RESEARCH PAPER

NATURAL POLYSACCHARIDE-BASED MATERIALS FOR DRUG DELIVERY AND CLINICAL APPLICATIONS

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ABSTRACT

Natural polysaccharides such as chitosan, sodium alginate, and pectin are used in drug delivery, tissue engineering, 3D bioprinting, and sensing. They can absorb water and form hydrogels or films. These materials can also be chemically modified for different applications. However, each polymer has its own limitations, and its performance depends on how it is prepared and used. Proper formulation and optimization are needed to improve stability. This review examines polysaccharide-based hydrogels for controlled drug release, especially naringenin delivery, and discusses hydrogel and film formation. It also covers nanotechnology-based drug carriers and their use in detecting environmental contaminants, including microplastics. The effects of polymer structure, crosslinking, swelling, mechanical strength, drug loading, and release behaviour are also discussed. Agricultural residues such as banana pseudostem are considered as sources of cellulose-rich fibres for paper products, including tissue paper.

KEYWORDS: Natural polysaccharides; controlled drug delivery; naringenin; polysaccharide hydrogels; 3D bioprinting; nanocarriers; microplastic detection; tissue engineering.

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INTRODUCTION:

Drug delivery systems are used to deliver bioactive compounds to the injured site and release them at a suitable rate. Conventional formulations may not always maintain the desired drug concentration or provide the required release rate. Materials used in tissue engineering and sensing have different requirements, including suitable mechanical strength and structural stability. [1], [7], [13]

Natural polysaccharides such as sodium alginate, alginate dialdehyde (ADA), chitosan and pectin are being used for these purposes. Depending on their structure and preparation, they can form hydrogels, films, fibres and composite materials. Their properties can also be modified through oxidation, crosslinking, polymer blending and the introduction of different functional groups. Their performance depends not only on the polymer but also on the preparation conditions, formulation composition and oxidation time. [1], [7], [20]

Recent research has explored polysaccharide-based systems for delivering bioactive compounds such as naringenin, producing bioinks for 3D printing and supporting tissue engineering. Naringenin is of interest because of its biological activities, including its potential wound-healing properties. However, its low water solubility presents a major challenge in formulation. Nanotechnology-based sensors can help detect pollutants such as microplastics, but they need to be tested with real samples to check how well they work. [4], [6], [12]

This review explains the use of natural polysaccharides in drug delivery, biomaterials, 3D bioprinting and nanotechnology-based sensing. It discusses how modification and formulation affect material performance, along with naringenin-loaded delivery systems and the limitations related to safety, characterization and practical applications. The potential use of cellulose-rich agricultural residues is also considered. [2], [5], [8]

1. Natural polysaccharides as drug-delivery platforms

Natural polysaccharides can be widely applied for drug delivery due to their ability to form hydrogels, films, beads and nanoparticles, which are capable of carrying drugs and controlling their release rate. Moreover, their properties can be tuned by crosslinking or graft copolymerization with other polymers or by chemical modification. Nevertheless, the application depends on the polymer's properties, the drug to be delivered and the target tissues or cells. For instance, sodium alginate is a good choice for encapsulating drugs with the formation of calcium crosslinked networks of sodium alginate chains. The reason is that calcium ions coordinate with alginate polymers, thus, allowing to trap macromolecules in the network and to control the release rate by the choice of crosslinker concentration and the preparation method. On the other hand, chitosan is considered as a promising polymer for pharmaceutical engineering due to the presence of amino groups able to interact

with various compounds and the possibility to form films. Moreover, the combination of chitosan and sodium alginate is a great option to prepare nanoparticles with improved properties due to the opposite charges of these polymers leading to the formation of a network with unique characteristics. [1], [5], [7], [13], [19]

