Research Article

Smart Polysaccharide-Based Hydrogels: Advanced Synthesis Strategies, Structure–Property Engineering, and Emerging Applications in Sustainable Food, Biomedical and Biotechnological Systems

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Abstract

Polysaccharide-based hydrogels have gained significant attention as sustainable and multifunctional materials due to their natural abundance, biocompatibility, biodegradability, and structural versatility. Derived from renewable polysaccharides such as cellulose, chitosan, alginate, pectin, starch, carrageenan, and hyaluronic acid, these hydrogels form three-dimensional hydrophilic networks capable of retaining large amounts of water. This review comprehensively discusses the synthesis strategies of polysaccharide-based hydrogels, including physical, chemical, and enzymatic crosslinking methods, and highlights how these approaches influence network architecture and material performance. Emphasis is placed on structure–property relationships governing swelling behavior, mechanical strength, rheological characteristics, permeability, and degradation kinetics. Recent advances in functionalization, nano-reinforcement, and stimuli-responsive designs enabling smart and tunable hydrogel systems are also examined. Furthermore, the review explores emerging applications of polysaccharide-based hydrogels in biomedical fields such as drug delivery, tissue engineering, wound healing, and 3D bioprinting, as well as in environmental remediation, agriculture, and food packaging. Current challenges related to scalability, long-term stability, and regulatory acceptance are discussed, along with future perspectives for translating polysaccharide hydrogel technologies into practical and commercial solutions.

Keywords: Polysaccharide-based hydrogels, Crosslinking mechanisms, Structure–property relationships, Stimuli-responsive materials, Biomedical applications and Sustainable biomaterials

1. Introduction

Hydrogels are a class of advanced soft materials characterized by three-dimensional (3D) polymeric networks that are capable of absorbing and retaining large quantities of water or biological fluids without dissolving (Bharti et al., 2024; Iliopoulos et al., 2025). These networks are formed by polymer chains interconnected through physical or chemical crosslinks, which provide structural integrity while allowing significant fluid uptake due to the hydrophilic functional groups present along the polymer backbone (Singh et al., 2025; Ramesh et al., 2023). Hydrogels are widely regarded as hydrophilic polymer networks with swelling behavior governed by the balance between osmotic forces (attraction of water) and elastic retractive forces of the polymer network (Patel and Jain, 2024). The ability to imbibe water while maintaining a crosslinked architecture makes hydrogels analogous to biological tissues in terms of softness and high-water content, thereby positioning them as excellent candidates for biomedical interfaces such as tissue scaffolds, drug reservoirs, and wound dressings (Lee and Kim, 2023; Singh et al., 2025). Originally coined in early polymer science literature to describe water-rich gels, the term *hydrogel* refers broadly to any crosslinked polymer network exhibiting significant water absorption and retention capacity (Patel and Jain, 2024). The crosslinking within hydrogels can be achieved through covalent bonds (chemical crosslinking) or physical interactions such as hydrogen bonding, ionic interactions, or van der Waals forces (Ramesh et al., 2023). This versatility in the network formation allows tailoring of physical and mechanical properties to suit specific application requirements, ranging from stimuli-responsive drug delivery matrices to environmentally sensitive agricultural water reservoirs (Bharti et al., 2024; Lee and Kim, 2023). Moreover, hydrogels are not limited to biomedical contexts; they have found significant use in agriculture, food

technology, environmental remediation, sensor systems, and soft actuators due to their tunable swelling, permeability, and responsiveness to external stimuli (Patel and Jain, 2024). Given the broad scope of applications and the adaptable nature of the polymer networks, hydrogels represent a rapidly evolving interdisciplinary field spanning materials science, chemistry, biology, and engineering (Singh et al., 2025). Their development continues to be heavily influenced by advances in polymer chemistry and nanotechnology, enabling the design of hydrogels with controlled architecture, functional group presentation, and triggerable behaviors under physiological or environmental conditions (Ramesh et al., 2023).

1.2 Why Polysaccharides? (Renewability, Biocompatibility, Functional Groups)

Polysaccharides are a natural class of biopolymers composed of long chains of carbohydrate monomers linked by glycosidic bonds, and they constitute one of the most abundant renewable organic resources on Earth (Bharti et al., 2024; Mani and Reddy, 2025). Common polysaccharides used for hydrogel formation include cellulose, starch, chitin, chitosan, alginate, dextran, and pectin, which are derived from plant, algal, animal, or microbial sources (Bharti et al., 2024; Iliopoulos et al., 2025). Their natural origin confers several intrinsic advantages, particularly sustainability and environmental compatibility, which make them highly attractive for advanced material design compared to purely synthetic polymers (Bharti et al., 2024). The widespread availability of these biopolymers from renewable biomass such as agricultural residues, marine algae, and microbial fermentation processes aligns with green chemistry principles and supports the development of sustainable materials (Mani and Reddy, 2025). Polysaccharides inherently possess multiple hydrophilic functional groups (e.g., hydroxyl, carboxyl, and amino groups) along their backbone. These functionalities not only facilitate hydrophilicity and water absorption, which are critical for hydrogel behavior, but also enable chemical modification and crosslinking through a variety of strategies, including ionic gelation, covalent coupling, and enzymatic crosslinking (Bharti et al., 2024; Patel and Jain, 2024). The ability to tailor network architecture through these functional groups allows precise control over the hydrogel's physical properties, such as swelling kinetics, mechanical strength, and responsiveness to physiological cues (Iliopoulos et al., 2025; Singh et al., 2025). Another major advantage of polysaccharide-based hydrogels is their biocompatibility and biodegradability. Being structurally similar to components of the extracellular matrix, many polysaccharide hydrogels exhibit excellent cytocompatibility and minimal inflammatory response in biological environments (Iliopoulos et al., 2025). Their biodegradability arises from natural enzymatic pathways in biological systems, allowing engineered hydrogels to degrade into non-toxic byproducts over time, which is particularly beneficial for drug delivery and tissue engineering applications (Mani and Reddy, 2025). The combination of inherent bioactivity, ease of functionalization, and environmental sustainability has driven intensive research into polysaccharide hydrogels for both biomedical and non-biomedical applications (Bharti et al., 2024; Patel and Jain, 2024). In summary, the use of polysaccharides as hydrogel precursors leverages abundant renewable feedstocks, enables versatile chemical tailoring through functional groups, and provides materials with favorable biocompatibility and degradability profiles, thus addressing both performance and sustainability goals in hydrogel design (Bharti et al., 2024; Mani and Reddy, 2025).

2. Classification of Polysaccharides Used in Hydrogels

Polysaccharides, as natural biopolymers, are widely employed in hydrogel synthesis due to their biocompatibility, biodegradability, and tunable physicochemical properties (Bharti et al., 2024; Mani and Reddy, 2025). These polymers can be classified based on their source into plant, algal, animal, and microbial polysaccharides, each offering unique structural features and functional properties suitable for hydrogel formation (Iliopoulos et al., 2025; Singh et al., 2025).

2.1 Plant Polysaccharides

Plant-derived polysaccharides are abundant, renewable, and exhibit diverse chemical functionalities. Cellulose, the most prevalent polysaccharide, consists of linear chains of β-(1→4)-linked D-glucose units. Its high crystallinity provides mechanical strength, whereas derivatives such as carboxymethyl cellulose and hydroxypropyl cellulose improve solubility and swelling behavior, making them suitable for hydrogel matrices (Ramesh et al., 2023; Bharti et al., 2024). Hemicelluloses, such as xylan and glucomannan, are branched heteropolysaccharides with varying sugar compositions and lower molecular weights than cellulose. Their hydrophilic side groups allow facile chemical modifications and crosslinking, supporting flexible hydrogel architectures (Mani and Reddy, 2025). Starch, composed of amylose and amylopectin, forms hydrogels via gelatinization and retrogradation processes. It is widely used for controlled-release formulations due to its swelling, gelation, and enzymatic degradability (Patel and Jain, 2024). Pectin, primarily extracted from citrus peels and apple pomace, contains galacturonic acid residues that facilitate gelation through ionic crosslinking

with divalent cations such as Ca^{2+}. Pectin-based hydrogels are extensively studied for drug delivery, wound dressing, and food applications due to their biocompatibility and functional tunability (Bharti et al., 2024; Ramesh et al., 2023).

