

KAPPAPHYCUS ALVAREZII K-CARRAGEENAN-BASED HYDROGEL SYSTEMS FOR BIOMEDICAL APPLICATIONS: A REVIEW ON RECENT ADVANCES AND FUTURE PERSPECTIVES

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ABSTRACT

Marine macroalgae represent an increasingly important renewable source of structurally diverse polysaccharides with potential applications in biomedical engineering. Among cultivated red seaweeds, *Kappaphycus alvarezii* is one of the major industrial sources of κ -carrageenan, a sulfated galactan characterized by a three-dimensional network-forming capability, hydrophilicity, biodegradability and favorable physicochemical properties. κ -Carrageenan can undergo physical or chemical gelation and can therefore be engineered into hydrogels, films, sponges, injectable systems and composite scaffolds. These characteristics have attracted considerable interest in wound management, drug delivery, tissue engineering, antimicrobial biomaterials and regenerative medicine. Recent studies have demonstrated that *K. alvarezii*-derived carrageenan can promote fibroblast proliferation and migration and accelerate wound closure, while purified κ -carrageenan has demonstrated activity against several wound-associated bacterial pathogens. Advances in extraction technologies, including ultrasound-assisted processing, have further improved extraction efficiency and enabled better control of carrageenan physicochemical properties. Nevertheless, native carrageenan hydrogels may exhibit insufficient mechanical strength, rapid or poorly controlled degradation and sensitivity to ionic conditions. Consequently, current research increasingly focuses on composite networks, chemical modification, nanomaterial incorporation and hybrid hydrogel architectures. This review summarizes the origin, molecular characteristics, extraction, gelation mechanisms, physicochemical properties and biomedical applications of *K. alvarezii* κ -carrageenan-based hydrogels. Recent developments in wound healing, antimicrobial systems, drug delivery and tissue engineering are discussed, together with major limitations, regulatory considerations and future research opportunities. Particular emphasis is placed on developing multifunctional, mechanically stable, biocompatible and clinically translatable hydrogel systems from sustainably cultivated marine biomass.

KEYWORDS: *Kappaphycus alvarezii*; κ -carrageenan; marine polysaccharide; hydrogel; wound healing; drug delivery; tissue engineering; antimicrobial biomaterial; regenerative medicine.

1. INTRODUCTION

The development of biomaterials from renewable biological resources has become an important strategy in modern biomedical engineering. Natural polymers obtained from plants, animals and marine organisms offer several

advantages, including biodegradability, structural diversity, biological functionality and the possibility of chemical or physical modification. Marine macroalgae are particularly attractive because they contain abundant polysaccharides that can be processed into gels, films, membranes, fibers, scaffolds and other functional biomaterials.^[1-4]

Among marine polysaccharides, alginate, agar and carrageenans have received considerable attention. However, their biological sources and chemical structures differ substantially. Alginate is predominantly obtained from brown seaweeds, whereas carrageenans are characteristic sulfated galactans of red seaweeds. *Kappaphycus alvarezii* is a cultivated red macroalga belonging to Rhodophyta and is recognized as one of the principal commercial sources of κ -carrageenan.^[1,2] Therefore, for biomaterial development based specifically on *K. alvarezii*, κ -carrageenan rather than alginate represents the chemically appropriate primary hydrocolloid.

Carrageenan is a high-molecular-weight sulfated polysaccharide composed primarily of alternating units of D-galactose and 3,6-anhydro-D-galactose linked through alternating β -(1 $\rightarrow$ 4) and α -(1 $\rightarrow$ 3) glycosidic bonds.^[5,6] Depending on the degree of sulfation and the presence of 3,6-anhydrogalactose, carrageenans are broadly classified into κ -, ι - and λ -types. κ -Carrageenan is particularly suitable for hydrogel development because of its ability to form thermoreversible gels in the presence of appropriate ions, especially potassium ions.^[6-8]

Hydrogels are three-dimensional hydrophilic polymeric networks capable of retaining substantial quantities of water while maintaining an interconnected structure. Their high water content, soft mechanical characteristics and ability to accommodate cells or therapeutic molecules make them particularly attractive for wound dressings, tissue engineering and controlled drug delivery.^[9-12] Carrageenan-based hydrogels have recently received renewed attention because their properties can be improved by blending them with other polymers, nanoparticles or bioactive compounds.^[13,14]