Table 1: Natural Polysaccharides used as Drug-Delivery

Polysaccharide	**Structural and physicochemical characteristics**	**Functional role in drug-delivery systems**	**Limitations**
Sodium alginate	Anionic polysaccharide containing mannuronic and guluronic acid residues	Hydrogel formation, aqueous drug encapsulation and ion-mediated crosslinking	Limited mechanical stability under some formulation conditions
Pectin	Anionic polysaccharide containing galacturonic acid-rich regions	Film formation, matrix structuring and modulation of hydration and drug release	Performance depends on degree of esterification, composition and crosslinking conditions
Chitosan	Cationic polysaccharide containing protonatable amino groups	Mucoadhesion, polyelectrolyte complex formation and drug encapsulation	Solubility and charge characteristics are pH-dependent
Alginate dialdehyde	Oxidized alginate containing aldehyde functional groups	Reactive matrix formation and potential covalent crosslinking with suitable functional groups	Oxidation degree influences molecular integrity and material properties

Acidic polysaccharides such as pectin can be isolated from citrus fruits and other plants and used for the preparation of gels and films. Cellulose is another natural polysaccharide that can be applied for the fabrication of fibrous membranes with high mechanical stability, which is applicable for wound dressing. [1], [20]

Modified cellulose derivatives are also used in drug formulations because ordinary cellulose does not dissolve easily in water. [20]

Although these materials have useful properties, their performance depends on the preparation method and the drug being delivered. For example, a material that absorbs a large amount of water may not necessarily release its drug at the required rate. Therefore, drug loading, swelling, stability and release behaviour should be tested before selecting a material for a particular application. [5], [13]

2. Molecular engineering of polysaccharide-based delivery systems

Polysaccharides can be modified to improve their strength, swelling and drug-release behaviour. Crosslinking joins polymer chains to form a network. Blending combines different polymers, while oxidation introduces new chemical groups. [1], [5], [13], [19]

Alginate can be oxidised to form alginate dialdehyde (ADA). Its aldehyde groups can react with amino groups in chitosan to form a crosslinked network. β-cyclodextrin can also help carry certain poorly water-soluble drugs. However, excessive crosslinking may reduce swelling and slow drug release. [1], [7], [10], [12]

Table 2: modification ways of polysaccharide-based drug delivery systems.

Method	**Modification**	**Functional outcome**
Oxidation	Introduction of aldehyde groups	Facilitates chitosan crosslinking

Ionic crosslinking	Ionic bonding between polymer chains	Hydrogel formation
Covalent crosslinking	Covalent bond formation	Improved network stability
Polymer blending	Combination of multiple polymers	Tunable strength, flexibility and swelling
β-Cyclodextrin complexation	Drug inclusion within cyclodextrin cavities	Improved drug solubility and stability
Nanocomposite formation	Incorporation of nanomaterials	Modified strength, drug loading and release

Oxidation and crosslinking: Oxidation introduces new chemical groups into a polysaccharide. For example, oxidation of alginate produces alginate dialdehyde (ADA), whose aldehyde groups can react with the amino groups of chitosan to form a crosslinked network. Crosslinking helps maintain the hydrogel structure and can influence swelling and drug release. However, excessive crosslinking may reduce water absorption and slow drug movement. [1], [7], [13], [19]

Cyclodextrin-assisted drug encapsulation: Cyclodextrins have a cavity that can hold suitable drug molecules. This method may improve the solubility of poorly water-soluble drugs such as naringenin. The resulting complex can be incorporated into a suitable polysaccharide carrier for drug delivery. However, the improvement depends on the drug, the type of cyclodextrin and the preparation method. [4], [12]

3. Polysaccharide-based hydrogels for controlled drug delivery

Hydrogels are 3D networks that can hold a lot of water. They are useful for drug delivery because the drug can be trapped inside and released slowly. Natural polysaccharides like sodium alginate, chitosan, pectin etc. are commonly used because they are biocompatible and can form gels.The properties of the hydrogel depend on the polymer type, concentration and how it is cross-linked. Cross-linking connects the polymer chains and makes the network stable.In most studies, drugs are loaded during gel formation. The release of the drug happens by diffusion, swelling or degradation of the polymer. [1] , [5], [13], [19]

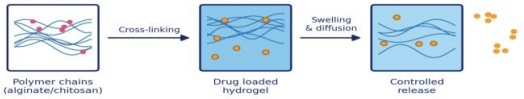


Fig. 1. Schematic representation of drug loading and release from a polysaccharide hydrogel.