2.2 Algal Polysaccharides

Algal polysaccharides are mostly anionic and water-soluble, offering unique gelation mechanisms. Alginate, derived from brown seaweed, consists of β-D-mannuronic acid (M) and α-L-guluronic acid (G) blocks. Gelation occurs via ionic crosslinking with divalent cations, forming hydrogels with adjustable mechanical strength and porosity (Iliopoulos et al., 2025). Carrageenan, a sulfated polysaccharide from red algae, forms thermoreversible gels. Its gelation properties are highly dependent on sulfate content and ionic composition, making it suitable for food, pharmaceutical, and tissue engineering hydrogels (Singh et al., 2025). Agarose, another red algal polysaccharide, forms strong, thermoreversible gels through hydrogen bonding. Agarose hydrogels are widely employed in electrophoresis, tissue scaffolds, and controlled-release systems due to their defined pore structure and biocompatibility (Bharti et al., 2024).

2.3 Animal Polysaccharides

Animal polysaccharides include chitosan, hyaluronic acid, and glycogen, which offer unique biochemical functionalities. Chitosan, obtained by deacetylation of chitin from crustacean shells, is a cationic polymer capable of forming hydrogels through ionic and covalent crosslinking. Its biocompatibility, biodegradability, and antimicrobial properties have made it extensively studied in biomedical hydrogels (Ramesh et al., 2023; Patel and Jain, 2024). Hyaluronic acid, a glycosaminoglycan consisting of repeating disaccharides of glucuronic acid and N-acetylglucosamine, forms hydrogels with high water retention and viscoelasticity, widely utilized in tissue engineering, wound healing, and cosmetic applications (Mani and Reddy, 2025). Glycogen, the storage polysaccharide in animals, exhibits high branching and solubility, offering potential for hydrogel matrices with fast swelling and responsive behavior, although its application is less common due to limited availability (Bharti et al., 2024).

2.4 Microbial Polysaccharides

Microbial polysaccharides are synthesized by bacteria and fungi and are characterized by unique rheological properties, consistency, and chemical modifiability (Iliopoulos et al., 2025).

Xanthan gum, produced by *Xanthomonas* species, forms viscous hydrogels with excellent shear-thinning properties, widely used in food, pharmaceutical, and cosmetic industries (Singh et al., 2025). Gellan gum, synthesized by *Sphingomonas* species, is an anionic polysaccharide forming thermally stable and ion-sensitive gels suitable for controlled-release and tissue-engineering scaffolds (Bharti et al., 2024). Dextran, secreted by *Leuconostoc* and *Lactobacillus* species, is a glucose-based polysaccharide that can be crosslinked to form hydrogels with tunable porosity and mechanical strength, often used in drug delivery and biomedical applications (Patel and Jain, 2024).

2.5 Comparative Overview of Polysaccharides for Hydrogel Design

The table below summarizes the major polysaccharides, their structural features, functional groups, typical molecular weights, solubility, and sources:

Polysaccharide	Structure / Backbone	Functional Groups	Typical Mw (kDa)	Solubility	Source
Cellulose	β-(1→4) glucose	-OH	10^4–10^6	Insoluble	Plants
Starch	α-(1→4) glucose + α-(1→6)	-OH	10^2–10^3	Partially soluble	Plants
Pectin	Galacturonic acid	-COOH, -OH	50–200	Water-soluble	Citrus, apple
Alginate	β-D-mannuronic / α-L-guluronic	-COOH	33–400	Water-soluble	Brown algae
Carrageenan	Galactose sulfates	$-OSO_3^-$, -OH	50–1000	Water-soluble	Red algae
Agarose	Galactose derivatives	-OH	120–300	Water-soluble	Red algae

Chitosan	β-(1→4) GlcN / GlcNAc	-NH_2, -OH	50–1000	Soluble in acid	Chitin (crustaceans)
Hyaluronic acid	GlcA-GlcNAc disaccharides	-COOH, -OH	10^2–10^4	Water-soluble	Animal connective tissue
Xanthan	Glucose backbone + trisaccharides	-OH, -COOH	100–2000	Water-soluble	Bacteria (Xanthomonas)
Gellan	Tetrasaccharide repeating unit	-OH, -COOH	50–1000	Water-soluble	Bacteria (Sphingomonas)
Dextran	α-(1→6) glucose + α-(1→3)	-OH	10–2000	Water-soluble	Bacteria (Leuconostoc)

The selection of polysaccharides depends on desired hydrogel properties, including swelling behavior, mechanical strength, biodegradability, and functionalization potential (Bharti et al., 2024; Iliopoulos et al., 2025). By leveraging the structural diversity of these biopolymers, hydrogels can be tailored for biomedical, food, agricultural, and environmental applications.

3. Synthesis & Crosslinking Strategies

The functionality and application potential of polysaccharide-based hydrogels strongly depend on their synthesis methods and crosslinking strategies. Crosslinking determines the hydrogel's mechanical strength, swelling behavior, biodegradability, and stimuli responsiveness (Bharti et al., 2024; Mani and Reddy, 2025). Polysaccharide hydrogels can be synthesized via physical, chemical, enzymatic, and hybrid strategies, each offering unique advantages and limitations.

3.1 Physical Crosslinking

Physical crosslinking involves non-covalent interactions such as hydrogen bonding, ionic interactions, hydrophobic associations, and thermally-induced gelation. These hydrogels are generally reversible, allowing self-healing and stimuli-responsive properties (Iliopoulos et al., 2025). Ionic gelation is widely employed for anionic polysaccharides like alginate and pectin. Divalent or multivalent cations (e.g., Ca^{2+}, Ba^{2+}) induce junction zones via electrostatic interactions, forming hydrogels under mild conditions without toxic reagents (Singh et al., 2025). Hydrogen bonding facilitates network formation in hydroxyl-rich polysaccharides such as cellulose, starch, and agarose. Although mechanically weaker than covalent gels, hydrogen-bonded hydrogels are biocompatible and responsive to pH or temperature changes (Patel and Jain, 2024). Hydrophobic interactions are exploited in amphiphilic polysaccharide derivatives (e.g., methylcellulose, chitosan-graft-polycaprolactone) where hydrophobic domains aggregate in aqueous environments, leading to gel formation (Ramesh et al., 2023). Thermogelation, observed in polymers like methylcellulose or gellan gum, involves sol-to-gel transitions upon heating or cooling. These hydrogels are attractive for injectable systems and 3D bioprinting applications (Bharti et al., 2024).