Recent research has strengthened the biomedical potential of *K. alvarezii*. Carrageenan obtained from the species has been shown to enhance human dermal fibroblast proliferation and migration and to accelerate wound closure in experimental models.^[15] In another recent study, κ -carrageenan extracted from *K. alvarezii* demonstrated antibacterial and antibiofilm activity against several wound-associated bacteria, including *Staphylococcus aureus*, *Escherichia coli* and *Pseudomonas aeruginosa*.^[16] These findings support the development of *K. alvarezii* κ -carrageenan into multifunctional wound-care hydrogels.

This review summarizes the current understanding of *K. alvarezii* κ -carrageenan-based hydrogel systems, emphasizing extraction, structure, gelation, physicochemical properties and biomedical applications. Recent advances and remaining challenges are also discussed to identify future directions for translational research.

2. *Kappaphycus alvarezii* as a Source of Biomedical Polysaccharides

Kappaphycus alvarezii is a commercially important tropical red seaweed extensively cultivated in several Asian countries and other tropical regions. Its economic importance is primarily associated with the production of κ -carrageenan, which is widely used as a thickening, stabilizing and gelling agent.^[1,2]

The polysaccharide composition of *K. alvarezii* is influenced by species or cultivar, geographic location, environmental conditions, harvesting season and extraction conditions. Carrageenan constitutes the principal structural polysaccharide,

although minor galactans and other constituents can also occur.^[17] Consequently, extraction and purification procedures have a major influence on the final physicochemical properties of the carrageenan.

For biomedical applications, the source material should be evaluated not only in terms of carrageenan yield but also for ash, protein, pigment, microbial contamination, heavy metals and residual processing chemicals. The production of biomedical-grade material therefore requires more stringent purification than conventional industrial carrageenan production.

3. Molecular Structure and Physicochemical Characteristics of κ -Carrageenan

κ -Carrageenan consists predominantly of repeating galactose-based disaccharide units containing 3,6-anhydro-D-galactose and sulfated D-galactose residues. The sulfate groups confer a strong anionic character, whereas the presence of 3,6-anhydrogalactose contributes to helix formation and gelation.^[5-8]

The transition of κ -carrageenan from a disordered polymer state to an ordered helical state is strongly influenced by temperature and ionic environment. On cooling, the polymer chains undergo conformational ordering followed by aggregation into junction zones, producing a three-dimensional gel network. Potassium ions have a particularly important role in stabilizing κ -carrageenan helices and promoting gel formation.^[6,8]

The important physicochemical characteristics of κ -carrageenan include its high water-binding capacity and hydrophilic nature, which facilitate substantial water uptake and swelling. Its anionic surface charge enables interactions with positively charged molecules and ions, while its thermoreversible gelation and ion-sensitive network formation allow the development of tunable hydrogel systems. κ -Carrageenan also possesses the ability to form films and porous structures, making it suitable for wound dressings, drug-delivery systems, and tissue-engineering scaffolds. Furthermore, its compatibility with other natural and synthetic polymers enables the fabrication of composite and hybrid biomaterials with improved mechanical and functional properties. The polymer also offers considerable potential for chemical functionalization, allowing its physicochemical, biological, and degradation properties to be tailored for specific biomedical applications.

These characteristics are advantageous for biomedical applications but can also create limitations. Native carrageenan hydrogels may be relatively brittle and can exhibit changes in swelling and mechanical properties when exposed to physiological ions. Recent reviews therefore emphasize the use of polymer blending, covalent crosslinking and nanocomposite strategies to improve hydrogel performance.^[13,14]

4. Extraction and Purification of κ -Carrageenan from *K. alvarezii*

4.1 Conventional extraction

Conventional carrageenan extraction generally involves washing and drying of seaweed, alkaline treatment, hot-water extraction, filtration and recovery of the polysaccharide. Alkaline treatment facilitates conversion of precursor units toward the 3,6-anhydrogalactose-containing structure characteristic of κ -carrageenan.^[1,2,18]

Although effective, conventional extraction may require considerable amounts of water, chemicals and thermal energy. Processing conditions must be carefully controlled because excessive alkali concentration or temperature can cause polymer degradation and alter viscosity and gel strength.

