al.*, 2013; Lee *et al.*, 2011; Zhang *et al.*, 2012). Additionally, xanthan gum enhances the soil's water retention capacity, which can be beneficial in arid regions where water conservation is critical (Lee *et al.*, 2011; Zhang *et al.*, 2012).

In agriculture, xanthan gum is used as a biostimulant to improve plant growth and yield (Youssef *et al.*, 2017; Mishra *et al.*, 2013). Its ability to retain moisture and improve soil structure enhances seed germination and root development (Kumar *et al.*, 2012). Research has indicated that xanthan gum treatments can lead to increased crop yields and better-quality produce, making it a valuable tool for sustainable agriculture (Youssef *et al.*, 2017; Mishra *et al.*, 2013; Kumar *et al.*, 2012). Furthermore, xanthan gum can be used to formulate biopesticides and biofertilizers, contributing to the reduction of chemical inputs in farming (Mishra *et al.*, 2013; Kumar *et al.*, 2012).

Agarose

Agarose, a polysaccharide extracted from seaweed, is widely utilized in biotechnology and molecular biology due to its unique physical properties and biocompatibility (Alberts *et al.*, 2002; Berg *et al.*, 2002). It forms the foundation of agarose gel electrophoresis, a fundamental technique for separating biomolecules based on size.

Agarose gels are essential tools in molecular biology laboratories for analyzing DNA, RNA, and proteins (Maniatis *et al.*, 1982; Sambrook & Russell, 2001). These gels provide a stable matrix through which biomolecules migrate under an electric field, allowing researchers to separate and visualize fragments of nucleic acids or proteins according to their molecular weight. The porosity and composition of agarose gels can be adjusted to optimize resolution for specific applications, such as detecting gene mutations or analyzing PCR products (Sambrook & Russell, 2001; Alberts *et al.*, 2002).

Beyond electrophoresis, agarose is integral to the preparation of solid culture media in microbiology (Maniatis *et al.*, 1982; Sambrook & Russell, 2001). Agarose's ability to solidify at low temperatures and form a clear, gel-like structure makes it suitable for supporting the growth of microorganisms in laboratory settings. It provides a stable environment for microbial colonies to develop and facilitates the isolation and identification of different bacterial strains (Sambrook & Russell, 2001; Alberts *et al.*, 2002).

In pharmaceuticals, agarose serves as a stabilizing agent in formulations due to its inert nature and ability to maintain the integrity of active compounds over time (Sambrook & Russell, 2001; Green & Sambrook, 2012). It is particularly useful in encapsulating drugs or biomolecules for controlled release applications, where maintaining stability and bioactivity is critical.

The versatility of agarose extends to its use in biotechnology research, where it is employed in techniques such as immunodiffusion assays and protein purification. Agarose-based resins are used to selectively bind biomolecules, facilitating their isolation and purification from complex mixtures. (Zhang et al., 2019; Trivedi et al., 2014; Cook & Witt, 1981)

Despite its widespread applications, agarose production faces challenges related to sustainability and environmental impact. Efforts are underway to develop more eco-friendly extraction methods and to explore alternative sources of agarose that reduce dependence on wild-harvested seaweed. (Sambrook & Russell, 2001; Green & Sambrook, 2012; Hanahan, 1985; Trivedi et al., 2014)

Hyaluronic Acid [HA]

Hyaluronic acid (HA), a naturally occurring polysaccharide found in the extracellular matrix of connective tissues, plays a crucial role in various biological processes, such as cell proliferation, migration, and wound healing (Stern *et al*., 2006; Fraser *et al*., 1997; Necas *et al*., 2008). Its unique physicochemical properties, including high water retention, viscoelasticity, and biocompatibility, have made it a valuable material in both biomedical and environmental applications (Balazs & Gibbs, 1970; Toole, 2004).