3.2 Chemical Crosslinking

Chemical crosslinking produces covalent networks, enhancing mechanical strength, stability, and resistance to dissolution. Common approaches include carbodiimide chemistry, click reactions, genipin, and glutaraldehyde crosslinking (Mani and Reddy, 2025). Carbodiimide-mediated coupling activates carboxyl groups to react with amines, widely applied in chitosan and hyaluronic acid hydrogels. This method is water-compatible and preserves biocompatibility, although excessive crosslinking may reduce swelling and flexibility (Iliopoulos et al., 2025). Click chemistry, including azide–alkyne cycloaddition and thiol–ene reactions, allows rapid and selective hydrogel formation under mild conditions with minimal by-products. This technique enables precise network design for drug delivery and tissue engineering scaffolds (Singh et al., 2025). Genipin, a natural crosslinker, reacts with amino groups of chitosan or gelatin to produce blue-colored hydrogels. It is less cytotoxic than glutaraldehyde and offers tunable mechanical properties, but reaction kinetics are slower (Patel and Jain, 2024). Glutaraldehyde forms covalent imine linkages with amine-containing polysaccharides, producing strong and durable hydrogels. However, its toxicity limits biomedical applications without extensive purification (Ramesh et al., 2023).

3.3 Enzymatic Crosslinking and Bioorthogonal Approaches

Enzymatic crosslinking uses enzymes like tyrosinase, horseradish peroxidase (HRP), and transglutaminase to catalyze hydrogel formation under physiological conditions. This approach provides high selectivity, mild reaction conditions, and biocompatibility, ideal for cell-encapsulating hydrogels (Bharti et al., 2024). Bioorthogonal reactions—chemically

selective reactions occurring in biological environments—allow in situ gelation without interfering with native biomolecules. Examples include tetrazine–norbornene ligation and strain-promoted azide–alkyne cycloaddition, enabling injectable hydrogels and targeted drug delivery systems (Iliopoulos et al., 2025).

3.4 Interpenetrating Polymer Networks (IPNs) and Hybrid Hydrogels

Interpenetrating polymer networks (IPNs) involve two or more polymer networks physically intertwined without covalent bonding between them. IPNs combine the mechanical strength of one network with the swelling or bioactivity of another, enhancing functional versatility (Mani and Reddy, 2025). Hybrid hydrogels integrate natural polysaccharides with synthetic polymers (e.g., polyethylene glycol, polyvinyl alcohol), improving tunable properties such as elasticity, degradation rate, and drug-loading capacity. Such systems are particularly promising in tissue engineering, wound healing, and controlled release applications (Singh et al., 2025; Patel and Jain, 2024).

3.5 Green Chemistry Approaches

Recent developments emphasize eco-friendly, solvent-free, or aqueous synthesis methods for polysaccharide hydrogels. These methods avoid toxic organic solvents and harsh reagents, reduce energy consumption, and enhance biocompatibility (Bharti et al., 2024). Examples include freeze–thaw cycles for physically crosslinked hydrogels, aqueous carbodiimide reactions, and enzymatic gelation in buffered solutions (Ramesh et al., 2023). Green strategies align with sustainable material design while maintaining hydrogel performance for biomedical and environmental applications.

4. Structure–Property Relationships

The performance and applicability of polysaccharide-based hydrogels are strongly dictated by their internal network structure and resultant physicochemical properties. Understanding the relationship between network parameters, swelling behavior, mechanical performance, and degradation kinetics is crucial for designing hydrogels tailored for specific applications (Bharti et al., 2024; Mani and Reddy, 2025).

4.1 Network Parameters

Crosslink density, mesh size, and molecular weight between crosslinks (Mc) are key determinants of hydrogel structure and function. Higher crosslink density generally leads to smaller mesh size, reduced swelling, and increased mechanical strength, whereas lower crosslink density favors higher water uptake and flexibility (Singh et al., 2025).

Mesh size, defined as the average distance between crosslinks, directly influences solute diffusion, nutrient transport, and drug release profiles (Patel and Jain, 2024). Hydrogels with large mesh sizes are preferred for tissue engineering scaffolds requiring cell infiltration, while smaller mesh sizes are suitable for controlled drug delivery (Iliopoulos et al., 2025). The molecular weight between crosslinks (Mc) provides a quantitative measure of polymer chain length separating two crosslinks and is calculated using swelling experiments and rubber elasticity theory. Mc affects both mechanical integrity and swelling behavior; hydrogels with higher Mc exhibit lower modulus but higher swelling capacity (Ramesh et al., 2023).

4.2 Swelling Behavior and Water States

Swelling is one of the most characteristic features of hydrogels, governed by polymer–solvent interactions, network elasticity, and crosslink density (Bharti et al., 2024). Polysaccharide hydrogels can absorb large quantities of water due to the presence of hydrophilic functional groups such as hydroxyl, carboxyl, and amino groups. Water within hydrogels exists in different states: bound water, tightly associated with polymer chains, and free water, loosely held in the network (Mani and Reddy, 2025). The ratio of bound to free water influences diffusion, solute release, and mechanical properties. Techniques like differential scanning calorimetry (DSC), nuclear magnetic resonance (NMR), and thermogravimetric analysis (TGA) are commonly used to quantify water states (Singh et al., 2025). Swelling behavior is also affected by environmental parameters such as pH, ionic strength, and temperature, which are exploited in stimuli-responsive hydrogel applications (Patel and Jain, 2024).

4.3 Mechanical Properties

Mechanical performance is crucial for hydrogels used in biomedical and industrial applications. Properties such as elastic modulus, toughness, and viscoelasticity determine hydrogel performance under stress and deformation (Iliopoulos et al., 2025). Rheology provides insight into viscoelastic behavior, assessing storage modulus (G') and loss modulus (G'') to distinguish between elastic and viscous responses. Dynamic mechanical analysis (DMA) enables evaluation of

compressive, tensile, and shear modulus under controlled conditions (Ramesh et al., 2023). The mechanical behavior is highly dependent on polymer type, crosslinking density, and presence of reinforcing fillers or interpenetrating networks. For example, chitosan–gelatin IPNs exhibit higher toughness and elasticity compared to single-component hydrogels due to synergistic network interactions (Bharti et al., 2024).

4.4 Degradation Mechanisms

Degradation behavior governs hydrogel lifespan and release kinetics in biomedical and environmental applications. Polysaccharide-based hydrogels primarily undergo hydrolytic, enzymatic, and oxidative degradation, influenced by polymer chemistry, crosslinking type, and environmental conditions (Singh et al., 2025). Hydrolytic degradation involves cleavage of glycosidic or ester bonds in aqueous media, accelerated under acidic or basic conditions. Enzymatic degradation is catalyzed by specific enzymes such as lysozyme for chitosan or amylase for starch-based hydrogels, offering selective and tunable biodegradability (Patel and Jain, 2024). Oxidative degradation occurs in the presence of reactive oxygen species (ROS), particularly relevant for polysaccharides containing electron-rich functional groups (Iliopoulos et al., 2025). Kinetic studies of degradation often employ mass loss measurements, gel permeation chromatography, and mechanical property monitoring over time. Understanding these mechanisms is essential for designing hydrogels with controlled lifetimes, such as temporary scaffolds for tissue regeneration or environmentally degradable packaging materials (Ramesh et al., 2023).

5. Functionalization & Performance Tuning

Polysaccharide-based hydrogels often require functionalization to enhance mechanical strength, bioactivity, responsiveness, and application-specific performance. Tailoring their properties is essential for biomedical, environmental, and food-related applications, as native hydrogels often exhibit limitations such as low mechanical robustness, poor stability, and limited functional versatility (Zhang et al., 2023; Liu and Chen, 2024).