Many papers have shown that changing the polymer ratio, cross-linker concentration or pH can alter the swelling behaviour and release rate, Feyissa et al. (2023) used double-cross-linked alginate-chitosan hydrogels for metronidazole delivery and found that the formulation affected porosity, swelling and release. They also reported a Korsmeyer-Peppas model fit, which suggests a combination of diffusion and swelling. Other studies have also shown pH-responsive release, where the hydrogel releases more drug at different pH. [13], [19]

From these studies, it is clear that hydrogels can control release well, but there are still some challenges like poor stability, batch-to-batch variation and limited long-term studies. [5], [13]

4. Naringenin-loaded polysaccharide delivery systems

Naringenin is a flavonoid with good antioxidant and anti-inflammatory activity. But it is not very soluble in water, so it is hard to deliver in the body. It is mostly soluble in methanol/ethanol. To solve this, researchers have tried different carriers like β-cyclodextrin, nanoparticles, liposomes, micelles and hydrogels. [4]

Maity et al. (2017) prepared alginate-coated chitosan nanoparticles for oral naringenin delivery. They reported high encapsulation efficiency (around 91%) and good release in simulated fluids. The study also showed some biological activity in diabetic rats. Kamble et al. (2026) used naringenin-loaded nanocochleates in a hydrogel with alginate and Carbopol for topical delivery. This study showed that the combined system improved release and skin retention. [4], [12]

ADA has aldehyde groups which can react with chitosan and form a stable network. This may help in better loading and controlled release. The encapsulation efficiency, swelling, stability and in-vitro release are necessary. FTIR and SEM (if available) can be used for characterisation. [1], [7], [13], [19]



Fig. 2. Preparation of naringenin-loaded ADA-chitosan hydrogel (illustrative diagram).

Most studies on naringenin have used nanoparticles or other carriers. There are a few reports on naringenin-loaded polysaccharide hydrogels. It is also not clear how well the drug is retained in the

hydrogel for long time or how it behaves in real biological conditions. [4], [12]

5. Polysaccharide-Based Films and Membranes for Drug Delivery

Polysaccharide-based films are thin structures that can carry and deliver specific amounts of drug substances to the target site. They are used in wound dressing applications to cover the wound area and maintain the desired hydration while providing a platform for the local delivery of therapeutics. The physicochemical properties of such structures are determined by the type of polymer, preparation method and the amount of entrapped drug molecules. [1], [5], [20]

Alginate–pectin films can carry various types of drug-loaded particles that control the release rate. Bacterial cellulose membranes are suitable for wound-care applications due to the developed fibrous structure that resembles the extracellular matrix and provides excellent moisture-retaining properties. Composite films comprised of cellulose and other materials are also extensively studied to develop enhanced mechanical stability, flexibility and functional properties. [1], [20]

The drug release rate can be controlled by the film thickness, polymer composition, membrane swelling degree and the interaction between the drug and the polymer matrix. However, the presence of good flexibility and moisture absorption properties is not enough for the effective delivery of bioactive compounds. Therefore, such films and membranes require additional testing of their ability to ensure the desired drug release rate, stability, biomechanical properties and biological performance to verify their potential for practical applications. [5], [13] , [20]

Table 3: Examples of polysaccharides films and membranes

Material/system	Active component/application	Key findings
Alginate–pectin crosslinked film	Cefazolin-loaded nanoparticles	Wound-dressing film (Shahzad et al., 2019)
Alginate–aloe vera–cellulose nanocrystal film	Aloe vera	Film properties and antibacterial activity (Thomas et al., 2020)
Bacterial cellulose membranes	Wound care and local drug delivery	Potential wound-dressing and drug-delivery applications (Portela et al., 2019)
Pectin-based films/gels	Drug delivery	Composition and crosslinking influence drug release (Han et al., 2022)

6. Polysaccharide-based biomaterials for therapeutic and tissue-engineering applications

Polysaccharides like cellulose, chitosan, alginate and pectin are natural polymers that are capable of degrading under specific conditions, and they can absorb water. These polymers are utilized for manufacturing films, fibres, hydrogels, scaffolds with porous structure and other biomaterials. Cellulose can increase mechanical strength, chitosan can impart antimicrobial properties, alginate can be used to prepare gels, and pectin can be utilized for film formation. A combination of these materials can improve certain qualities, but their mechanical strength, safety for the human body, and biodegradation rate should be evaluated. [1], [5], [13], [20]

