

# Kappa-Carrageenan as a Natural Biopolymer for Dental and Biomedical Applications: A Narrative Review

Ummey Salma<sup>1\*</sup>, Pushpalatha C<sup>2</sup>, Shazia Fathima J.H<sup>3</sup>, Jalis Aaisha Khan<sup>4</sup>, Arshiya Shakir<sup>5</sup> and Mohammed Imran Khaisar<sup>6</sup>

<sup>1</sup>Research scholar, Department of Pediatric and Preventive Dentistry, Faculty of Dental Science, Ramaiah University of Applied Sciences, Bengaluru-560054, Karnataka, India.

<sup>2</sup>Professor and Head of the Department, Department of Pediatric and Preventive Dentistry, Faculty of Dental Science, Ramaiah University of Applied Sciences, Bengaluru-560054, Karnataka, India.

<sup>3</sup>Global Research Cell, Dr.D.Y.Patil Dental College & Hospital, Dr.D.Y.Patil Vidyapeeth (Deemed to be University), Pimpri, Pune 411018, India

<sup>4</sup>Associate Professor, Department of Prosthodontics, AJ Institute of Dental Sciences, Rajiv Gandhi University of Health Sciences, Mangalore -575004, Karnataka, India

<sup>5</sup>Research Scholar, Department of Pediatric and Preventive Dentistry, Faculty of Dental Science, Ramaiah University of Applied Sciences, Bengaluru- 560054, India

<sup>6</sup>Endodontist, Department of Conservative Dentistry and Endodontics, Speciality Dental Center, Al Madinah Munawwarah, Kingdom of Saudi Arabia

<sup>1</sup>drpeadz01@gmail.com, <sup>2</sup>drpushpalatha29@gmail.com, <sup>3</sup>drshaziaopath@gmail.com, <sup>4</sup>jalisaaisha@gmail.com, <sup>5</sup>arsh1036@gmail.com and <sup>6</sup>drimrankhaisar@gmail.com

Corresponding author: Ummey Salma (drpeadz01@gmail.com)

Received: 28<sup>th</sup> Feb, 2026; Revised: 6<sup>th</sup> March 2026; Accepted: 7<sup>th</sup> April, 2026; Available Online: 20<sup>th</sup> April, 2026

## ABSTRACT

Carrageenan, a class of linear, anionic biopolymers derived from red macroalgae (Rhodophyceae), has evolved from a conventional rheology modifier in oral care products to a promising biomaterial for translational dental research. Among its isoforms, κ-carrageenan (KC) is uniquely capable of cation-mediated, thermosensitive gelation, forming stable hydrogel matrices suitable for biological containment. This narrative review aims to critically examine KC's structure–function relationships, functional properties, and applications in dentistry. Key findings indicate that KC exhibits robust cytocompatibility with dental stem cells (e.g., DPSCs), intrinsic antimicrobial activity against endodontic pathogens, reactive oxygen species (ROS) scavenging, and viscoelastic shear-thinning behavior that facilitates minimally invasive delivery. These features collectively support its use as an injectable scaffold for dentin–pulp complex regeneration and as a platform for sustained therapeutic release in periodontal and endodontic applications. By consolidating mechanistic insights and emerging experimental evidence, this review highlights KC's translational potential in advancing regenerative and restorative dental therapeutics

**Keywords:** Dentistry, Kappa Carrageenan, Dental Biomaterials, Hydrogel Scaffold, Pulp Regeneration, Tissue Engineering.

**How to cite this article:** Salma U, Pushpalatha C, Fathima JH, Khan JA, Shakir A, Khaisar MI, Kappa-Carrageenan as a Natural Biopolymer for Dental and Biomedical Applications: A Narrative Review. Int J Drug Deliv Technol. 2026;16(5): 12-19. DOI: 10.25258/ijddt.16.5.3

**Source of support:** Nil.

**Conflict of interest:** None

## 1. INTRODUCTION

Carrageenan is a natural sulfated polysaccharide extracted from red marine algae (Rhodophyceae) and represents one of the most widely studied marine-derived biopolymers due to its unique physicochemical and biological properties [1,2]. Traditionally, carrageenan found applications in the food industry as a thickening, stabilizing, and gelling agent; however, over the past few decades, its utility has expanded into biotechnology,

pharmaceuticals, and biomedical fields, particularly in dentistry and tissue engineering. In dental applications, carrageenan was first introduced in the 20th century as a component of toothpaste and other oral care formulations, primarily serving as a rheology modifier. Beyond these traditional roles, contemporary research has focused on its potential as a functional biomaterial for advanced restorative and regenerative therapies, largely because it can form thermosensitive hydrogels, demonstrates excellent biocompatibility, and provides a supportive

\*Author for Correspondence: drpeadz01@gmail.com

microenvironment for cellular attachment and proliferation.