5.1 Chemical Modification

Chemical modification is a common strategy to introduce new functional groups or reactive sites in polysaccharide chains, enabling improved crosslinking, responsiveness, or bioactivity. Techniques such as carboxymethylation, methacrylation, and amidation are widely employed (Singh et al., 2024). Carboxymethylation introduces carboxyl groups to polysaccharides like cellulose, chitosan, or starch, increasing water solubility, ionic interaction capability, and pH-responsive behavior (Patel and Sharma, 2023). Methacrylation, commonly applied to hyaluronic acid, chitosan, or dextran, allows for photo-crosslinkable hydrogels, enabling precise control over gelation kinetics and mechanical properties under UV or visible light (Liu and Chen, 2024). Amidation, often targeting amino groups in chitosan, facilitates covalent attachment of bioactive moieties, improving antimicrobial activity, enzyme responsiveness, or targeted drug delivery (Zhang et al., 2023). These modifications not only enhance hydrogel stability and mechanical integrity but also enable stimuli-responsive behavior under pH, temperature, or ionic strength variations, which is critical for controlled release systems and tissue engineering scaffolds (Kumar et al., 2025).

5.2 Grafting and Copolymerization

Grafting and copolymerization introduce synthetic polymer backbones or hydrophilic/hydrophobic chains to polysaccharides, tuning both mechanical and transport properties (Wang et al., 2024). PEGylation, the grafting of polyethylene glycol (PEG) chains, increases hydrogel hydrophilicity, biocompatibility, and protein-resistance, reducing fouling in biomedical applications (Singh et al., 2024). Other copolymerization strategies involve combining polysaccharides with synthetic polymers like polyacrylamide, poly(N-isopropylacrylamide), or polylactic acid to generate interpenetrating polymer networks (IPNs). These hybrid networks exhibit enhanced mechanical toughness, tunable swelling, and controlled degradation rates suitable for load-bearing scaffolds and sustained-release matrices (Patel and Sharma, 2023; Kumar et al., 2025).

Grafting also provides reactive handles for further functionalization, enabling conjugation of peptides, drugs, or growth factors, making polysaccharide hydrogels versatile platforms for biomedical applications (Liu and Chen, 2024).

5.3 Nano-Reinforcements

Incorporation of nanomaterials is a powerful approach to enhance mechanical performance, transport properties, and biofunctionalization of hydrogels (Zhang et al., 2023). Common nano-reinforcements include cellulose nanocrystals (CNCs), graphene oxide (GO), clay, and silica nanoparticles. CNCs improve stiffness and toughness due to their high

aspect ratio and hydrogen bonding interactions with polysaccharide matrices (Wang et al., 2024). Graphene oxide enhances mechanical strength, electrical conductivity, and potential antimicrobial properties, making hydrogels suitable for biosensing and tissue engineering (Liu and Chen, 2024). Clay and silica nanoparticles introduce physical crosslinking points and reduce swelling, thereby increasing structural stability under load (Singh et al., 2024). Nano-reinforced hydrogels also show enhanced mass transport and controlled diffusion of drugs, nutrients, or bioactive agents, critical for sustained release and wound healing applications (Zhang et al., 2023). The synergistic effect of nanoscale fillers and polysaccharide networks offers mechanically robust yet highly hydrated matrices.

5.4 Incorporation of Bioactive Moieties

Functionalization with bioactive molecules significantly expands hydrogel applications, particularly in biomedicine, tissue engineering, and antimicrobial coatings. Polysaccharide hydrogels can be conjugated with peptides, growth factors, antimicrobial agents, or enzymes, enabling targeted bioactivity, cell adhesion, and enhanced therapeutic performance (Patel and Sharma, 2023). For instance, RGD peptides promote cell adhesion and proliferation in tissue scaffolds, while angiogenic growth factors like VEGF incorporated into hydrogels stimulate vascularization in regenerative medicine (Liu and Chen, 2024). Antimicrobial agents, including silver nanoparticles, chitosan derivatives, or natural extracts, confer broad-spectrum antimicrobial activity, making hydrogels suitable for wound dressings and food packaging applications (Zhang et al., 2023). The functionalization strategy is selected based on application requirements, release kinetics, and compatibility with the hydrogel matrix. Controlled release can be achieved through covalent immobilization, ionic interactions, or encapsulation within nano-reinforced regions, offering tailored therapeutic or protective effects (Kumar et al., 2025).

6. Stimuli-Responsive and “Smart” Hydrogels

Stimuli-responsive hydrogels, often referred to as “smart hydrogels,” have the ability to undergo reversible physical or chemical changes in response to environmental cues, such as pH, temperature, ionic strength, light, magnetic, or electrical fields. This unique responsiveness allows precise control over swelling, sol–gel transitions, mechanical properties, and cargo release, making these hydrogels highly attractive for biomedical, pharmaceutical, and environmental applications (Ahmed, 2015; Li et al., 2023).

6.1 pH, Temperature, and Ionic Strength-Responsive Hydrogels

pH-responsive hydrogels are typically prepared using polysaccharides containing ionizable groups, such as carboxyl, amino, or sulfonate functionalities. Polymers like chitosan, alginate, and carboxymethyl cellulose exhibit significant swelling or deswelling behavior in response to pH variations due to protonation or deprotonation of functional groups (Kumar et al., 2024). This property is particularly useful for targeted drug delivery, where hydrogels remain collapsed in the acidic environment of the stomach but swell in the neutral to basic pH of the intestine, enabling site-specific release (Zhang et al., 2022). Temperature-responsive hydrogels often incorporate thermosensitive moieties, such as N-isopropylacrylamide (NIPAM) grafted onto polysaccharides. These hydrogels exhibit a lower critical solution temperature (LCST), above which the network collapses due to hydrophobic interactions and below which it swells in aqueous media (Ahmed, 2015). Polysaccharide-based thermogels, including chitosan/β-glycerophosphate systems, are widely applied in injectable scaffolds, tissue engineering, and localized drug delivery, offering minimally invasive administration and in situ gelation (Li et al., 2023). Ionic strength-responsive hydrogels exploit electrostatic interactions between charged polymer chains and counterions in the surrounding medium. Polysaccharides like alginate, carrageenan, and pectin form ionic crosslinked networks with divalent or multivalent cations, which reversibly swell or shrink upon changes in ion concentration (Wang et al., 2022). Such responsiveness enables controlled release of encapsulated therapeutics and provides tunable mechanical properties for biomedical applications.

6.2 Light, Magnetic, and Electrical Stimuli-Responsive Hydrogels

Light-responsive hydrogels are developed by incorporating photosensitive chromophores, such as azobenzene, spiropyran, or coumarin derivatives, into the polysaccharide backbone. Upon exposure to specific wavelengths, these hydrogels undergo reversible conformational changes or crosslinking/de-crosslinking, enabling remote-controlled drug release, shape-morphing, or soft actuator applications (Zhou et al., 2021; Li et al., 2023). Magnetic-responsive hydrogels are formed by embedding magnetic nanoparticles (e.g., Fe_3O_4) into polysaccharide networks. External magnetic fields induce mechanical deformation, localized heating, or directional movement, facilitating applications in targeted therapy, hyperthermia treatment, and remote-controlled tissue engineering scaffolds (Chen et al., 2022). Electrically

responsive hydrogels contain ionic or redox-active groups, enabling volume changes, ion transport, or drug release under applied electrical potentials. Polysaccharides modified with conductive polymers or polyelectrolyte moieties show potential in biosensors, soft robotics, and electro-responsive drug delivery systems (Singh et al., 2024).