The fabrication of construct using polysaccharide inks for 3D bioprinting requires smart materials that can flow under pressure to produce filaments when extruded from the printer nozzle and retain their shape after being printed. The main challenge related to such materials is to find an optimal balance between processability, mechanical properties, and cell adhesion. [11]

Polysaccharide biomaterials can also be used for other industrial applications like packaging films

and coatings, paper production, textiles, fabrication of certain membranes, and composite materials. The ability of these polymers to form films and their sustainability makes them attractive for replacing some petroleum-based materials. However, the mechanical properties, flexibility, hydrophobicity or hydrophilicity, and biodegradation rate should be investigated since these qualities depend on the type of polymer, its fabrication method, and the intended application. [20]

Cellulose-rich agricultural by-products like banana pseudostem and sugarcane bagasse can be utilized for manufacturing papers and other cellulosic materials. The use of enzymes can make it possible to isolate fibres from bagasse with minimal negative impact on the environment, but temperature, pH, and the duration of treatment should be optimized. Our project focuses on using banana pseudostem and bagasse pulp for producing tissue paper, which is a sustainable material, but further research is needed to evaluate the possibility of using such biomaterials in biomedical applications. [20]

The most important properties of tissue paper are tensile strength, flexibility, liquid absorbency, and resistance to water. The addition of glycerol can make it possible to enhance the flexibility of film, but it can also decrease its tensile strength or hydrophobicity. The incorporation of therapeutic molecules into the film or hydrogel can also be considered in order to ensure the controlled release of drugs. Prior to any biomedical application, the safety, biocompatibility, and effectiveness of the material should be assessed. [5], [20]

7. Nanotechnology-enabled drug-delivery systems

Polysaccharides have been widely studied as materials for drug delivery due to their biocompatibility, biodegradability and amenability to chemical modification. Their success is dependent on the ability of the carrier system to incorporate the drug and protect it before release. Herein, Pushpamalar et al. review polysaccharide-based hydrogels whereas Damiri et al. discuss the use of polysaccharide nanohydrogels in controlled drug delivery. [16,22]

Table 4. Polysaccharide-based materials for nanotechnology-enabled drug delivery

Material/ system	Physicochemical characteristics	Drug-delivery applications	Key limitations
Chitosan	Cationic polysaccharide with reactive amino and hydroxyl groups	Drug encapsulation and nanocarrier fabrication	pH-dependent solubility and stability
Alginate	Anionic polysaccharide with divalent-ion-mediated gelation capacity	Hydrogel-based drug encapsulation and controlled release	Crosslinking-dependent stability and release behaviour
Cellulose and derivatives	Modifiable hydroxyl-rich polymer backbone	Nanocarrier fabrication and hydrogel-based delivery	Properties depend on derivative and modification
Starch	Biodegradable polysaccharide capable of hydrogel formation	Encapsulation and delivery of therapeutic agents	Limited stability under some physiological conditions
Hyaluronic acid	Glycosaminoglycan containing carboxyl and hydroxyl groups	Ligand-mediated targeting and drug-carrier functionalisation	Targeting efficiency depends on formulation and biological validation

Stimuli-responsive polymeric nanohydrogels	Dynamic response to pH, temperature, light or redox conditions	Triggered drug release under defined environmental conditions	Response specificity and release performance require validation

Hydrogels are three-dimensional hydrophilic polymeric networks capable of taking up and retaining large quantities of water. The polymers that can be used for their creation include chitosan, alginate, cellulose, starch and hyaluronic acid. The material's properties are determined by the type and source of polymer, the method of preparation, and the nature of physical or chemical crosslinking that has taken place. The functional groups present allow for chemical modification and interaction with therapeutic compounds. [5,16,18]

Nanohydrogels are hydrogel networks at the nanoscale that can incorporate therapeutic compounds. Surface functionalisation of nanohydrogels is discussed by Damiri et al. and includes the addition of ligands for the recognition of defined cellular receptors. Additionally, systems responsive to pH, temperature, light or redox conditions, that can change the hydrogel network and therefore control the rate of drug release, are reviewed. [22]