Experimental investigations have demonstrated that carrageenan can enhance the viability and functional activity of dental pulp stem cells (DPSCs) and other odontogenic cell types, thereby promoting the deposition of reparative dentin—a critical requirement for pulp-capping agents, protective liners, and regenerative scaffolds [3,4]. In addition, carrageenan's gel-forming capacity, combined with its viscoelastic and shear-thinning properties, facilitates minimally invasive delivery as injectable scaffolds, making it particularly attractive for clinical applications in endodontics and periodontal therapy. Animal studies conducted in the 1980s and 1990s provided early evidence of its safety and regenerative efficacy, demonstrating favorable pulp healing, enhanced odontoblast activity, and deposition of tertiary dentin following *in vivo* application [5,6].

The interest in carrageenan as a biomaterial is further supported by its multifunctional properties, including modulation of inflammatory responses, antioxidant activity, and potential antimicrobial effects against oral pathogens, which together may enhance clinical outcomes in regenerative procedures. Collectively, these findings highlight carrageenan's capacity to support pulp cell

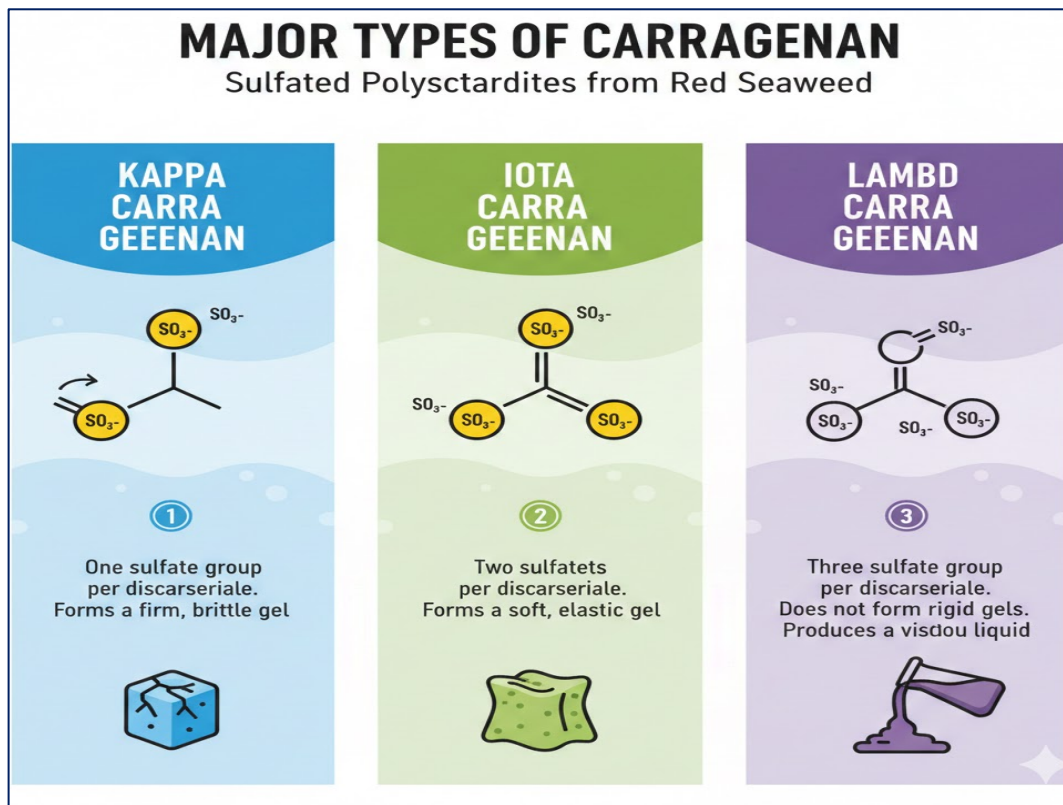
survival, promote tissue regeneration, and provide a biomimetic microenvironment conducive to dentin-pulp complex repair. This body of evidence underscores the rationale for continued and focused investigation of carrageenan, particularly  $\kappa$ -carrageenan, as a promising scaffold material for restorative and regenerative dental applications where induction of reparative dentin and preservation of pulp vitality are critical objectives

## 2. CHEMICAL STRUCTURE OF CARRAGEENAN

Carrageenans are linear sulfated polysaccharides composed of repeating units of D-galactose and 3,6-anhydro-D-galactose linked through alternating  $\alpha$ -1,3 and  $\beta$ -1,4 bonds [1]. Variations among carrageenan types are determined by the number and arrangement of ester sulfate groups on these repeating units.