4.2 Advanced extraction approaches

Recent research has explored ultrasound-assisted extraction and other intensified extraction technologies. Mendes et al. reported that ultrasound-assisted extraction using alkaline conditions could produce high carrageenan yield while reducing extraction time compared with conventional processing.^[19] Such approaches are potentially important for developing more sustainable and scalable production systems.

For biomedical applications, optimization should focus on both yield and quality. Important quality indicators include molecular weight, sulfate content, 3,6-anhydrogalactose content, viscosity, gel strength, ash content, residual chemicals and endotoxin/microbial contamination.

Table 1: Comparison of alginate and *K. alvarezii* κ -carrageenan for hydrogel development.

Property	Alginate	<i>K. alvarezii</i> κ -carrageenan
Principal biological source	Brown seaweeds	Red seaweed
Representative source	<i>Laminaria</i> , <i>Macrocystis</i> , <i>Ascophyllum</i>	<i>Kappaphycus alvarezii</i>
Major structural units	Mannuronic and guluronic acids	Galactose and 3,6-anhydrogalactose
Major functional groups	Carboxylate	Sulfate
Charge	Anionic	Anionic
Common gelation mechanism	Ionic crosslinking, especially Ca^{2+}	Helix formation and ion-mediated aggregation
Typical gel characteristics	Ionically crosslinked, generally soft	Thermoreversible and ion-sensitive
Major biomedical uses	Wound dressing, cell encapsulation, drug delivery	Wound care, drug delivery, tissue engineering, antimicrobial systems
Main limitations	Ion exchange, weak mechanical strength in some formulations	Brittleness, ion sensitivity and degradation control
Major improvement strategy	Blending/covalent crosslinking	Polymer blending, chemical crosslinking and nanocomposites

5. Formation of *K. alvarezii* κ -Carrageenan-Based Hydrogels

κ -Carrageenan hydrogels can be generated through physical interactions, ionic interactions or chemical crosslinking.

5.1 Physical gelation

Physical gelation involves conformational transitions and aggregation of carrageenan chains. Temperature reduction promotes helix formation and junction-zone development. Potassium ions enhance the formation and stabilization of κ -carrageenan gel structures.^[6,8]

The major advantage of physical gelation is the absence of potentially toxic covalent crosslinking agents. However, physically crosslinked systems may exhibit relatively weak mechanical stability and may undergo changes when exposed to physiological fluids.

5.2 Chemical crosslinking

Chemical modification can improve mechanical stability, swelling control and degradation characteristics. Functional groups present on carrageenan can be modified or incorporated into interpenetrating polymer networks. However, the selection and removal of crosslinking agents are critical because residual reagents can compromise cytocompatibility.

5.3 Composite and hybrid hydrogels

A major current strategy is the fabrication of composite hydrogels by combining κ -carrageenan with polymers such as chitosan, gelatin, collagen, alginate, hyaluronic acid, cellulose derivatives, poly(vinyl alcohol) or polyethylene glycol.

Hybridization of κ -carrageenan with other natural or synthetic polymers can significantly enhance the functional performance of the resulting hydrogel systems. Such hybridization can improve tensile and compressive strength, elasticity, water-retention capacity, cell adhesion, and structural stability, while also providing better control over degradation behavior. In addition, incorporation of complementary polymers or bioactive components can enhance antimicrobial activity and drug-loading capacity, thereby expanding the suitability of κ -carrageenan-based hydrogels for wound healing, controlled drug delivery, and tissue-engineering applications.