Despite their potential applications, such systems require investigation of the release characteristics, stability, biological safety and production requirements. Indeed, Pushpamalar et al. highlight potential challenges, including long-term cytotoxicity and the necessity for improved stability and control in vivo conditions. The biocompatibility of a polysaccharide is not sufficient to determine the safety and efficacy of the final formulation. [16], [22]

8. Nanotechnology-enabled sensing and emerging biomedical applications

Polysaccharide hydrogels are also reviewed as materials for biosensing and point-of-care testing. Kim et al. discuss agarose-, alginate- and chitosan-based hydrogel materials, in the form of paper-based devices, microfluidic devices and other point-of-care formats. Hydrogels can be used to hold sensing components and can provide functions such as filtration, hydrophilic coating, and stimulus response. [23]

Such use can be limited by mechanical, chemical and thermal stability, and low conductivity can compromise certain electrical or electrochemical sensors. Kim et al. discuss combining hydrogels with other polymers or nanomaterials, as ways of overcoming some limitations – the appropriateness of each design depends on the intended application. [23]

The detection of microplastics is challenging due to the diversity of sizes and polymer types, and the complexity of sampling, pretreatment, separation and analytical methods. Nene et al. note the lack of standardised procedures as a problem in comparing results across studies.[24]

Grumelot et al. reported a colorimetric array comprising five responsive dyes, used to distinguish between tested micro- and nano plastics particles in buffered water, including pristine and protein-corona-coated polystyrene: the combination of colours provided a response signature, but it is not mentioned how this method applies to packaged drinking water. [25]

Taken together, these papers highlight opportunities for portable sensing platforms, but do not establish that any specific polysaccharide–nanomaterial hybrid has been validated for the intended purpose (microplastic detection in packaged drinking water). Such a system would require testing across types of plastic and sizes of particles, assessment of any interfering substances in real samples, and comparison with appropriate reference methods. [23], [25]

Table 5. Polysaccharide-based sensing and microplastic detection

Approach	Key findings	Technical limitations	Potential applications
Hydrogel-based biosensors	Polysaccharide hydrogels support diverse biosensing platforms	Limited mechanical and chemical stability	Point-of-care diagnostics
Paper-based and microfluidic devices	Enable portable sensing and sample analysis	Performance depends on material composition and device design	Rapid, decentralised detection
Microplastic detection methods	Sampling, separation and	Small particle size and lack of	Environmental monitoring

	analytical techniques have been investigated	standardised protocols	
Colorimetric sensor arrays	Dye-response patterns enable differentiation of tested plastic particles	Validation in real environmental samples is required	Plastic particle screening and classification
Polysaccharide–nanomaterial hybrids	Combine hydrogel support with functional sensing materials	Detection performance remains to be experimentally validated	Emerging microplastic-screening technologies

9. Material structure influencing performance

The properties of polysaccharide materials are determined by their chemical composition, concentration and preparation. These in turn determine the nature of gelation, water absorption, drug loading and release profiles. It is therefore essential to characterise the final formulation to verify its characteristics. [3], [13], [18]

Alginate is able to form gels in the presence of calcium ions, while chitosan possesses amino groups that can interact with alginate. Mixing these two polymers yields hydrogels whose properties are governed by the ratio of the two components and the preparation conditions. [1], [7], [19]

Crosslinking is required to stabilise hydrogel structures, but insufficient crosslinking may lead to weak gels that release the payload too quickly, while excessive crosslinking may reduce water uptake and prolong release. The polymer ratio and crosslinking conditions must therefore be optimised for a particular application [13], [19], [13]

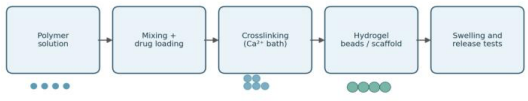


Fig. 3. Representative workflow for preparing and evaluating polysaccharide hydrogels (schematic illustration).