### 2.1 Major Types of Carrageenan

- **Kappa carrageenan:** Contains one sulfate group per disaccharide. It forms a firm, brittle gel on hydration.
- **Lambda carrageenan:** Contains two sulfate groups. It does not form rigid gels and produces a more viscous, elastic consistency.
- **Iota carrageenan:** Contains three sulfate groups and forms a soft, elastic gel.



**Figure 1:** Major types of carrageenan.

All three share the same carbohydrate backbone, but their sulfate patterns determine their behaviour. Kappa carrageenan is commonly evaluated for dental use due to its gelling strength and acceptable biocompatibility.



**Figure 2:** Variants of carrageenan.

Several modified variants have also been reported, including neo-kappa, epsilon, hepta-carrageenan and hydroxyethyl carrageenan. These typically show altered gelling temperatures or mechanical characteristics. Their relevance to dentistry remains limited, as current evidence is mainly experimental and not yet translated into clinical formulations.

### 3. KAPPA CARAGEENAN

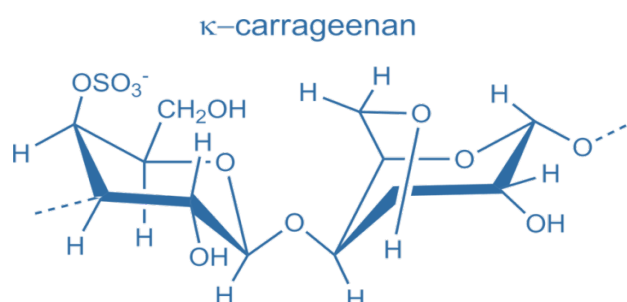
Kappa-carrageenan is a naturally occurring linear polysaccharide extracted from red seaweeds (Rhodophyceae). Its structure consists of repeating disaccharide units of D-galactose and 3,6-anhydro-D-galactose, connected via alternating  $\alpha$ -1,3 and  $\beta$ -1,4 glycosidic bonds [1]. The polysaccharide carries negatively charged sulfate groups and multiple hydrophilic hydroxyl moieties, which confer high water affinity and enable gel formation in the presence of monovalent cations such as potassium (2). Gelation occurs through a coil-to-helix transition and subsequent aggregation into double-helical networks, producing mechanically stable and porous gels suitable for tissue scaffolding [7]

In addition to its long-standing use as a thickener and stabilizer in the food industry,  $\kappa$ -carrageenan has gained attention in biomedical applications, particularly dental tissue engineering. Its biocompatibility and ability to

support cell adhesion, proliferation, and differentiation make it a promising scaffold material for pulp regeneration (8). Composite scaffolds combining  $\kappa$ -carrageenan with polymers such as gelatin or chitosan have demonstrated enhanced odontogenic differentiation of dental pulp stem cells (DPSCs), with increased mineral deposition and expression of dentin-related markers such as DSPP and RunX2 (9).

Other notable properties include high water-holding capacity, mechanical tunability, and relative stability in varying pH and ionic conditions, which are advantageous for dental applications where electrolytes and saliva can affect scaffold performance (2,8). Emerging studies also suggest potential antibacterial and anti-inflammatory effects, further increasing its suitability for dental pulp and periodontal therapies (10). Furthermore,  $\kappa$ -carrageenan-based hydrogels can serve as controlled-release matrices for growth factors or therapeutic agents, combining structural support with biochemical signaling in regenerative endodontics (9).

Overall,  $\kappa$ -carrageenan's combination of biocompatibility, bioactivity, gel-forming capacity, and tunable mechanical properties positions it as a promising biomaterial for dental pulp regeneration, particularly when used in composite scaffolds with bioactive polymers or ceramics.



**Figure 3:** The chemical structure of  $\kappa$ -carrageenan

#### 4. PROPERTIES OF KAPPA CARRAGEENAN IN DENTISTRY

Kappa-carrageenan ( $\kappa$ -carrageenan) is emerging as a highly promising material for contemporary dental applications, transcending its conventional use as a simple hydrocolloid. This advancement is largely attributed to its sulfated polysaccharide structure, which confers a broad spectrum of bioactive and biomedical properties [11].