Recent reviews identify composite carrageenan hydrogels and nanoparticle-containing systems as promising platforms for tissue engineering, drug delivery and wound healing.^[13,14]

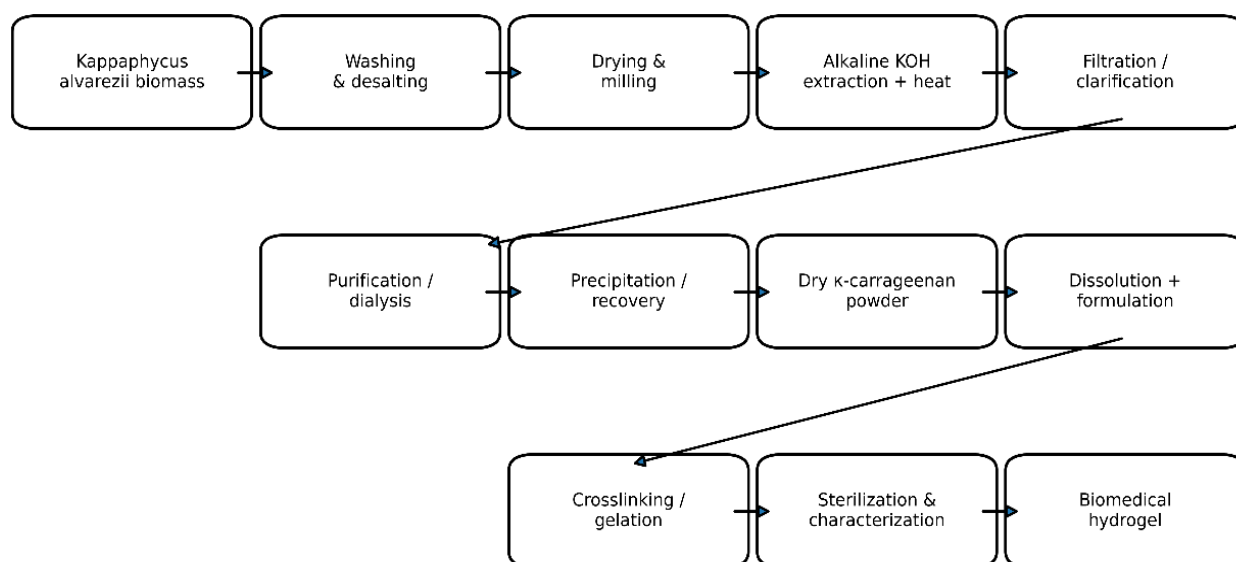


Figure 1: Schematic representation of κ -carrageenan hydrogel production from *Kappaphycus alvarezii*.

6. Biomedical Applications

6.1 Wound healing and wound dressings

Wound management requires materials capable of maintaining moisture, protecting the wound from external contamination, allowing gaseous exchange and, ideally, supporting tissue regeneration. Hydrogels are particularly appropriate because their high water content can maintain a moist wound environment.

κ -Carrageenan contributes hydrophilicity and gel-forming capability and can serve as a matrix for therapeutic agents. Recent evidence specifically supports the wound-healing potential of *K. alvarezii* carrageenan. Chang et al. demonstrated enhanced proliferation and migration of human dermal fibroblasts and accelerated wound closure in experimental animals following treatment with *K. alvarezii* carrageenan.^[15]

Fibroblast proliferation and migration are critical stages of tissue repair because fibroblasts contribute to extracellular matrix deposition and wound contraction. The reported modulation of genes associated with cytoskeletal activity and collagen production further supports the biological relevance of the seaweed-derived material.^[15]

κ -Carrageenan can therefore be developed into a diverse range of wound-care biomaterials, including hydrogel wound dressings, porous wound sponges, carrageenan–chitosan composite dressings, drug-loaded wound hydrogels, antimicrobial hydrogel membranes, and injectable wound-repair matrices. These different formulations can be tailored to provide moisture retention, controlled release of therapeutic agents, antimicrobial protection, and a supportive environment for cellular proliferation and tissue regeneration, making κ -carrageenan a promising biomaterial for advanced wound-management applications.

6.2 Antimicrobial wound-care systems

Infected wounds present a major challenge because microbial colonization can delay tissue repair. The incorporation of antimicrobial functionality into a hydrogel can provide simultaneous structural support and microbial control.