In the field of biomedicine, HA is extensively utilized for its therapeutic and regenerative capabilities (Necas *et al*., 2008; Stern *et al*., 2006; Balazs & Gibbs, 1970). One of its prominent applications is in osteoarthritis treatment, where HA injections into the joint cavity provide lubrication, reduce inflammation, and promote the restoration of normal joint function (Balazs & Gibbs, 1970; Toole, 2004; Necas *et al*., 2008). Clinical studies have demonstrated that intra-articular HA injections can significantly alleviate pain and improve joint mobility in patients suffering from osteoarthritis, thus enhancing their quality of life (Necas *et al*., 2008; Balazs & Gibbs, 1970; Toole, 2004; Larsen *et al*., 2008).

HA's role in wound healing is another area of significant interest. Due to its ability to maintain a moist environment, HA-based dressings promote faster wound healing, reduce scar formation, and enhance tissue regeneration (Graca *et al*.,2020; Alven *et al*.,2021). Research indicates that HA facilitates the migration of fibroblasts and keratinocytes to the wound site, accelerating the repair process (Driskell *et al*., 2013; Fraser *et al*., 1997; Sinha *et al*., 2018). Furthermore, HA can be incorporated with antimicrobial agents to create advanced wound dressings that prevent infections and promote optimal healing (Stern *et al*., 2006; Necas *et al*., 2008; Fraser *et al*., 1997; Balazs & Gibbs, 1970).

In cosmetic and dermatological applications, HA is prized for its hydrating and anti-aging properties (Necas *et al*., 2008; Toole, 2004; Balazs & Gibbs, 1970). Its ability to retain large amounts of water makes it an ideal ingredient in skin care products, where it helps maintain skin hydration, improve elasticity, and reduce the appearance of wrinkles (Stern *et al*., 2006; Toole, 2004; Necas *et al*., 2008; Balazs & Gibbs, 1970). Studies have shown that topical application of HA can enhance skin hydration and texture, leading to a more youthful and radiant appearance (Stern *et al*., 2006; Toole, 2004; Necas *et al*., 2008; Balazs & Gibbs, 1970). Additionally, HA fillers are widely used in aesthetic medicine for soft tissue augmentation and facial contouring, providing a minimally invasive option for enhancing facial features and achieving a more youthful look (Necas *et al*., 2008; Toole, 2004; Balazs & Gibbs, 1970; Larsen *et al*., 2008).

In the realm of drug delivery, HA's biocompatibility and ability to form hydrogels are leveraged to create advanced delivery systems (Necas *et al*., 2008; Toole, 2004; Balazs & Gibbs, 1970). HA-based hydrogels can encapsulate a variety of therapeutic agents, including small molecules, proteins, and nucleic acids, providing controlled release and targeted delivery (Stern *et al*., 2006; Toole, 2004; Necas *et al*., 2008). Research has demonstrated that HA can enhance the stability and bioavailability of drugs, improving their therapeutic efficacy (Stern *et al*., 2006; Toole, 2004; Necas *et al*., 2008). Furthermore, HA-drug conjugates have shown promise in cancer therapy, where HA can target CD44 receptors overexpressed on tumor cells, facilitating the delivery of cytotoxic agents directly to the tumor site (Stern *et al*., 2006; Toole, 2004; Necas *et al*., 2008; Balazs & Gibbs, 1970).

Chitin

Chitin, abundant in the exoskeletons of crustaceans, insects, and fungi cell walls, stands as a prominent biopolymer due to its unique properties like biocompatibility, biodegradability, and robustness (Muzzarelli, 2010; Rinaudo, 2006; Pillai *et al*., 2009; Kumar, 2000).

In biotechnology, chitin and its derivative chitosan are notably versatile. Chitosan, formed by chitin's deacetylation, possesses excellent film-forming, antimicrobial, and wound-healing properties (Muzzarelli, 2010; Rinaudo, 2006). This makes it invaluable in biomedical applications, including tissue engineering, wound dressings, and drug delivery (Jayakumar *et al*., 2010). Chitosan-based hydrogels facilitate controlled drug release, enhancing the therapeutic impact of encapsulated drugs (Kumar, 2000).

Environmental science also benefits significantly from chitin. Chitin and chitosan, with their high affinity for heavy metals and dyes, are utilized in wastewater treatment to eliminate pollutants from industrial effluents (Crini & Badot, 2008; Babel & Kurniawan, 2003). They act as natural adsorbents, promoting environmental sustainability. Moreover, chitin-based materials in agriculture enhance soil fertility and promote plant growth, improving soil structure and water retention (Sharp, 2013; Badawy & Rabea, 2011).

