RESEARCH PAPER

GREEN AND SUSTAINABLE DESIGN OF ALGINATE-BASED STIMULI-RESPONSIVE SUPRAMOLECULAR HYDROGELS FOR BIOMEDICAL APPLICATIONS: MOLECULAR INTERACTIONS, ADAPTIVE FUNCTIONALITY, AND TRANSLATIONAL PERSPECTIVES

Shreyansh Chaturvedi[1*], **Dr. Arti Malviya**[1]

[1*]Department of Chemistry, LNCT University, Bhopal, Madhya Pradesh, India

[1]Email: shreyansh02chaturvedi@gmail.com

[1]Research Supervisor (Dr. Arti Malviya)

***Corresponding Author:** Shreyansh Chaturvedi, Department of Chemistry, LNCT University, Bhopal, Madhya Pradesh, India | Email: shreyansh02chaturvedi@gmail.com

Received: 25th May, 2026; **Revised:** 6th June, 2026; **Accepted:** 8th June, 2026; **Available Online:** 09th June, 2026

ABSTRACT

The search for better biomedical materials is now tied to another question as well: can these materials be made in a way that is less demanding on the environment? Alginate, a renewable polysaccharide obtained mainly from brown seaweed, offers a useful starting point. It is biocompatible, biodegradable, rich in carboxyl groups, and capable of forming hydrogels under relatively mild aqueous conditions. Still, native alginate has its limits. Mechanical weakness, limited cell-adhesion signals, variable degradation, and poor control over complex biological responses can restrict its use. This is where supramolecular design becomes particularly interesting. Reversible interactions—electrostatic attraction, hydrogen bonding, host–guest recognition, hydrophobic association, metal coordination, and dynamic covalent chemistry—can give alginate networks a more flexible and adaptive character. Depending on the molecular design, the resulting hydrogels may show self-healing, injectability, shear-thinning, adhesion, controlled swelling, and stimulus-triggered release. This review discusses how green chemistry and supramolecular engineering can be brought together to develop alginate-based hydrogels that respond to pH, temperature, light, glucose, redox conditions, enzymes, and ionic changes. Their roles in drug delivery, wound healing, tissue engineering, cell encapsulation, biosensing, and 3D/4D biofabrication are critically considered. The review also argues that "green" should not be judged only by the natural origin of the polymer. Water use, energy demand, purification, crosslinkers, sterilization, manufacturing, and end-of-life behaviour matter too. In the coming years, progress will depend on better material standardization, safer chemistry, realistic biological testing, life-cycle assessment, and more reliable scale-up. Overall, green supramolecular alginate hydrogels offer a promising, though still developing, route toward adaptive and more sustainable biomedical materials.

Keywords: Alginate; Green chemistry; Supramolecular hydrogel; Stimuli-responsive biomaterials; Self-healing; Biomedical applications

How to cite this article: Chaturvedi S, Malviya A. Green and sustainable design of alginate-based stimuli-responsive supramolecular hydrogels for biomedical applications: molecular interactions, adaptive functionality, and translational perspectives. Int J Drug Deliv Technol. 2026;16(74s): 590-597. DOI: 10.25258/ijddt.16.74s.71

Source of support: Nil.

Conflict of interest: Nil

INTRODUCTION

Hydrogels have become some of the most useful materials in biomedical research. Their high water content, soft nature, and three-dimensional structure make them feel, in many ways, closer to biological tissues than conventional solid materials. That is one reason they have found roles in drug delivery, wound care, tissue engineering, cell encapsulation, biosensing, and biofabrication.

But there is a complication. Many high-performance hydrogels still depend on synthetic polymers, organic solvents, permanent crosslinkers, photoinitiators, and energy-intensive processing. These approaches can work very well from a materials point of view. At the same time, they may bring concerns about solvent use, chemical waste, residual reagents, and the environmental cost of production. So the question is no longer only whether a hydrogel performs well. Increasingly, researchers are asking how that performance is achieved.

This has pushed natural polymers into the spotlight. Alginate is one of the most widely explored. It is obtained mainly from brown marine algae and contains carboxylate groups that make it chemically versatile. In water, it can be processed relatively gently, and in the presence of divalent ions such as calcium, it can form a three-dimensional gel network. The chemistry is straightforward enough to be useful, but the material itself is far from simple.

The composition of alginate matters. Its mannuronic acid/guluronic acid ratio, molecular weight, block distribution, and purification history can all influence gelation, swelling, mechanical strength, degradation, and biological behaviour. Two materials both labelled "alginate" may therefore perform quite differently.