Ramachandran et al. recently reported antibacterial activity of *K. alvarezii*-derived κ -carrageenan against *S. aureus*, *E. coli*, *P. aeruginosa*, *Proteus vulgaris* and *Vibrio parahaemolyticus*.^[16] The study also reported antibiofilm activity and evidence of increased membrane permeability in bacterial cells. These findings suggest that κ -carrageenan may have potential as an active component of antimicrobial wound biomaterials.

Nevertheless, antimicrobial activity demonstrated for isolated carrageenan should not automatically be interpreted as clinical efficacy. Future hydrogel studies must establish antibacterial activity within the final formulation under physiologically relevant conditions and determine cytocompatibility toward keratinocytes, fibroblasts and other relevant cells.

6.3 Drug delivery

The three-dimensional structure and high water content of hydrogels make them useful reservoirs for therapeutic molecules. Drugs may be physically entrapped within the polymer network or incorporated through ionic or covalent interactions.

κ -Carrageenan-based hydrogel systems can serve as versatile platforms for the **encapsulation and controlled delivery of a wide range of therapeutic and bioactive agents**, including antibiotics, anti-inflammatory drugs, antioxidants, growth factors, peptides, proteins, plant-derived bioactive compounds, and nanoparticles. The hydrophilic three-dimensional network of these hydrogels can facilitate the incorporation and protection of active compounds while enabling their localized and sustained release at the target site. Such controlled-delivery characteristics can improve therapeutic efficacy, reduce premature degradation or systemic exposure, and support applications in wound healing, tissue regeneration, antimicrobial therapy, and localized drug delivery.

Drug release can be influenced by swelling, diffusion, polymer relaxation and degradation. Composite hydrogel systems can provide additional control over release kinetics.

A particularly promising approach is the development of multifunctional wound hydrogels in which κ -carrageenan provides the structural matrix, while a secondary polymer improves mechanical strength and a therapeutic compound provides antimicrobial or regenerative activity.

6.4 Tissue engineering

Tissue-engineering scaffolds should provide an appropriate three-dimensional environment for cell attachment, proliferation and extracellular matrix formation. Carrageenan hydrogels can mimic some aspects of the hydrated extracellular environment and can be modified to achieve appropriate porosity and mechanical characteristics.^[13,14]

κ -Carrageenan-based hydrogel systems have considerable potential in tissue engineering and regenerative medicine because their hydrated three-dimensional networks can provide a supportive microenvironment for cells and bioactive molecules. Potential applications include skin regeneration, cartilage engineering, soft-tissue regeneration, cell encapsulation, and osteochondral tissue engineering. Through appropriate modification and incorporation of complementary biomaterials, these hydrogels can be tailored to improve mechanical properties, cell adhesion, nutrient diffusion, and controlled degradation, thereby supporting tissue formation and regeneration.

Recent systematic evidence indicates increasing interest in carrageenan-based hydrogels and composite scaffolds for cartilage and osteochondral regeneration, although long-term mechanical stability and degradation remain important challenges.^[20]

6.5 Antioxidant and bioactive delivery

Seaweed polysaccharides can exhibit biological activities associated with their molecular size, sulfation pattern and structural characteristics. However, biological activity is strongly dependent on extraction, purification and molecular modification.

Rather than relying exclusively on intrinsic antioxidant activity, future hydrogel systems may use κ -carrageenan as a carrier for antioxidant molecules or marine-derived bioactives. This strategy could provide localized delivery while reducing systemic exposure.

6.6 Injectable and minimally invasive systems

Injectable hydrogels are attractive because they can be delivered through minimally invasive methods and conform to irregular tissue defects. For κ -carrageenan systems, injectable behavior must be carefully balanced with post-injection gel formation and mechanical stability.

Temperature-responsive or ion-responsive formulations may provide useful routes toward injectable carrageenan-based biomaterials. However, extensive rheological, cytotoxicity, degradation and sterilization studies are required before clinical translation.

7. Recent Biomedical Research on *K. alvarezii* κ -Carrageenan.

Table 2: Selected recent studies relevant to *K. alvarezii* κ -carrageenan and biomedical applications.