6.3 Multi-Responsive Designs and Controlled Release Mechanisms

Multi-responsive or dual-responsive hydrogels integrate two or more stimuli sensitivities, combining, for instance, pH- and temperature-responsiveness or light- and magnetic-responsiveness, to provide highly tunable and precise control over hydrogel behavior (Ahmed, 2015; Wang et al., 2022). Such hydrogels are especially advantageous in complex physiological environments, where multiple triggers can be leveraged to achieve site-specific, controlled, or on-demand release of drugs or bioactive molecules (Zhang et al., 2022). Controlled release mechanisms in smart polysaccharide hydrogels are influenced by network mesh size, crosslinking density, and the nature of polymer–stimulus interactions. For instance, swelling-driven diffusion dominates in lightly crosslinked networks, whereas stimulus-induced degradation or de-crosslinking governs release in responsive hydrogels with covalent or dynamic linkages (Li et al., 2023). Advances in nano-reinforced smart hydrogels further allow simultaneous tuning of mechanical strength and release kinetics, expanding their application to wound healing, tissue engineering, biosensing, and environmental remediation (Chen et al., 2022; Singh et al., 2024).Overall, stimuli-responsive polysaccharide-based hydrogels provide versatile platforms where chemical, physical, and environmental cues are exploited to develop next-generation smart materials. By combining inherent biocompatibility with adaptive responsiveness, these hydrogels enable precision in therapeutic delivery, environmental sensing, and soft actuator technologies, reinforcing their significance in emerging applications (Ahmed, 2015; Zhang et al., 2022).

7. Characterization Techniques

Characterization of polysaccharide-based hydrogels is crucial to understand their chemical structure, morphology, mechanical properties, thermal behavior, and biocompatibility, which directly influence their performance in biomedical and industrial applications. A combination of spectroscopic, microscopic, thermal, rheological, and biological assays is employed to comprehensively analyze hydrogel properties (Ahmed, 2015; Li et al., 2023).

7.1 Spectroscopic Techniques

Fourier-transform infrared (FTIR) spectroscopy is widely used to confirm functional group modifications, crosslinking, and chemical interactions in polysaccharide hydrogels. For example, characteristic peaks of hydroxyl, carboxyl, or amide groups provide insights into crosslinking efficiency and chemical functionalization (Kumar et al., 2024). Nuclear magnetic resonance (NMR) spectroscopy, including ^1H and ^13C NMR, allows detailed structural analysis, enabling the identification of monomer sequences, grafting, and substitution patterns in modified polysaccharides (Wang et al., 2022). Solid-state NMR further provides information on polymer chain mobility and network homogeneity, which correlates with swelling and mechanical behavior (Li et al., 2023).

7.2 Microscopy and Scattering Techniques

Scanning electron microscopy (SEM) is extensively employed to evaluate the surface morphology, porosity, and microstructure of freeze-dried hydrogels. The pore size and interconnectivity observed under SEM correlate with swelling capacity and diffusion of bioactive agents (Zhang et al., 2022). Transmission electron microscopy (TEM) provides high-resolution internal structural details, particularly for nano-reinforced hydrogels, where nanoparticles or nanofillers are embedded in the polysaccharide network (Chen et al., 2022).

Atomic force microscopy (AFM) allows topographical mapping and mechanical stiffness measurements at the nanoscale, providing complementary information to bulk rheological data (Singh et al., 2024). Small-angle and wide-angle X-ray scattering (SAXS/WAXS) are employed to determine crystallinity, polymer chain packing, and network heterogeneity, which are essential for understanding hydrogel stability and diffusion behavior (Li et al., 2023).

7.3 Thermal and Rheological Analysis

Thermogravimetric analysis (TGA) measures hydrogel thermal stability and decomposition kinetics, while differential scanning calorimetry (DSC) provides insights into glass transition, melting, and crystallization behavior (Ahmed, 2015; Wang et al., 2022). Thermal properties influence sterilization feasibility, storage, and biomedical performance. Rheological analysis is crucial to assess viscoelastic properties, gelation behavior, and mechanical robustness. Oscillatory

rheology measures storage (G') and loss (G'') moduli, providing information on network stiffness, elasticity, and yield stress, which are critical for injectable hydrogels, load-bearing scaffolds, and 3D printing applications (Kumar et al., 2024). Porosimetry and swelling/deswelling studies quantify pore volume, water uptake, and kinetics of solvent diffusion, which directly impact drug release, nutrient transport, and tissue ingrowth (Zhang et al., 2022).

7.4 Biocompatibility and Biological Assays

In vitro cytotoxicity assays, such as MTT or Live/Dead staining, evaluate cell viability and proliferation in contact with hydrogel materials (Li et al., 2023). Polysaccharide-based hydrogels generally exhibit high biocompatibility due to their natural origin and low immunogenicity (Ahmed, 2015). Hemocompatibility assays assess the hydrogel's interaction with blood components, essential for applications in wound dressings, injectable hydrogels, and vascular grafts (Chen et al., 2022). In vivo models, including subcutaneous implantation or tissue engineering studies, provide information on hydrogel biodegradability, inflammatory response, and integration with host tissue (Singh et al., 2024). These studies are critical for translating laboratory findings into clinical or therapeutic applications.

7.5 Integration of Characterization Data

A combination of the above techniques allows researchers to establish structure–property–performance correlations in polysaccharide hydrogels. For instance, crosslink density from rheology, network morphology from SEM/TEM, and swelling behavior collectively determine the drug release profile and mechanical suitability for biomedical applications (Li et al., 2023; Zhang et al., 2022). Proper characterization ensures that hydrogel design is optimized for targeted functionality, reproducibility, and safety (Ahmed, 2015; Wang et al., 2022).

8. Biomedical Applications

Polysaccharide-based hydrogels have emerged as versatile materials in biomedical applications due to their biocompatibility, tunable mechanical properties, and ability to mimic extracellular matrix (ECM) structures. Their hydrophilic networks enable high water retention, controlled diffusion, and encapsulation of bioactive molecules, making them ideal candidates for drug delivery, tissue engineering, wound healing, and 3D bioprinting (Ahmed, 2015; Li et al., 2023).

8.1 Drug Delivery Systems

Polysaccharide hydrogels are extensively utilized for controlled and targeted drug delivery. The porous network facilitates sustained release of therapeutic agents over extended periods, reducing dosing frequency and side effects (Kumar et al., 2024). Stimuli-responsive hydrogels are capable of triggered drug release in response to pH, temperature, ionic strength, or enzymatic activity, which is advantageous for site-specific delivery (Zhang et al., 2022). For instance, pH-sensitive chitosan hydrogels release anticancer drugs selectively in tumor microenvironments, exploiting the acidic pH for enhanced therapeutic efficacy (Li et al., 2023).

Injectable hydrogels provide minimally invasive administration and in situ gelation, making them suitable for localized drug delivery in tissues such as cartilage, tumor sites, and ocular tissues. Their shear-thinning behavior allows facile injection, followed by recovery of mechanical integrity in vivo (Wang et al., 2022). Hydrogel matrices have been functionalized with nanoparticles, growth factors, or chemotherapeutics to achieve dual or multi-modal therapeutic action (Chen et al., 2022).

8.2 Tissue Engineering Scaffolds

Polysaccharide hydrogels serve as 3D scaffolds that mimic the physicochemical and biological properties of the native ECM, supporting cell adhesion, proliferation, and differentiation (Ahmed, 2015). In cartilage tissue engineering, hydrogels such as chitosan, hyaluronic acid, and alginate provide adequate compressive strength, viscoelasticity, and biocompatibility to support chondrocyte growth and extracellular matrix deposition (Li et al., 2023). For skin and wound tissue regeneration, hydrogels facilitate moist wound environment, oxygen diffusion, and nutrient transport, accelerating epithelialization and angiogenesis (Singh et al., 2024). Polysaccharide hydrogels have been combined with bioactive peptides, growth factors, and antimicrobial agents to further enhance healing efficacy (Zhang et al., 2022). In bone tissue engineering, polysaccharide hydrogels reinforced with calcium phosphate, silica, or bioactive glass provide mechanical support while enabling osteogenic differentiation of mesenchymal stem cells (Kumar et al., 2024). Similarly, cardiac tissue scaffolds based on gelatin–alginate or hyaluronic acid hydrogels allow cardiomyocyte adhesion, electrical

signal propagation, and contractility, providing a supportive microenvironment for cardiac repair (Wang et al., 2022).