Swelling describes the amount of water incorporated into a material and reflects the ability of the network to imbibe water. This influences the potential for a hydrogel to act as a vehicle for a drug, but greater swelling is not necessarily advantageous because this may compromise the integrity of the matrix structure. A highly swollen hydrogel may allow rapid diffusion of drug molecules, but a compact hydrogel network will restrict diffusion and hinder drug release. The degree of swelling is influenced by the nature of the polymer, the extent of crosslinking and the pH of the surrounding medium, in addition to the physicochemical properties of the drug. [13]

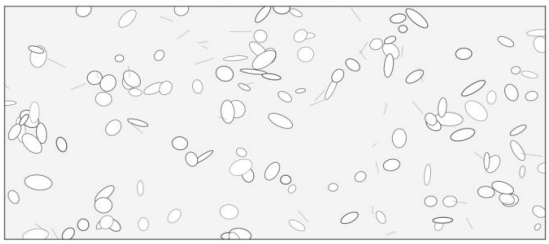


Fig. 4. Conceptual illustration of a porous hydrogel network; non experimental SEM micrograph.

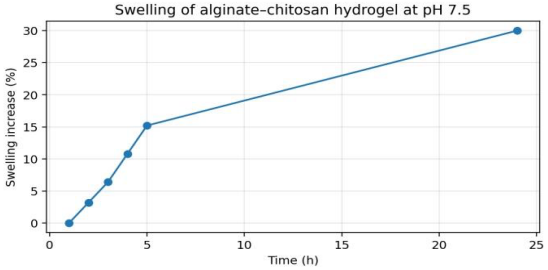


Fig. 5. Reported swelling increase of an alginate–chitosan hydrogel at pH 7.5. Data reproduced from Khatibi et al.

Rheological properties such as mechanical strength are important if the hydrogel is to retain its shape after fabrication. In the case of 3D bioprinting, the bioink must be able to extrude from the printing nozzle but possess sufficient structure to retain its shape upon deposition. Increasing the stiffness of the hydrogel may enhance the ability to retain shape, but will increase resistance to extrusion. Printability and structural integrity must therefore be assessed in parallel. [11], [13]

The amount of drug incorporated into a carrier depends on the nature of the interactions with the polymer and the method of preparation. Encapsulation efficiency describes the proportion of the amount of drug added to the system that ends up in the final formulation. A high encapsulation efficiency does not guarantee that an appropriate release profile will be achieved since drug molecules situated close to the surface of a hydrogel will be released more quickly than those entrapped within the structure. Drug release may also be affected by the rate of water uptake and the degradation of the hydrogel matrix. [4], [13], [18]

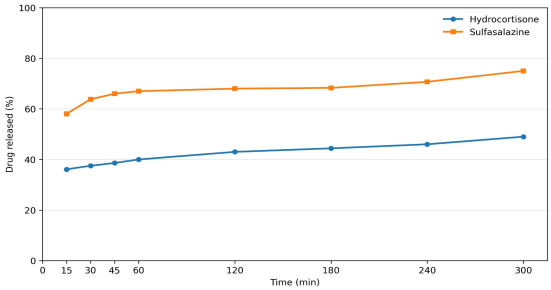


Fig. 6. Drug release after 5 h from an alginate–chitosan hydrogel. Values reported by Khatibi et al; UV–Vis and HPLC measurements were similar.

Drug molecules can diffuse out of a hydrogel matrix, or be released as a result of swelling and/or degradation of the matrix. Mathematical models such as Higuchi and Korsmeyer–Peppas can be employed to describe drug release behaviour and to compare different formulations. However, an adequate fit to a particular model is not sufficient evidence of the mechanism of drug release; comparison studies should ideally be performed under common conditions, using appropriate descriptions of the release medium, pH, temperature and sampling methodology. [13]

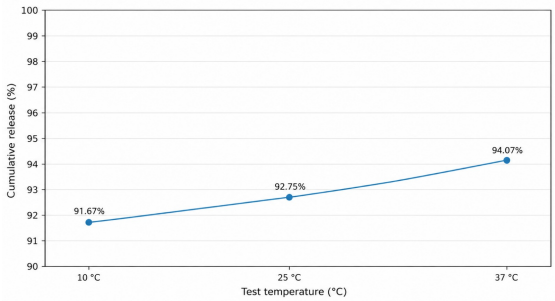


Fig. 7. Cumulative release reported for alginate–chitosan scaffolds tested at different temperatures.