Study	Material/approach	Major findings	Biomedical relevance
Rupert et al. (2022) ^[1]	<i>K. alvarezii</i> carrageenan	Reviewed metabolism, structure, production and applications	Fundamental basis for biomaterial development
Mendes et al. (2024) ^[19]	Advanced extraction of <i>K. alvarezii</i> carrageenan	Ultrasound-assisted alkaline extraction improved extraction efficiency and viscosity	Improved production of biomaterial-grade carrageenan
Edo et al. (2025) ^[13]	Carrageenan-based hydrogels	Reviewed hybrid networks, chemical modification and biomedical uses	Wound healing, drug delivery and tissue engineering

Yan et al. (2025) ^[14]	Functional carrageenan hydrogels	Reviewed physical/chemical gelation and biomedical applications	Design of advanced hydrogel systems
Chang et al. (2025) ^[15]	<i>K. alvarezii</i> carrageenan	Enhanced fibroblast proliferation/migration and wound closure	Wound healing
Ramachandran et al. (2025) ^[16]	Purified κ -carrageenan	Antibacterial and antibiofilm effects against wound-associated bacteria	Antimicrobial wound-care materials
Recent hydrolysate study (2025) ^[21]	<i>K. alvarezii</i> / κ -carrageenan hydrolysates	Antioxidant and other biological activities reported	Bioactive biomaterial development
Talouki et al. (2026) ^[20]	Carrageenan-based hydrogels/composite scaffolds	Evidence for cartilage and osteochondral regeneration potential	Tissue engineering

8. Advantages of *K. alvarezii* κ -Carrageenan Hydrogels

The principal advantages of *Kappaphycus alvarezii* κ -carrageenan-based hydrogels arise from their renewable marine origin, versatile physicochemical properties, and adaptability to different biomedical applications. *K. alvarezii* is cultivated on a large scale and represents a renewable source of marine polysaccharides, with cultivation requiring less dependence on conventional terrestrial agricultural land. κ -Carrageenan is also attractive because of its biodegradability and potential biocompatibility; however, these properties should be evaluated for the final hydrogel formulation rather than assumed solely from the natural origin of the polymer. Its versatile processing characteristics allow the fabrication of hydrogels, films, sponges, fibers, and composite structures, facilitating the development of diverse wound-care and tissue-engineering materials. Furthermore, the sulfate groups and hydroxyl-containing carbohydrate backbone provide opportunities for chemical functionalization and interactions with biomolecules, enabling the modification of its physicochemical and biological properties. Another important advantage is its compatibility with composite materials, as κ -carrageenan can be combined with chitosan, gelatin, collagen, cellulose derivatives, alginate, and synthetic polymers to improve mechanical strength, stability, bioactivity, degradation characteristics, and overall biomedical performance.

9. Future Perspectives

Future development of *Kappaphycus alvarezii* κ -carrageenan-based hydrogels should move beyond conventional single-function gels toward multifunctional, stimuli-responsive, and application-specific hydrogel systems designed to meet the requirements of particular biomedical applications. One promising direction is the development of smart wound-healing hydrogels that respond to changes in pH, temperature, enzymatic activity, or reactive oxygen species (ROS), thereby enabling controlled and site-specific release of therapeutic agents according to the physiological conditions of the wound. Nanocomposite carrageenan hydrogels represent another important area of development, as the incorporation of appropriately selected nanoparticles may enhance mechanical strength, antimicrobial activity, antioxidant properties, and controlled drug release; nevertheless, the potential toxicity, biodistribution, and long-term safety of nanoparticles must be carefully evaluated.

The development of carrageenan–chitosan composite systems is particularly attractive because the oppositely charged nature of κ -carrageenan and chitosan can promote polyelectrolyte complex formation, potentially combining the gel-forming characteristics of carrageenan with the film-forming and antimicrobial properties of chitosan. Similarly, bioactive-loaded hydrogel systems incorporating growth factors, antimicrobial peptides, plant-derived compounds, marine bioactive molecules, and extracellular vesicles could provide advanced platforms for localized therapy and

tissue regeneration. Another emerging opportunity is 3D bioprinting, in which rheologically tunable κ -carrageenan composites could serve as components of bioink formulations. However, successful implementation will require optimization of shear-thinning behavior, print fidelity, cell viability, crosslinking kinetics, and post-print mechanical stability.