There is another limitation. Native alginate is not always mechanically strong, and it does not naturally provide many of the biological signals that cells need for adhesion and communication. Its degradation can also be difficult to match to a specific application. Supramolecular chemistry offers a way to work around some of these problems. Instead of building the entire hydrogel through permanent covalent bonds, reversible molecular interactions can be introduced as dynamic junctions within the network.

That changes the behaviour of the material. Bonds can break and reform. Networks can rearrange. A damaged hydrogel may recover, and a material may respond to changes in pH, temperature, ions, enzymes, or other biological signals. The design becomes more dynamic—and, potentially, more useful.

This review explores the meeting point between green chemistry, alginate science, and supramolecular engineering. The focus is on the molecular interactions that create responsive behaviour, the structure–property relationships that control performance, and the challenges that still stand in the way of translation. Just as importantly, the review considers what "green" should really mean in this field. A natural polymer is a good starting point, but it is not the whole sustainability story.

ALGINATE: A NATURAL POLYMER WITH A COMPLEX PERSONALITY

Alginate is a linear anionic polysaccharide made mainly from β-D-mannuronic acid and α-L-guluronic acid residues linked through 1→4 glycosidic bonds. These residues are arranged in M-rich, G-rich, and alternating regions. The pattern is not just a structural detail. It affects how the polymer interacts with water, ions, other polymers, and biological molecules.

The G-rich regions are especially important for calcium-mediated gelation. When calcium ions coordinate with carboxylate groups on neighbouring alginate chains, junction zones are formed and a three-dimensional network develops. This behaviour is commonly described using the "egg-box" model. It is a useful model, although real alginate networks can be more heterogeneous than the name suggests.

The M/G ratio, molecular weight, and block distribution all influence the final hydrogel. Higher molecular weight can improve chain entanglement and viscosity, but it may also make processing more difficult. Lower molecular weight material can be easier to handle, yet may form weaker networks. Similarly, a composition that gives excellent stiffness may reduce swelling or limit molecular diffusion.

This is why detailed material characterization matters. Reporting only the polymer name is not enough for reproducible research. A good study should, where possible, describe the alginate source, molecular weight, M/G ratio, viscosity, purification, and relevant biological quality parameters. Without that information, comparing one study with another becomes surprisingly difficult.

Alginate is also often described simply as biodegradable. The reality is more nuanced. Degradation depends on molecular size, chemical environment, formulation, and the intended route of use. A short-lived injectable depot and a long-term

tissue scaffold should not be expected to behave in the same way. In practice, degradation needs to be designed around the biological task.

The polymer also has a clear weakness: alginate is relatively bioinert. It does not naturally provide strong cell-adhesion signals. This has led researchers to combine it with peptides, proteins, other polysaccharides, polyphenols, and supramolecular motifs. The goal is not to make the formulation as complicated as possible.

Usually, the better strategy is simpler—give each component a clear job.

GREEN CHEMISTRY: BEYOND THE LABEL

The phrase "green hydrogel" sounds attractive, but it should be used carefully. A material does not become sustainable simply because one of its components comes from nature. The full preparation route matters.

Alginate does offer several advantages. It is renewable, can often be processed in water, and can form gels under mild conditions. These features can reduce the need for volatile organic solvents and harsh processing. Still, the environmental footprint does not disappear. Seaweed collection or cultivation, extraction, purification, washing, drying, transport, and sterilization all require resources.

Water is a good example. Aqueous processing is generally preferable to using hazardous organic solvents, especially for biomedical materials. But "water-based" does not mean "impact-free." Large volumes of water may be needed during purification, and the energy required to treat or remove that water also matters.

The same thinking applies to crosslinkers and functionalization reagents. Calcium ions are attractive because calcium-mediated gelation is well established and relatively mild. Other chemistries may produce stronger or more sophisticated networks, but the safety of the reagents, residual compounds, and degradation products must be considered.

A safe-by-design approach is therefore useful. Instead of asking only whether the final hydrogel works, researchers should ask a broader set of questions: Where did the raw materials come from? How much solvent and energy were used? What waste was generated? What happens during sterilization? What products are released during degradation?

These questions are not always easy to answer, especially at the early research stage. Still, they are becoming increasingly important. In the long run, life-cycle assessment should become a more routine part of hydrogel development. Sustainability needs to be measured, not simply assumed.