In the food industry, chitin and chitosan serve as natural preservatives due to their antimicrobial properties (Shahidi *et al*., 1999). They extend the shelf life of perishable products by preventing spoilage organisms and pathogens. Chitosan coatings on fruits and vegetables reduce respiration rates and moisture loss, maintaining freshness during storage (Devlieghere *et al*., 2004).

Despite these applications, commercial use of chitin is limited by extraction and processing costs. Traditional extraction methods involve harsh chemicals and generate significant waste. Recent biotechnological advances aim to develop sustainable extraction methods like enzymatic processes and microbial fermentation to lower costs and reduce environmental impact (Rinaudo, 2006; Kumar, 2000).

In summary, chitin's diverse applications in biotechnology, environmental science, and other industries highlight its importance as a sustainable biopolymer. Ongoing research and innovation in extraction and processing will enhance its commercial viability, expanding its applications in future technological and environmental solutions (Muzzarelli, 2010; Rinaudo, 2006; Kumar, 2000).

Gum Mucilage (Guar Gum)

Guar gum, also known as guaran, is derived from the seeds of the guar plant (Cyamopsis tetragonoloba). It is widely used in various industries due to its unique thickening, emulsifying, and stabilizing properties. In the food industry, guar gum is utilized to improve the texture and shelf life of products such as ice cream, dairy, and baked goods (Mudgil *et al*., 2014). Its high solubility in water and ability to form viscous solutions make it an excellent ingredient in gluten-free baking, where it helps bind and stabilize ingredients (Singh *et al*., 2017).

In pharmaceuticals, guar gum is employed as a binder and disintegrant in tablet formulations, enhancing the drug release profile and bioavailability (Kumar *et al*., 2018). Additionally, its application in controlled drug delivery systems has shown promise due to its biocompatibility and biodegradability (Sharma *et al*., 2018). Guar gum is also used in the cosmetics industry, where it serves as a thickening agent in lotions and creams, providing a smooth and consistent texture (Mudgil *et al*., 2014).

Honey Locust Gum

Honey locust gum is derived from the seeds of the honey locust tree (Gleditsia triacanthos). It has gained attention for its unique properties and potential applications across various industries. Honey locust gum is primarily composed of polysaccharides, which exhibit excellent water solubility and gelling properties (Barak & Mudgil, 2014). These characteristics make it a valuable ingredient in the food industry, where it is used as a thickener, stabilizer, and emulsifier in products like sauces, dressings, and dairy items (Mudgil *et al*., 2014).

In the pharmaceutical sector, honey locust gum is explored for its use in drug delivery systems. Its ability to form hydrogels and control the release of active pharmaceutical ingredients makes it suitable for developing sustained and controlled release formulations (Kumar *et al*., 2018). Additionally, its biocompatibility and non-toxicity are advantageous for medical applications, including wound dressings and tissue engineering scaffolds (Sharma *et al*., 2018).

Moreover, honey locust gum has shown potential in environmental applications. Due to its natural biodegradability, it can be used in bioremediation efforts to treat polluted water and soil (Singh *et al*., 2017).

Khaya Gum

Khaya gum is extracted from the Khaya tree *(Khaya senegalensis*), commonly found in Africa. This natural polysaccharide is increasingly being recognized for its multifunctional applications in various industries. Khaya gum's high viscosity and emulsifying properties make it a valuable ingredient in the food industry, where it is used to stabilize emulsions and improve the texture of food products such as beverages, sauces, and dairy items (Adebayo *et al*., 2012). Its ability to form gels and bind water enhances the quality and shelf life of food products, offering a natural alternative to synthetic additives (Emeje *et al*., 2009).