From a sustainability perspective, biorefinery-based extraction approaches should be developed according to circular-bioeconomy principles, with the objective of maximizing the recovery of κ -carrageenan and other valuable seaweed-derived compounds while minimizing the consumption of chemicals, water, and energy. Finally, standardization and regulatory translation will be essential for moving these materials toward clinical applications. Future studies should establish reproducible specifications for molecular weight distribution, sulfate content, viscosity, gel strength, endotoxin concentration, residual processing chemicals, microbial load, degradation behavior, and biological safety. Such standardization will improve batch-to-batch consistency, facilitate comparison between studies, support quality control, and ultimately contribute to the regulatory acceptance and clinical translation of *K. alvarezii* κ -carrageenan-based biomedical hydrogels.

10. Proposed Mechanism of Biomedical Action

The potential biomedical function of *K. alvarezii* κ -carrageenan hydrogel can be conceptualized as a combination of physical, chemical and biological effects. The hydrated three-dimensional network maintains a moist microenvironment, while the porous structure permits diffusion of oxygen, nutrients and therapeutic molecules. The negatively charged polysaccharide matrix can interact with proteins and bioactive molecules, thereby affecting their retention and release.

When incorporated into a wound dressing, the hydrogel may provide a protective barrier while allowing localized delivery of antimicrobial or regenerative compounds. In tissue engineering, the hydrated network can provide a temporary extracellular-matrix-like environment. In drug delivery, swelling and diffusion through the polymer network can be exploited to control release.