SUPRAMOLECULAR INTERACTIONS AND DYNAMIC NETWORK DESIGN

Supramolecular chemistry gives hydrogel design a useful kind of flexibility. Rather than relying only on permanent covalent bonds, the network can be built partly from interactions that are reversible. They may be weaker individually, but when many of them work together, the overall material can become both stable and adaptable.

Electrostatic interactions are a natural starting point for alginate. Its carboxylate groups carry negative charges under many conditions, allowing interaction with positively charged polymers such as chitosan or quaternised chitosan.

These polyelectrolyte complexes can form dynamic networks that respond to changes in pH and ionic strength.

Recent work has shown the value of this approach. A 2025 study reported an injectable and self-healing supramolecular hydrogel assembled through quaternised chitosan/alginate polyelectrolyte complexation. The system showed cytocompatibility and sustained protein release, illustrating how reversible electrostatic association can support both processing and biomedical function.

Hydrogen bonding adds another layer of reversibility. Hydroxyl, carboxyl, amide, and related groups can form multiple interactions throughout the network. When some of these bonds break under stress, others may reform once the material is allowed to recover. The result can be a degree of self-healing.

Host–guest chemistry is more specific. Cyclodextrins, for example, contain hydrophobic cavities that can accommodate suitable guest molecules. In an alginate hydrogel, this type of recognition can be used to regulate drug binding, support reversible crosslinking, or create a more controlled release environment.

Hydrophobic association can also produce temporary junctions in water. These interactions may strengthen the network while remaining capable of dissociation and reformation. Their behaviour, however, depends strongly on the hydrophobic group, substitution level, polymer concentration, temperature, and surrounding biological environment.

Metal coordination provides another route. Alginate already interacts with ions such as calcium, but additional ligand chemistry can make the network more dynamic and tunable. The biological safety of the selected metal remains essential.

Dynamic covalent bonds sit somewhere between conventional covalent networks and non-covalent assemblies. Imine, boronate ester, and disulfide chemistry can provide stronger connections that are still capable of exchange under suitable conditions. These systems are promising, although the chemistry used to introduce them must be evaluated carefully from both biological and environmental perspectives.

STIMULI-RESPONSIVE BEHAVIOUR

A responsive hydrogel changes when its surroundings change. That may sound simple, but the useful response is usually the result of several

molecular events happening together.

pH is one of the most common triggers. Alginate contains carboxylic acid groups that can become protonated or deprotonated. As the charge state changes, so do electrostatic repulsion, swelling, permeability, and molecular diffusion. This makes pH-responsive alginate systems attractive for gastrointestinal delivery, wound environments, tumour-associated conditions, and intracellular applications.

Temperature can influence hydration, chain mobility, and hydrophobic association. Thermoresponsive alginate systems are especially interesting for injection because a formulation may be fluid during administration and become more structured at physiological temperature. The transition, however, needs to be reliable. A narrow operating window can be useful, but it can also make the formulation sensitive to small changes in composition.

Light offers a different kind of control. In principle, a clinician or researcher can apply light at a selected time and location to trigger molecular rearrangement, bond cleavage, or drug release. The practical limitations are equally important: wavelength, tissue penetration, exposure time, and phototoxicity cannot be ignored.

Glucose-responsive hydrogels have attracted attention for diabetes-related applications. Recognition chemistry can link changes in glucose concentration to swelling or permeability, creating a possible route toward more responsive insulin delivery.

Redox and enzyme responsiveness are particularly interesting for biological environments. Different tissues and cellular compartments can have different redox conditions, while disease-associated enzymes may provide local molecular triggers. These systems could, in principle, release cargo where it is needed rather than everywhere at once.

Still, there is a tendency in the field to add more and more stimuli. More responsiveness is not automatically better. A hydrogel that responds to one biologically meaningful signal, reliably and safely, may be more useful than a highly complex system that responds to everything but is difficult to control.

SELF-HEALING, INJECTABILITY, AND ADHESION

Self-healing is one of the most appealing features of supramolecular hydrogels. The basic idea is straightforward: when the network is damaged, reversible interactions can break and then reform across the damaged region. The material may recover part of its original structure.

The important word here is “part.” Self-healing should be measured, not assumed. Recovery of storage modulus, mechanical strength, fracture resistance, and the number of repeated healing cycles all provide useful information. A photograph showing two pieces joining together can be interesting, but it is not enough by itself.

Injectability requires a different balance. The hydrogel should flow when force is applied, preferably with manageable injection pressure, and then recover enough structure after administration to remain in place.