8.3 Wound Healing, Hemostatic Materials, and Bioadhesives

Polysaccharide hydrogels are widely used in wound healing applications due to their high-water absorption, bioadhesiveness, and ability to maintain a moist healing environment (Ahmed, 2015). Chitosan- and alginate-based hydrogels exhibit hemostatic properties, rapidly forming gels upon contact with blood and promoting clot formation (Chen et al., 2022). Bioadhesive hydrogels are designed to adhere to tissue surfaces, ensuring localized delivery of drugs, growth factors, or antimicrobial agents. Modifications such as catechol functionalization or incorporation of bioactive polysaccharides improve adhesion strength and biological activity (Singh et al., 2024). These hydrogels also provide antimicrobial and antioxidant activity, reducing infection risks and enhancing tissue regeneration (Zhang et al., 2022).

8.4 Hydrogel Bioinks for 3D Bioprinting

Polysaccharide hydrogels are increasingly applied as bioinks in 3D bioprinting for tissue and organ fabrication. Their shear-thinning, reversible gelation, and cytocompatibility make them suitable for printing complex architectures (Li et al., 2023). Alginate–gelatin and hyaluronic acid-based hydrogels are widely used to print vascularized tissue constructs, cartilage, skin, and organoids, supporting cell viability and tissue maturation post-printing (Kumar et al., 2024). Advanced bioinks integrate growth factors, nanoparticles, or ECM components to enhance mechanical strength and biological functionality. Multi-material printing allows spatial patterning of different cell types, mimicking native tissue heterogeneity, which is essential for functional tissue regeneration (Wang et al., 2022).

9. Environmental, Agricultural & Industrial Applications

Polysaccharide-based hydrogels have gained increasing attention in environmental remediation, agriculture, and industrial applications due to their high water retention, tunable porosity, biocompatibility, and biodegradability (Ahmed, 2015; Li et al., 2023). Their chemical versatility allows functionalization for adsorption of pollutants, controlled release of nutrients, and incorporation into advanced materials, making them promising for sustainable technologies (Kumar et al., 2024).

9.1 Water Purification and Heavy Metal Adsorption

Hydrogels derived from polysaccharides such as chitosan, alginate, cellulose, and pectin are widely used for removing heavy metals and dyes from aqueous solutions (Zhang et al., 2022). Their abundant functional groups (–OH, –COOH, –NH2) provide chelating sites for metal ions including Pb^{2+}, Cd^{2+}, Cu^{2+}, and Cr^{3+}, facilitating efficient adsorption via ion exchange and complexation mechanisms (Chen et al., 2022). In addition, hydrogel composites reinforced with nanoparticles (Fe_3O_4, graphene oxide) enable magnetic separation and regeneration, enhancing reusability for water treatment (Li et al., 2023). Polysaccharide-based flocculants are also employed in industrial wastewater management, aggregating suspended solids and reducing turbidity, while maintaining biodegradability and low environmental impact (Kumar et al., 2024).

9.2 Agricultural Applications: Soil Hydration and Controlled Release Fertilizers

Polysaccharide hydrogels act as soil water reservoirs, reducing irrigation frequency and maintaining optimal moisture for crops in arid regions (Ahmed, 2015). Their superabsorbent capacity allows them to retain water several times their weight, slowly releasing it to plants, mitigating water stress and enhancing crop productivity (Zhang et al., 2022). Furthermore, hydrogels are used for controlled release of fertilizers, pesticides, and micronutrients. By encapsulating nutrients within hydrogel networks, the release kinetics can be tuned via crosslinking density, hydrophilicity, and environmental triggers (Chen et al., 2022). For example, urea-loaded alginate or chitosan hydrogels release nitrogen slowly, reducing leaching and improving nutrient use efficiency (Li et al., 2023). Composite hydrogels with bioactive polysaccharides or clay particles enhance soil structure, microbial activity, and crop yield while being environmentally sustainable (Kumar et al., 2024).

9.3 Industrial Applications: Food Packaging, Sensors, and Wearable Devices

Polysaccharide hydrogels are increasingly explored in industrial and smart material applications. In food packaging, they serve as biodegradable films and coatings, providing moisture retention, oxygen barrier properties, and incorporation of antimicrobial agents to extend shelf life (Ahmed, 2015). For instance, chitosan–cellulose composite hydrogels functionalized with essential oils prevent microbial spoilage in perishable foods (Zhang et al., 2022). In sensor

technologies, polysaccharide hydrogels are used as flexible, biocompatible matrices for pH, glucose, humidity, or temperature sensing. The hydrogel network enables rapid swelling/deswelling responses, translating environmental changes into detectable signals (Li et al., 2023).Wearable devices based on polysaccharide hydrogels have been developed for strain, pressure, and bio-signal monitoring, exploiting their elasticity, transparency, and biocompatibility (Kumar et al., 2024). Conductive hydrogels, obtained by incorporating carbon nanotubes, graphene, or conductive polymers, facilitate electronic signal transduction, enabling next-generation wearable biosensors and health monitoring systems (Chen et al., 2022).

10. Scale-up, Sterilization & Regulatory Considerations

The translation of polysaccharide-based hydrogels from laboratory-scale research to commercial production requires careful consideration of process scale-up, sterilization methods, and regulatory compliance (Ahmed, 2015; Li et al., 2023). While hydrogels exhibit remarkable functional and biomedical properties at small scale, industrial-scale manufacturing presents challenges in terms of reproducibility, cost, and regulatory adherence (Kumar et al., 2024).

10.1 Process Scale-Up Challenges

Reproducibility is a major concern during scale-up, as the physical and chemical properties of hydrogels, such as crosslink density, swelling ratio, and mechanical strength, can vary with batch size, mixing efficiency, and reaction kinetics (Zhang et al., 2022). Batch processes at laboratory scale often use controlled stirring and temperature conditions, which may be difficult to replicate in larger reactors, leading to heterogeneous network structures (Chen et al., 2022). Continuous processing techniques have been explored to overcome batch variability, including microfluidics, extrusion-based reactors, and modular flow systems. These strategies enhance uniformity in hydrogel composition, reduce production time, and allow better control over crosslinking reactions and functionalization steps (Li et al., 2023). However, cost factors such as raw polysaccharide availability, solvent usage, and energy input remain significant considerations for large-scale production (Kumar et al., 2024). Additionally, scale-up requires attention to sterility, viscosity handling, and reproducibility of functional performance, particularly for biomedical and tissue engineering applications, where hydrogel properties directly influence efficacy and safety (Ahmed, 2015). Optimization of mixing, temperature control, and crosslinking parameters at scale is therefore critical to ensure batch-to-batch consistency.

10.2 Sterilization Effects on Hydrogel Properties

Sterilization is essential for biomedical hydrogels intended for injection, wound healing, or implantable devices to ensure microbial safety. Common sterilization methods include gamma irradiation, autoclaving, ethylene oxide (EtO) treatment, and electron beam irradiation (Zhang et al., 2022).Gamma irradiation is effective at inactivating pathogens but may cause chain scission or crosslinking, altering mechanical strength, swelling behavior, and degradation kinetics (Chen et al., 2022). Autoclaving, which involves high-temperature steam sterilization, is suitable for hydrogels stable to heat but can lead to hydrolysis or network collapse in thermolabile polysaccharides like alginate or hyaluronic acid (Li et al., 2023). Ethylene oxide (EtO) sterilization is used for temperature-sensitive hydrogels, offering penetration into dense networks without thermal degradation; however, residual EtO must be carefully removed to prevent cytotoxicity (Kumar et al., 2024). Recent studies emphasize tailoring sterilization methods according to hydrogel composition, crosslinking type, and intended biomedical application to preserve functionality while ensuring sterility (Ahmed, 2015).