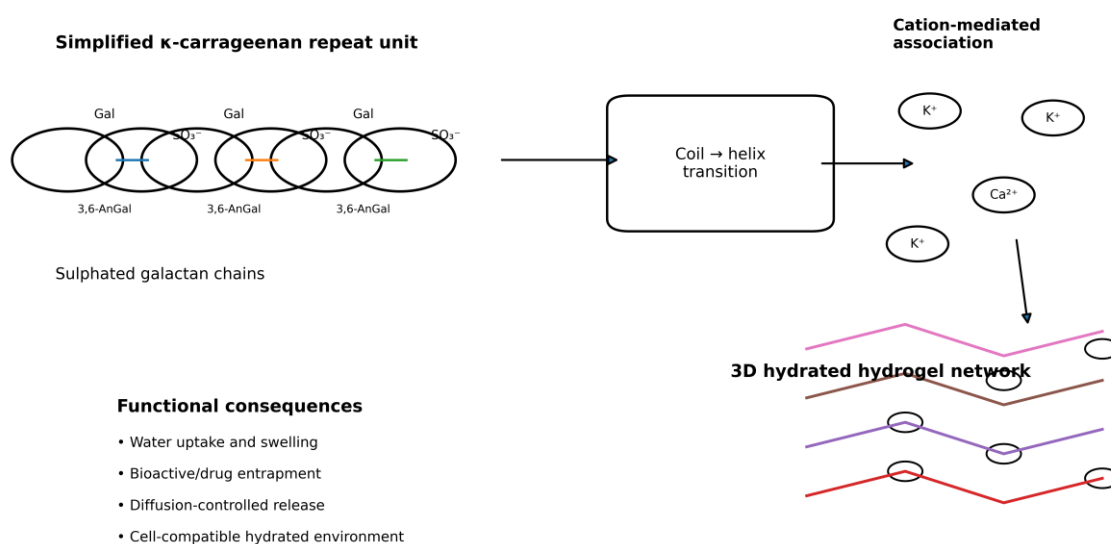


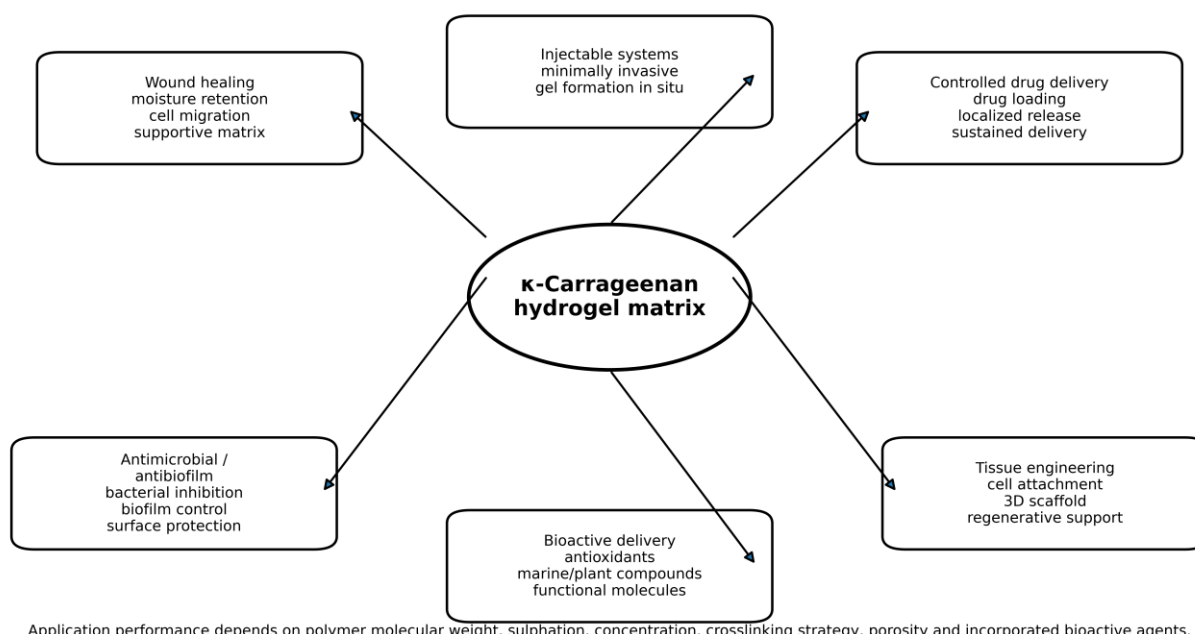
Figure 2: Molecular structure and gelation mechanism of *K. alvarezii* κ -carrageenan.

11. Integrated Biomedical Application Model

A promising future design is a multifunctional *K. alvarezii* κ -carrageenan composite hydrogel containing four functional components:

1. **κ -Carrageenan:** primary marine polysaccharide matrix;
2. **Secondary polymer:** mechanical reinforcement and improved cell interaction;
3. **Bioactive compound:** antimicrobial, anti-inflammatory or regenerative activity;
4. **Nanostructured component:** controlled release and/or mechanical reinforcement.

Such an architecture could enable simultaneous moisture management, antimicrobial protection, controlled therapeutic release and tissue regeneration.



Application performance depends on polymer molecular weight, sulphation, concentration, crosslinking strategy, porosity and incorporated bioactive agents.

Figure 3: Multifunctional biomedical applications of *K. alvarezii* κ -carrageenan hydrogels.

12. CONCLUSION

Kappaphycus alvarezii represents an important sustainable marine source of κ -carrageenan with significant potential for biomedical hydrogel development. The polysaccharide combines hydrophilicity, gel-forming capacity, structural tunability and compatibility with other biomaterials. Recent evidence demonstrates that *K. alvarezii* carrageenan can promote fibroblast proliferation and migration and enhance wound closure, while purified κ -carrageenan has demonstrated antibacterial and antibiofilm activity against clinically relevant wound-associated microorganisms.

Advances in extraction technology, particularly ultrasound-assisted processing, provide opportunities to improve yield and control physicochemical properties. At the same time, composite and hybrid hydrogel strategies are addressing the limitations of native carrageenan, including mechanical weakness, ion sensitivity and degradation control.

The future of *K. alvarezii* κ -carrageenan biomaterials lies in multifunctional systems combining structural support with controlled therapeutic activity. Integration with chitosan, gelatin, cellulose derivatives, nanoparticles, antimicrobial agents and regenerative molecules may enable advanced wound-care and tissue-engineering platforms. Nevertheless,

rigorous characterization, standardized extraction, long-term biocompatibility studies, degradation analysis, sterilization validation and clinically relevant animal models are essential before translation into medical products. Overall, *K. alvarezii* κ -carrageenan represents a promising marine-derived platform for the development of next-generation sustainable biomedical hydrogels.

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