Shear-thinning and thixotropic recovery are therefore important properties.

The design challenge is obvious. A very dynamic network may flow easily and heal quickly, but it may lack long-term stability. A very strongly crosslinked material may be mechanically robust, but difficult to inject. Hybrid networks can help by combining permanent structural elements with reversible, energy-dissipating interactions.

Adhesion is increasingly important in wound care and tissue interfaces. Hydrogen bonding, electrostatic attraction, catechol chemistry, and other interactions can help a hydrogel remain attached to wet biological surfaces. The material should, however, be strong enough to stay in place without causing damage when it is removed. That balance is not always easy to achieve.

CHARACTERIZATION: CONNECTING CHEMISTRY TO PERFORMANCE

Hydrogel characterization is sometimes treated as a checklist. FTIR, microscopy, swelling, rheology, and a cell viability assay are performed, and the material is declared successful. In reality, the most useful studies go further.

They connect what the material is made of to what it actually does.

FTIR can reveal functional groups and changes in the chemical environment. It can support the presence of interactions, but a small peak shift should not automatically be treated as definitive proof of a specific supramolecular mechanism. NMR, X-ray diffraction, thermal analysis, microscopy, and scattering methods can provide additional evidence.

Morphology also needs careful interpretation. The pore structure seen in a dried sample may not fully represent the hydrated hydrogel. Drying conditions can alter the network. Where possible, hydrated-state or cryogenic approaches may provide a more realistic picture.

Swelling is usually measured through the relationship $Q = (Ws - Wd)/Wd$, where Ws is the swollen mass and Wd is the dry mass. The calculation is simple. The interpretation is not always. pH, ionic strength, temperature, and the composition of the surrounding medium can all change swelling behaviour.

Rheology is particularly important for injectable and self-healing systems. Storage modulus, loss modulus, gelation, shear-thinning, and recovery should be selected according to the intended use. Mechanical testing should also match the application. A wound dressing, injectable depot, and tissue scaffold do not experience the same kind of stress.

Biological evaluation should be equally thoughtful. Cell viability is important, but it is only one part of the picture. Depending on the application, researchers may also need to examine inflammation, blood compatibility, cell adhesion, differentiation, bacterial interactions, degradation, and long-term tissue response.

BIOMEDICAL APPLICATIONS

Drug delivery remains one of the clearest applications for alginate-based hydrogels. A therapeutic molecule may be released through diffusion, swelling, matrix relaxation, degradation, or stimulus-triggered network changes.

Supramolecular interactions can also provide temporary binding sites for drugs and biological macromolecules.

The main goal is usually not simply to slow release. It is to make release more predictable and, ideally, more responsive to the biological environment. That is where dynamic networks can offer an advantage.

Injectable systems are particularly attractive because they can be placed through minimally invasive procedures. A well-designed supramolecular hydrogel may shear-thin during injection and then recover its structure after placement. Recent alginate–chitosan systems have demonstrated this combination together with sustained protein delivery and cell encapsulation.

For wound healing, alginate already offers a useful foundation because it can absorb exudate and help maintain a moist environment. Supramolecular design can add self-healing, antioxidant, antimicrobial, adhesive, or controlled-release functions. A responsive wound dressing could potentially react to pH, enzymes, oxidative stress, or inflammation as the wound changes.

In tissue engineering, alginate provides a hydrated three-dimensional matrix, but its limited cell-adhesion signalling often needs to be addressed. Peptides, extracellular-matrix components, proteins, and other polymers can provide additional biological cues. Dynamic interactions may also help the scaffold adapt to mechanical or biological changes.

Cell encapsulation benefits from the mild aqueous conditions used for alginate gelation. Even so, long-term performance depends on nutrient transport, oxygen diffusion, mechanical stability, ion exchange, and degradation. A gel that protects cells initially may not remain suitable over extended periods.

Alginate is also widely investigated as a bioink. Its rapid ionic gelation and favourable processing behaviour are useful for 3D printing. The difficulty is finding the right balance between print fidelity, mechanical stability, cell compatibility, and post-print function. Responsive networks may eventually support 4D biofabrication, where printed constructs change shape or properties after exposure to defined signals.

Biosensing offers another direction. Changes in swelling, optical behaviour, fluorescence, conductivity, or mechanics can be linked to the detection of glucose, enzymes, ions, and other biomolecules. The key question is whether the signal remains selective and reliable in real biological fluids, where many competing molecules are present.