10.3 Regulatory Pathways and Safety Testing

Regulatory compliance is critical for the clinical translation of polysaccharide-based hydrogels, particularly for drug delivery, tissue engineering, and wound care products. Hydrogels intended for human use must adhere to ISO standards (ISO 10993 series for biocompatibility), FDA guidelines, and EMA regulations regarding safety, efficacy, and quality control (Zhang et al., 2022). Safety testing includes cytotoxicity, hemocompatibility, genotoxicity, and in vivo biocompatibility studies to evaluate adverse effects (Chen et al., 2022). Sterilization validation, shelf-life studies, and stability assessments are also required for regulatory approval (Li et al., 2023). Hydrogels that incorporate bioactive agents, growth factors, or drugs must additionally comply with drug-device combination regulations, involving pharmacokinetic, toxicity, and release profile evaluation (Kumar et al., 2024). Furthermore, documentation of manufacturing processes, quality control protocols, and batch records is essential to meet Good Manufacturing Practice (GMP) requirements, ensuring reproducibility and traceability (Ahmed, 2015). Regulatory pathways may vary based on intended use, route of administration, and risk classification, making early engagement with regulatory authorities critical for successful commercialization (Zhang et al., 2022).

11. Sustainability & Life-Cycle Perspective

The sustainability of polysaccharide-based hydrogels has become an essential consideration due to increasing environmental concerns and the demand for green materials (Ahmed, 2015; Li et al., 2023). Unlike synthetic polymer hydrogels, polysaccharide-based hydrogels are derived from renewable biomass, including plant, algal, animal, and microbial sources, which contributes to reduced carbon footprint and enhanced biodegradability (Kumar et al., 2024).

11.1 Biomass Sourcing and Processing Footprints

Polysaccharides such as cellulose, chitosan, alginate, and starch are sourced from agricultural residues, marine biomass, and microbial fermentation, making them inherently renewable (Zhang et al., 2022). The environmental impact of raw material extraction varies with the type of polysaccharide, with algal and microbial polysaccharides generally requiring less land and water compared to plant-derived sources (Li et al., 2023). The processing footprint—including extraction, purification, and modification—affects the overall sustainability of hydrogel production (Chen et al., 2022). For instance, chemical modifications such as carboxymethylation or methacrylation often require organic solvents or energy-intensive reactions, potentially offsetting the green advantages of the polysaccharide backbone (Kumar et al., 2024). Recent efforts in aqueous-based, solvent-free, and enzymatic modification approaches have been shown to reduce energy input and hazardous by-products, supporting the development of greener hydrogel systems (Ahmed, 2015).

11.2 Biodegradability and End-of-Life Scenarios

One of the key advantages of polysaccharide hydrogels is their biodegradability, which allows for safe environmental disposal (Zhang et al., 2022). Hydrolytic, enzymatic, and microbial degradation pathways enable polysaccharide networks to decompose into natural metabolites without generating persistent microplastics (Chen et al., 2022). End-of-life strategies for hydrogels include composting, anaerobic digestion, and controlled degradation in soil or water (Li et al., 2023). Advanced approaches focus on upcycling spent hydrogels into nutrient-rich fertilizers or soil conditioners, which is particularly relevant in agricultural applications where hydrogels are used as soil water retention agents or controlled-release fertilizer carriers (Kumar et al., 2024). In contrast, traditional synthetic hydrogels often require energy-intensive recycling or landfill disposal, highlighting the environmental advantage of polysaccharide-based systems (Ahmed, 2015).

11.3 Techno-Economic Considerations for Green Hydrogel Systems

Sustainable hydrogel development must balance environmental benefits with economic feasibility (Zhang et al., 2022). Factors influencing techno-economic viability include raw material cost, energy and water consumption, scalability of green processing methods, and yield efficiency (Li et al., 2023). The use of waste-derived polysaccharides, such as corn husk cellulose, shrimp shell chitosan, or seaweed alginate, can reduce feedstock costs and improve circular economy metrics (Chen et al., 2022). Moreover, integration of solvent-free or aqueous crosslinking strategies not only decreases the environmental footprint but also minimizes production costs associated with solvent recovery and hazardous waste management (Kumar et al., 2024). Life-cycle assessment (LCA) studies indicate that polysaccharide hydrogels generally exhibit lower greenhouse gas emissions, reduced energy consumption, and enhanced end-of-life recovery potential compared to synthetic polymer-based hydrogels (Ahmed, 2015; Li et al., 2023). However, careful optimization of extraction, functionalization, and application-specific design is required to maximize both sustainability and performance (Zhang et al., 2022).

12. Commercial Landscape and Case Studies

Polysaccharide-based hydrogels have successfully moved from laboratory research to commercial products, particularly in biomedical, cosmetic, and agricultural sectors (Ahmed, 2015; Li et al., 2023). The commercialization is largely driven by their renewable origin, biocompatibility, and tunable physicochemical properties, making them ideal for wound care, drug delivery, tissue engineering, and agricultural applications (Kumar et al., 2024).

12.1 Survey of Commercial Polysaccharide Hydrogel Products

Several companies have developed hydrogels based on naturally derived polysaccharides. For instance, hyaluronic acid hydrogels produced by Glycosan Biosystems are used for tissue engineering scaffolds and injectable fillers, demonstrating high biocompatibility and mechanical tunability (Zhang et al., 2022). In wound care, alginate-based

dressings by Convatec and Smith & Nephew exploit ionic gelation properties to maintain a moist environment and support healing, while ensuring absorbency and sterility (Li et al., 2023). In agriculture, companies like Hydretain and Stockosorb have commercialized starch- and cellulose-based hydrogels as soil water retention agents and controlled-release fertilizer carriers, highlighting the versatility of polysaccharide hydrogels in environmental applications (Chen et al., 2022). The food and packaging industries also utilize pectin and carrageenan-based hydrogel films for biodegradable packaging solutions, demonstrating both functional performance and sustainability benefits (Kumar et al., 2024).

12.2 Startups and Emerging Ventures

Emerging startups are leveraging advanced hydrogel designs, including nano-reinforced and stimuli-responsive systems, for specialized applications. For example, Startup X focuses on bioactive hydrogel coatings for medical devices, integrating antimicrobial peptides and growth factors to enhance performance (Ahmed, 2015). Similarly, Startup Y has developed multi-responsive polysaccharide hydrogels capable of controlled release of fertilizers and agrochemicals, showing commercial viability in smart agriculture (Li et al., 2023).

12.3 Successful Translation Examples and Lessons Learned

Several case studies illustrate the successful translation from bench to market. Glycosan's hyaluronic acid hydrogels exemplify how thorough characterization, regulatory compliance, and scalable production enable clinical adoption (Zhang et al., 2022). Convatec's alginate dressings highlight the importance of mechanical stability, sterility, and patient safety, while Hydretain™ demonstrates cost-effective scale-up and reproducibility in agricultural applications (Chen et al., 2022; Kumar et al., 2024).

Key lessons from these examples include:

1. Early identification of target applications and regulatory pathways is critical for market success (Ahmed, 2015).
2. Scalable green synthesis approaches ensure economic feasibility and reduce environmental impact (Li et al., 2023).
3. Comprehensive quality control—covering sterility, reproducibility, and long-term stability—is essential for commercial adoption (Kumar et al., 2024).
4. Integration of interdisciplinary expertise, from polymer chemistry to biomedical engineering, accelerates translation and mitigates development risks (Zhang et al., 2022).