In the pharmaceutical industry, Khaya gum is employed as an excipient in drug formulations. It acts as a binder, disintegrant, and controlled release agent, improving the efficacy and bioavailability of drugs (Nep & Conway, 2011; Adebayo *et al*., 2012). Khaya gum-based hydrogels have been developed for sustained drug release, providing a biocompatible and biodegradable medium that ensures a steady release of therapeutic agents over time (Emeje *et al*., 2009). Additionally, Khaya gum's non-toxic nature makes it suitable for use in various medical applications, including wound dressings and tissue engineering scaffolds (Adebayo *et al*., 2012).

Environmental applications of Khaya gum are also noteworthy. Its biodegradability and natural origin make it an ideal candidate for bioremediation processes (Emeje *et al*., 2009). Khaya gum can be used to treat polluted water and soil, effectively adsorbing heavy metals and organic pollutants, thereby contributing to environmental sustainability (Odeku *et al*., 2014; Adebayo *et al*., 2012).

Starch

Starch, a naturally occurring polysaccharide, is one of the most abundant and versatile biopolymers on Earth, derived primarily from plants such as corn, potatoes, rice, and wheat (Hoover, 2001; Tester *et al*., 2004). Its diverse applications span across various industries, owing to its unique physicochemical properties, including gelatinization, pasting, and retrogradation behaviors (Singh *et al*., 2003; BeMiller & Whistler, 2009).

In the food industry, starch is widely used as a thickener, stabilizer, and gelling agent. Its ability to form a gel upon heating and cooling makes it an essential ingredient in the production of sauces, soups, and desserts (Hoover, 2001). Modified starches, which are chemically or physically altered, offer enhanced functionalities such as improved stability, clarity, and resistance to shear, making them suitable for use in processed foods and beverages (Singh *et al*., 2007; BeMiller & Whistler, 2009).

In pharmaceuticals, starch is commonly used as an excipient due to its inert nature and biocompatibility (Ahuja *et al*., 2015). It serves as a binder, disintegrant, and filler in tablet formulations, contributing to the drug release profile and mechanical strength of the tablets (Odeku & Itiola, 2003). Starch-based hydrogels are also explored for controlled drug delivery systems, providing a sustained release of therapeutic agents over extended periods (Zhao *et al*., 2007; Ahuja *et al*., 2015).

Starch has significant applications in the bioplastics industry, where it is used to produce biodegradable and compostable materials (Avérous, 2004). Starch-based bioplastics offer a sustainable alternative to conventional petroleum-based plastics, reducing environmental impact and promoting circular economy practices (Avérous, 2004; Halley & Dorgan, 2011). These bioplastics are employed in packaging, agricultural films, and disposable items such as cutlery and plates (Avérous, 2004; Halley & Dorgan, 2011).

In the textile industry, starch is used as a sizing agent to improve the strength and stiffness of yarns during weaving (BeMiller & Whistler, 2009). Its application in paper manufacturing enhances the paper's surface quality, printability, and strength (BeMiller & Whistler, 2009). Furthermore, starch is utilized in adhesives and coatings, providing excellent binding and film-forming properties (Singh *et al*., 2003).

Starch's role in biotechnology and medical fields is also notable. It is used in the production of bioethanol, a renewable energy source, through fermentation processes (Balat *et al*., 2008). Starch-derived oligosaccharides and polysaccharides are explored for their prebiotic effects, promoting gut health and overall well-being (Roberfroid, 2007). Additionally, starch-based scaffolds are investigated for tissue engineering applications, offering a biocompatible matrix for cell growth and tissue regeneration (Zhao *et al*., 2007).

Despite its numerous benefits, starch has some limitations, such as susceptibility to retrogradation and poor mechanical properties in its native form (Hoover, 2001; Tester *et al*., 2004). Advances in starch modification techniques, including cross-linking, acetylation, and hydroxypropylation, have addressed these challenges, enhanced its functional properties and expanded its application potential (Singh *et al*., 2007; BeMiller & Whistler, 2009 Tester *et al*., 2004).

Inulin

Inulin, a naturally occurring polysaccharide found in various plants, is composed of fructose units primarily linked by β-(2→1) bonds with a terminal glucose unit (Roberfroid, 2005; Flamm *et al*., 2001). Its unique properties have led to widespread applications in the food, pharmaceutical, and nutraceutical industries (Roberfroid, 2007; Coussement, 1999).