SUSTAINABILITY, SAFETY, AND TRANSLATION

The environmental advantages of alginate-based materials are real, but they should not be overstated. Renewable origin is a strength. It is not, by itself, a complete sustainability assessment.

The full life cycle matters. Seaweed sourcing, extraction, purification, water use, energy consumption, crosslinker production, formulation, sterilization, packaging, transport, and disposal all contribute to the overall impact. A hydrogel can be bio-based and still require a resource-intensive manufacturing process.

Safety is equally important. Residual reagents, catalysts, functional groups, nanoparticles, and degradation products may all influence biological performance. Sterilization can also change the material. Heat, radiation, and filtration may affect molecular weight, crosslink density, and mechanical properties in different ways.

Natural variability creates another problem. Alginate obtained from different species, locations, or processing methods may differ in molecular weight and composition. For biomedical translation, these differences need to be controlled. Material specifications should ideally include composition, viscosity, molecular weight, endotoxin status, microbial burden, and other relevant quality parameters.

Scale-up is often more difficult than expected. A formulation that mixes uniformly in a small laboratory vessel may behave differently in a larger reactor. Crosslinking kinetics, mixing, heat transfer, sterilization, and packaging all become more complicated.

Regulatory translation also becomes more challenging as the hydrogel becomes more multifunctional. A system containing a natural polymer, multiple crosslinkers, a drug, a bioactive molecule, and a responsive mechanism may offer impressive performance, but each additional component creates another question about safety and manufacturing. In many cases, a modular and well-characterized design may be more valuable than a highly complicated one.

RESEARCH GAPS AND FUTURE DIRECTIONS

Several questions remain open. The relationship between alginate composition and supramolecular network dynamics is still not fully understood. More systematic studies are needed, especially those that vary M/G ratio, molecular weight, crosslinking density, and supramolecular chemistry while measuring comparable outcomes.

Standardization is another major need. Researchers do not always define self-healing, injectability, degradation, or swelling in the same way. This makes direct comparison difficult. Shared testing methods would make the literature more useful.

Sustainability claims also need stronger evidence. Life-cycle assessment should become more common, particularly for systems described as green or eco-friendly. Reporting solvent and water use, energy demand, material yield, and waste would make such claims much more meaningful.

Artificial intelligence and machine learning may help with formulation design. If sufficiently large and reliable datasets become available, models could connect polymer composition and crosslinking conditions with rheology, degradation, mechanical behaviour, and drug release. The quality of the prediction, however, will depend entirely on the quality of the data.

Multi-stimuli systems will probably continue to grow, but restraint may be useful. The best material may not be the one with the greatest number of responses. A simpler hydrogel that responds accurately to one clinically relevant signal may have a better chance of translation.

Finally, biological testing needs to become more realistic. Short-term cell viability in a simple medium is useful, but it cannot predict everything. Long-term degradation, immune response, sterilization, manufacturing reproducibility, complex biological fluids, and appropriate in vivo models will all matter as the field moves forward.

CONCLUSION

Green alginate-based stimuli-responsive supramolecular hydrogels bring together three important areas of materials research: renewable biomaterials, dynamic molecular chemistry, and biomedical engineering. Alginate provides a versatile base because it is marine-derived, water-processable, rich in functional groups, and capable of forming ionic networks under mild conditions. Supramolecular chemistry adds something different—reversibility and adaptability.

Through electrostatic interactions, hydrogen bonding, host–guest recognition, hydrophobic association, metal coordination, and dynamic covalent chemistry, alginate networks can be designed to do more than simply hold water. They may self-heal, flow under shear, recover after injection, respond to biological signals, and control the release of therapeutic molecules.

The larger opportunity, however, is not simply to replace a synthetic polymer with a natural one. The more important goal is to rethink the whole material system. Renewable feedstocks, safer chemistry, low-impact processing, biological function, manufacturing, and end-of-life behaviour should be considered together.

The field still has work to do. Mechanical weakness, degradation control, batch variability, sterilization, scale-up, and regulation remain significant barriers. Yet the direction is promising. With better standardization, stronger life-cycle assessment, more realistic biological validation, and carefully chosen supramolecular interactions, alginate-based hydrogels could move closer to a new generation of biomedical materials that are not only intelligent and adaptable, but also more responsible in how they are made.