The incorporation of nanomaterials can improve the mechanical or functional properties of a polysaccharide composite, but the influence of the particles will depend on their size, surface chemistry and propensity for aggregation, which must be considered when examining the complete formulation. [8], [15]

Polysaccharides are promising materials for the fabrication of sensors and nano sensors for the detection of a wide range of target molecules. The performance of such devices is evaluated in terms of their sensitivity, selectivity, response time and signal stability, while potential interfering species that may be present in the sample must also be considered. [2]

In general, the performance of a device will depend on its formulation and its intended application, and appropriate testing should be performed to validate the performance characteristics. [2], [21]

Table 5: Material properties influencing performance

Parameter	Functional significance	Recommended characterisation
Polymer ratio and crosslinking	Influence network stability and drug transport	Gel strength, swelling and drug-release profile
Swelling and porosity	Govern water uptake and molecular diffusion	Swelling ratio and drug-release kinetics
Drug loading	Determines drug retention within the matrix	Drug content and encapsulation efficiency
Nanomaterial dispersion	Influences mechanical integrity and functional performance	Particle distribution and material characterisation
Sensor properties	Determine analytical detection performance	Sensitivity, selectivity, response time and stability

10. Challenges towards practical use

Natural polysaccharides are promising materials for drug delivery, wound healing, bioprinting and sensing applications, but it is not always clear if laboratory findings will be useful in practice. The properties of the polymer can vary depending on the source, purity and preparation, which can impact consistency and repeatability. Therefore, the research should be focused on reporting the preparation procedure, characterization and appropriate control groups. [5], [8], [21]

The safety and stability of the final formulation should also be evaluated. The chemical modifications, crosslinking agents, nanoparticles and drugs incorporated into the material can affect its biological properties. Changes in properties during storage, degradation and burst release of the drug, amongst other factors, can impact performance. Appropriate tests should therefore include assessments of drug-release characteristics, mechanical properties, stability and biological evaluation, depending on the intended application. [8], [13], [18], [21]

Challenges in upscaling can also arise, including inhomogeneous mixing, drug distribution, sterilization, and packaging. Additionally,

regulatory requirements may vary depending on a final application, for example drug delivery, wound healing, tissue engineering or sensing. These factors should therefore be taken into consideration at the research stage, including standardized preparation procedures, consistent quality and appropriate testing for each application. [9], [21]

11. Future Perspectives

Future polysaccharide-based delivery systems may use stimuli-responsive properties, such as responses to pH, temperature, enzymes, or light, to control drug release. Combining polysaccharides with nanomaterials and 3D printing may further improve mechanical strength, sensing capabilities, and structural design. However, these approaches require careful evaluation of stability, sensor performance, and biological compatibility. [8], [11], [15]

Practical applications will depend on reproducible fabrication, standardized characterization, sterilization, storage stability, and regulatory assessment. Agricultural by-products may also support more sustainable material production, provided they are properly purified and processed. Further experimental studies are needed to demonstrate the safety, reliability, and effectiveness of these materials in drug delivery and other biomedical applications. [9], [21]

CONCLUSION:

Natural polysaccharides such as alginate, chitosan, pectin, and cellulose have potential applications in drug delivery, films, bioinks, tissue engineering, and sensing. Their properties can be modified through crosslinking, blending, and the addition of nanomaterials. However, their performance depends on drug solubility, loading, release behaviour, swelling, mechanical strength, and biological properties. [1], [5], [11], [20]

Naringenin delivery systems highlight the potential of polysaccharide carriers for poorly water-soluble drugs, but improved dissolution does not necessarily guarantee increased bioavailability. Similarly, bioinks and sensors require application-specific testing to establish their performance and reliability. [4], [12]

Despite their versatility, further research is needed to improve formulation consistency, assess safety and stability, and address storage, scale-up, and regulatory requirements. Overall, a clear understanding of polymer properties and appropriate characterization is essential for translating natural polysaccharide-based materials into practical pharmaceutical and biomedical applications. [8], [9], [13], [21]

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