In the food industry, inulin is valued for its prebiotic effects and ability to improve the nutritional profile of products (Rao ., 1999). It is a soluble dietary fiber that resists digestion in the upper gastrointestinal tract and reaches the colon intact, where it is fermented by beneficial gut bacteria such as Bifidobacteria and Lactobacilli (Gibson *et al*., 2004). This fermentation process produces short-chain fatty acids, which contribute to gut health and overall well-being (Gibson *et al*., 2004; Kolida *et al*., 2002). Inulin's incorporation into food products can enhance texture, taste, and mouthfeel while providing a low-calorie alternative to fats and sugars (Franck, 2002; Coussement, 1999).

Inulin's role as a prebiotic is well-documented, with numerous studies highlighting its benefits for digestive health (Gibson *et al*., 2004; Kolida *et al*., 2002). Regular consumption of inulin has been associated with increased populations of beneficial gut bacteria, improved bowel function, and enhanced immune responses (Kolida *et al*., 2002; Kleessen *et al*., 1997). Furthermore, inulin has been shown to aid in the absorption of minerals such as calcium and magnesium, which are crucial for bone health (Roberfroid, 2005; Scholz-Ahrens *et al*., 2007).

In the pharmaceutical and nutraceutical industries, inulin is utilized for its functional properties and health benefits (Kolida & Gibson, 2007; Coussement, 1999). It serves as a filler, binder, and stabilizer in various formulations, improving the stability and bioavailability of active ingredients (Roberfroid, 2007; Kleessen *et al*., 1997). Inulin-based supplements are marketed for their potential to support digestive health, weight management, and metabolic health (Roberfroid, 2005; Kleessen *et al.*, 1997). Additionally, inulin has been investigated for its potential role in managing blood sugar levels and reducing the risk of metabolic disorders such as diabetes and obesity (Jackson & Apperly, 2004; Slavin, 2013).

The production of inulin from natural sources such as chicory roots and Jerusalem artichokes is well-established, providing a sustainable and renewable supply of this valuable polysaccharide (Franck, 2002; Flamm *et al.*, 2001). The extraction process typically involves hot water extraction followed by purification steps to obtain high-purity inulin (Franck, 2002; Coussement, 1999). Advances in biotechnology have also enabled the production of inulin through microbial fermentation, offering an alternative method to meet growing demand (Franck, 2002; Coussement, 1999).

Inulin's versatility extends to its use in functional foods, where it acts as a fat replacer, sugar substitute, and dietary fiber enhancer (Coussement, 1999; Franck, 2002). Its ability to form gels and enhance the texture of low-fat and reduced-sugar products makes it an ideal ingredient for health-conscious consumers (Franck, 2002; Gibson *et al.*, 2004).

Despite its numerous benefits, there are some challenges associated with the use of inulin, such as its potential to cause gastrointestinal discomfort in sensitive individuals (Kolida *et al.*, 2002; Roberfroid, 2005). However, these effects are generally mild and can be managed by gradually increasing the intake of inulin-containing products (Kolida *et al.*, 2002; Roberfroid, 2005).

Dextran

Dextran, a complex branched glucan composed of α-(1→6) linked D-glucose molecules with α-(1→3) and occasionally α-(1→4) linkages, is a natural polymer produced by certain bacteria, notably Leuconostoc mesenteroides (Tsuchiya *et al.*, 1952; Sarwat *et al.*, 2008). This polysaccharide exhibits unique properties that make it highly valuable across various industries, including food, pharmaceuticals, and biotechnology (Naessens *et al.*, 2005; Pollesello *et al.*, 1999).

In the food industry, dextran is utilized as a thickener, emulsifier, and stabilizer. Its ability to retain moisture and enhance texture makes it ideal for baked goods, confectionery, and dairy products (Sarwat *et al.*, 2008; Santos *et al.*, 2014). For instance, dextran improves the softness and shelf life of bread by preventing staling, and in confectionery, it acts as a crystal inhibitor in sugar syrups, contributing to a smoother texture (Gani & Pandit, 2019).