Table 1. Selected design variables in alginate-based supramolecular hydrogels

Design variable	What it mainly changes	Typical trade-off
M/G ratio	Ion binding and network formation	Strength versus flexibility
Molecular weight	Viscosity and chain entanglement	Processability versus stability
Ca^{2}■ concentration	Ionic crosslink density	Strength versus swelling
Chitosan/alginate ratio	Electrostatic complexation	Recovery versus long-term stability
Host–guest motif	Molecular recognition and reversible binding	Exchange rate versus network integrity
Hydrophobic association	Temporary physical junctions	Recovery versus formulation stability
Dynamic covalent chemist	yReversible chemical crosslinks	Stability versus reagent safety
Polymer concentration	Modulus and viscosity	Injectability versus mechanical strength

REFERENCES

1. Abdel-Rahman, R. M., et al. (2024). Alginate-based hydrogels: Recent advances in preparation, property tuning, and biomedical applications. International Journal of Biological Macromolecules.
2. Aderibigbe, B. A., & Nakiwogga, A. Z. (2023). Alginate-based hydrogels and scaffolds for

biomedical applications. Polymers, 15(5), 1132.

3. Ahmed, E. M. (2015). Hydrogel: Preparation, characterization, and applications. Journal of Advanced Research, 6, 105–121.
4. Augst, A. D., Kong, H. J., & Mooney, D. J. (2006). Alginate hydrogels as biomaterials. Macromolecular Bioscience, 6, 623–633.
5. Caló, E., & Khutoryanskiy, V. V. (2015). Biomedical applications of hydrogels: A review of patents and commercial products. European Polymer Journal, 65, 252–267.
6. Chai, Q., Jiao, Y., & Yu, X. (2017). Hydrogels for biomedical applications: Their characteristics and the mechanisms behind them. Gels, 3, 6.
7. Drury, J. L., & Mooney, D. J. (2003). Hydrogels for tissue engineering: Scaffold design variables and applications. Biomaterials, 24, 4337–4351.
8. Hoare, T. R., & Kohane, D. S. (2008). Hydrogels in drug delivery: Progress and challenges. Polymer, 49, 1993–2007.
9. Lee, K. Y., & Mooney, D. J. (2012). Alginate: Properties and biomedical applications. Progress in Polymer Science, 37, 106–126.
10. Li, J., & Mooney, D. J. (2016). Designing hydrogels for controlled drug delivery. Nature Reviews Materials, 1, 16071.
11. Li, L., et al. (2022). Dual-responsive alginate hydrogel constructed by sulfhydryl dendrimer as an intelligent system for drug delivery. Molecules, 27, 281.
12. Peppas, N. A., et al. (2006). Hydrogels in pharmaceutical formulations. European Journal of Pharmaceutics and Biopharmaceutics, 64, 1–14.
13. Ren, Y., Wang, Q., Xu, W., Yang, M., Guo, W., He, S., & Liu, W. (2024). Alginate-based hydrogels mediated biomedical applications: A review. International Journal of Biological Macromolecules, 279, 135019.
14. Rinaudo, M. (2008). Main properties and current applications of some polysaccharides as biomaterials. Polymer International, 57, 397–430.
15. Rowley, J. A., Madlambayan, G., & Mooney, D. J. (1999). Alginate hydrogels as synthetic extracellular matrix materials. Biomaterials, 20, 45–53.
16. Sousa, C. F. V., Borges, J., & Mano, J. F. (2025). Injectable and self-healable supramolecular hydrogels assembled by quaternised chitosan/alginate polyelectrolyte complexation for sustained drug delivery and cell encapsulation. Biomaterials Science, 13, 3617–3632.
17. Sun, J., & Tan, H. (2013). Alginate-based biomaterials for regenerative medicine applications. Materials, 6, 1285–1309.
18. Toews, P. M., Velraj, A., & Bates, J. S. (2025). Stimuli-responsive hydrogels, their mass transfer, intermolecular interactions, and applications in biomedical devices. Journal of Materials Science: Materials in Medicine.
19. Wang, H., Yang, L., & Yang, Y. (2025). A review of sodium alginate-based hydrogels: Structure, mechanisms, applications, and perspectives. International Journal of Biological Macromolecules, 292, 139151.
20. Zhang, Y., et al. (2025). Research progress of sodium alginate-based hydrogels in biomedical engineering. Gels, 11, 758.
21. Zhao, X., et al. (2025). Alginate-based hydrogels: Recent progress in preparation, property tuning, and multifunctional

applications. Gels.

22. Editorial note: This version intentionally uses more natural sentence rhythm, varied transitions, and less repetitive academic phrasing while retaining scientific terminology and publication-style structure. References and bibliographic metadata should be verified against the final target journal beforeubmission