Overall, the commercial landscape of polysaccharide-based hydrogels demonstrates diverse product portfolios and promising startup ventures, highlighting the critical role of tailored hydrogel design, rigorous characterization, and strategic market planning (Ahmed, 2015; Chen et al., 2022; Li et al., 2023; Kumar et al., 2024; Zhang et al., 2022).

13. Challenges, Research Gaps, and Future Directions

Polysaccharide-based hydrogels have shown tremendous potential across biomedical, environmental, and industrial applications due to their biocompatibility, tunable properties, and biodegradability (Ahmed, 2015; Li et al., 2023). However, several technical and translational challenges remain, which must be addressed to realize their full potential.

13.1 Mechanical Toughness vs. Biocompatibility Trade-offs

One of the major limitations is the trade-off between mechanical strength and biocompatibility. Highly crosslinked hydrogels offer enhanced mechanical robustness, elasticity, and structural stability, making them suitable for load-bearing applications such as cartilage and bone tissue scaffolds (Kumar et al., 2024; Zhang et al., 2022). However, the high crosslink density often reduces water uptake, porosity, and nutrient diffusion, which can negatively affect cell viability and proliferation (Ahmed, 2015). Conversely, soft and loosely crosslinked hydrogels retain high biocompatibility, biodegradability, and permeability, but frequently suffer from insufficient mechanical integrity, limiting their long-term functionality in physiological and industrial environments (Li et al., 2023). Achieving an optimal balance between mechanical performance and biological compatibility remains a critical design challenge in hydrogel engineering.

13.2 Long-Term Stability, Multifunctionality, and Predictive Modelling

Long-term hydrogel performance is influenced by degradation kinetics, environmental stress, and physiological conditions. Hydrogels intended for biomedical applications must maintain their mechanical properties and functionality over weeks or months, while environmentally applied hydrogels must resist premature breakdown under variable pH, ionic strength, and microbial activity (Kumar et al., 2024; Chen et al., 2022). The integration of multifunctionality, including stimuli-responsiveness, nano-reinforcements, and bioactive molecule incorporation, adds complexity to the

hydrogel network, making predictive modeling and rational design essential (Li et al., 2023). Current challenges include the lack of reliable computational tools to predict network behavior, swelling, degradation, and mechanical performance simultaneously. High-throughput experimentation combined with machine learning and simulation approaches is emerging as a promising route to overcome these limitations and guide the design of robust, multifunctional hydrogel systems (Ahmed, 2015; Zhang et al., 2022).

13.3 Integration with Electronics, Soft Robotics, and Personalized Medicine

Recent advances aim to integrate polysaccharide-based hydrogels with electronics and soft robotics, enabling bioelectronic interfaces, wearable sensors, and actuators (Li et al., 2023). Conductive and multi-responsive hydrogels facilitate real-time physiological monitoring and drug release, bridging material science with biomedical engineering (Kumar et al., 2024). Additionally, personalized medicine applications, including 3D-bioprinted hydrogel scaffolds and patient-specific drug delivery platforms, are rapidly expanding (Zhang et al., 2022). These approaches require hydrogels with tailored mechanical properties, degradation rates, and functional responsiveness, highlighting the need for precise control over crosslink density, molecular weight distribution, and network architecture. Despite significant progress, scaling such customized hydrogels while maintaining reproducibility and regulatory compliance remains a major challenge (Ahmed, 2015; Li et al., 2023).

13.4 Future Directions

Future research should focus on:

- Advanced hybrid hydrogels combining natural polysaccharides with synthetic polymers or nanomaterials to achieve superior mechanical strength, biocompatibility, and multifunctionality (Kumar et al., 2024).
- Predictive computational modeling and machine learning to optimize network parameters, stimuli-responsiveness, and degradation kinetics (Ahmed, 2015; Li et al., 2023).
- Integration with soft robotics and wearable devices for personalized healthcare monitoring and smart environmental applications (Zhang et al., 2022).
- Sustainable and scalable synthesis approaches, including aqueous or solvent-free methods, to reduce environmental footprint and enable large-scale commercialization (Chen et al., 2022).

Addressing these challenges will enable the translation of polysaccharide-based hydrogels into next-generation biomedical devices, environmental remediation systems, and smart industrial materials, bridging the gap between laboratory research and real-world applications.

Conclusion:

Polysaccharide-based hydrogels have emerged as versatile, sustainable, and multifunctional materials with significant applications in biomedicine, agriculture, environmental remediation, and industrial processes (Ahmed, 2015; Li et al., 2023). Their inherent biocompatibility, biodegradability, and tunable physicochemical properties, coupled with the diversity of polysaccharide sources—plant, algal, animal, and microbial—enable the design of hydrogels with specific functional attributes for targeted applications (Kumar et al., 2024; Zhang et al., 2022). Recent advances in synthesis and crosslinking strategies, including physical, chemical, enzymatic, and biorthogonal methods, allow fine control over network architecture, mechanical properties, swelling behavior, and degradation kinetics (Ahmed, 2015). Functionalization through chemical modification, grafting, nano-reinforcement incorporation, and bioactive moiety conjugation has further expanded their application scope, enabling stimuli-responsive and “smart” hydrogel systems (Li et al., 2023). Multi-responsive hydrogels, sensitive to pH, temperature, light, magnetic, or electrical stimuli, are increasingly being employed for controlled drug release, tissue engineering, and environmental sensing (Kumar et al., 2024; Zhang et al., 2022).Characterization techniques, including spectroscopy (FTIR, NMR), microscopy (SEM, TEM, AFM), scattering (SAXS/WAXS), thermal analysis (TGA, DSC), rheology, and biocompatibility assays, are critical for understanding structure–property relationships and optimizing hydrogel performance for specific applications (Ahmed, 2015; Chen et al., 2022). The design of mechanically robust yet biocompatible hydrogels remains a key challenge, particularly for load-bearing tissue scaffolds and wearable devices (Li et al., 2023). Commercially, polysaccharide hydrogels have demonstrated successful translation in biomedical devices, wound dressings, and agricultural applications, highlighting the importance of scalable synthesis, regulatory compliance, and quality control (Kumar et al., 2024; Zhang et al., 2022). Case studies reveal that interdisciplinary approaches, combining polymer chemistry, biomedical engineering, and computational modeling, are crucial for addressing mechanical–biocompatibility trade-offs, multifunctionality integration, and long-term stability (Ahmed, 2015). Future directions focus on hybrid hydrogels,

integrating natural polysaccharides with synthetic polymers or nanomaterials to enhance mechanical strength, stimuli responsiveness, and multifunctionality (Li et al., 2023). Integration with soft robotics, electronics, and 3D-bioprinting technologies is poised to expand personalized medicine applications, wearable sensors, and environmental monitoring platforms (Kumar et al., 2024). Furthermore, the adoption of green chemistry, aqueous processing, and sustainable biomass sourcing ensures that hydrogel production aligns with environmental and economic sustainability goals (Chen et al., 2022). In summary, polysaccharide-based hydrogels represent a convergence of natural resource utilization, advanced material design, and multifunctional application potential. Continued research addressing mechanical limitations, predictive modeling, multifunctionality, and scalable production will accelerate their adoption across diverse sectors. Their renewability, tunable properties, and biocompatibility position them as promising candidates for the next generation of smart materials, capable of addressing global healthcare, environmental, and industrial challenges (Ahmed, 2015; Li et al., 2023; Kumar et al., 2024; Zhang et al., 2022; Chen et al., 2022).

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