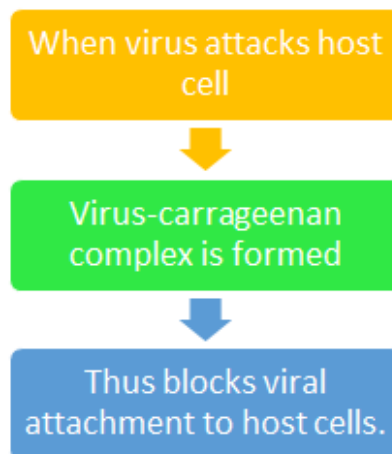
While it exhibits multifunctional activities, including antiviral, antibacterial, antihyperlipidemic, anticoagulant, antioxidant, antitumor, and immunomodulatory effects [12], its significance in dental and craniofacial tissue engineering is particularly notable [13, 11]. Its potential lies not merely as a stable structural scaffold component, but, critically, as a bioactive modulator capable of enhancing regenerative outcomes, such as promoting the differentiation of dental pulp stem cells into dentin-forming cells [11].

##### 4.1 ANTIVIRAL ACTIVITY

$\kappa$ -Carrageenan has been widely investigated for its antiviral potential due to its ability to interfere with early stages of viral infection. Experimental studies demonstrate that  $\kappa$ -carrageenan effectively suppresses Enterovirus-71 (EV-71) by significantly reducing plaque formation, disrupting intracellular viral replication, and attenuating

virus-induced apoptotic pathways. These antiviral effects are largely attributed to the strong electrostatic interactions between the sulfate groups of the polysaccharide and the viral capsid, which hinder the attachment of virions to host cell surface receptors and subsequently prevent internalisation [14]. In a related in-vitro evaluation, Abu-Galiyun and colleagues compared the antiviral activity of kappa ( $\kappa$ -),iota ( $\iota$ -), and lambda ( $\lambda$ -) carrageenans against varicella-zoster virus (VZV). All three variants demonstrated dose-responsive suppression of viral replication, with inhibitory efficacy exceeding that of acyclovir under the experimental conditions [15]. These findings reinforce the potential utility of carrageenan-based biomaterials as adjunct antiviral agents, particularly for mucosal applications.

Although current evidence is predominantly preclinical, the capacity of carrageenans to bind viral particles, block receptor-mediated entry, and modulate host-virus interactions has led to broad inhibitory activity across several virus families, including herpesviruses, enteroviruses, and respiratory viruses. This expanding body of literature supports further translational research to optimise formulation stability, enhance bioavailability, and determine clinical safety profiles before therapeutic use can be fully realised.



**Figure 4:** Mechanism of viral inhibition of carrageenan

##### 4.2 ANTIBACTERIAL ACTIVITY

Kappa-carrageenan exhibit pronounced antibacterial activity against a broad range of microorganisms. In vitro agar diffusion assays have demonstrated inhibition zones for Gram-negative and Gram-positive bacteria as well as fungi (including *Escherichia coli*, *Pseudomonas aeruginosa*, *Bacillus cereus*, *Staphylococcus aureus*, *Saccharomyces cerevisiae*), and filamentous species such as *Penicillium citrinum* and *Mucor* spp., with the most potent activity reported against *S. cerevisiae* [16]. Chemical modification of  $\kappa$ -carrageenan enhances these antimicrobial effects: oxidative modification was shown to compromise bacterial cell-wall and membrane integrity, producing broad-spectrum bactericidal action [17]. Similarly, carboxymethylated  $\kappa$ -carrageenan displays

growth-inhibitory effects against *S. aureus*, *B. cereus*, *E. coli* and *P. aeruginosa*; the antimicrobial mechanism is hypothesised to involve increased polymer nucleophilicity and altered local pH mediated by introduced carboxylate and retained sulphate groups, which together may disrupt membrane function and metabolic processes in microbes. Crucially, these chemically modified derivatives combine antimicrobial and antioxidant activity with acceptable biocompatibility in preliminary assessments, supporting their translational potential for incorporation into wound dressings and tissue-engineering scaffolds where infection control and host compatibility are both required [18]. Further work should quantify minimum inhibitory concentrations, time-kill kinetics, and cytotoxicity in

relevant cell types to inform safe formulation for clinical or dental regenerative applications.

#### 4.3 ANTIHYPERLIPIDEMIC EFFECTS

The investigation into the systemic effects of carrageenan, particularly its antihyperlipidemic properties, stems from its nature as a non-digestible sulfated polysaccharide and its significant interactions within the gastrointestinal (GI) tract [19].

Carrageenan's effect on lipid metabolism is intrinsically linked to its influence on gut microbiota and GI function [28]. As a viscous, non-digestible fiber, carrageenan can exert several effects:

1. **Reduced Nutrient Absorption:** Its presence in the GI tract can physically reduce the overall rate of nutrient absorption, including fats and cholesterol, by increasing the viscosity of the intestinal contents [19].
2. **Influence on Cholesterol Metabolism:** The proposed mechanism for its antihyperlipidemic effect centers on reduced exogenous cholesterol uptake from the diet.<sup>1</sup> This reduction in uptake is sometimes accompanied by a compensatory increase in endogenous cholesterol synthesis in the body, a complex interplay that requires further investigation to fully understand the net clinical benefit [19].

Reports suggest possible benefits related to colon health and local inflammation [19]. However, the direct evidence confirming a robust, clinically relevant antihyperlipidemic outcome in humans remains limited, especially when considering the variability in dietary intake and the challenge of isolating carrageenan's effect from other dietary fibers [20].

#### 4.4 ANTITUMOR AND IMMUNOMODULATORY ACTIVITY

Carrageenanin due course of time has garnered attention for its antitumor and immunomodulatory properties, which are increasingly relevant in biomedical and dental tissue engineering contexts. Mechanistically, carrageenan promotes apoptosis in tumor cells and inhibits angiogenesis, thereby suppressing tumor growth and metastasis. It also modulates cytokine production—particularly interleukin-6 (IL-6) and tumor necrosis factor-alpha (TNF- $\alpha$ )—enhancing immune responses against malignancies [21]. The biological activity of carrageenan is strongly influenced by its sulfation level and pattern;  $\kappa$ -carrageenan, with a higher sulfate content, exhibits more potent immunological and anti-inflammatory effects than  $\iota$ -carrageenan, which contains fewer sulfate groups [22]. Additionally, molecular weight plays a critical role: low molecular weight fractions demonstrate superior antitumor and immunomodulatory efficacy due to improved tissue penetration and cellular interaction. These properties make carrageenan derivatives particularly promising for dental tissue engineering applications, where immunomodulation and biocompatibility are essential for scaffold integration and pulp regeneration. In this context, sulfated carrageenan-based biomaterials may serve as bioactive

components in scaffolds designed to support stem cell recruitment, modulate local inflammation, and promote angiogenesis within the dental pulp microenvironment [22].

#### 4.5 ANTIOXIDANT ACTIVITY

Carrageenan exhibits notable antioxidant activity, which is influenced by its sulfate content, molecular weight, and formulation context. Studies confirm its potential for biomedical applications, especially when combined with other bioactive agents.

Several investigations have highlighted the antioxidant efficacy of carrageenan, particularly in relation to its structural characteristics. In a comparative study by Gómez-Ordoñez et al., different extraction methods were applied to obtain carrageenan fractions from *Mastocarpus stellatus*. The fraction extracted with water—characterized by a higher sulfate density and greater molecular weight—demonstrated superior in vitro antioxidant and anticoagulant activity, underscoring the correlation between sulfate substitution, polymer size, and biological performance [23]. Complementary findings were reported in a study focused on multilayer coatings composed of  $\kappa$ -carrageenan and lecithin/chitosan nanoparticles. The antioxidant behavior of these coatings was modulated by their structural configuration, and the incorporation of quercetin—a known flavonoid antioxidant—further enhanced their functional properties. This synergistic approach suggests that carrageenan-based composite systems can be strategically engineered to improve antioxidant capacity, making them promising candidates for biomedical coatings, wound dressings, and drug delivery platforms [24].

### 5. APPLICATIONS OF KAPPA CARRAGEENAN IN DENTISTRY

#### 5.1. Pulp and Bone Regeneration

Hydrogels continue to be explored as scaffolds for regenerative procedures. Natural polymers often perform better than synthetic alternatives because of their lower cytotoxicity and favourable interaction with cells [25]. An ideal scaffold maintains neutral pH, does not trigger inflammation and supports adhesion, proliferation and migration of cells involved in healing [26,27].

Carrageenan-based hydrogels are of interest due to their structural similarity to glycosaminoglycans found in the extracellular matrix. This similarity may support integration within pulp or bone defects. Injectable hydrogels are advantageous in endodontic applications because they can adapt to the internal anatomy of the tooth and serve as carriers for bioactive components or stem cells [28–31]. Although direct studies on carrageenan in dentin–pulp regeneration are limited, related research has demonstrated its usefulness in controlled laboratory settings [32], bone tissue engineering [33] and wound healing models [34]. These findings support further investigation of carrageenan formulations for endodontic regenerative procedures.

However carrageenan, particularly the kappa-carrageenan type, shows significant promise in the field of bone and hard tissue regeneration, primarily due to its ability to form stable hydrogel matrices that can be engineered into functional scaffolds [35]. As a natural, biocompatible polymer, it is frequently combined with osteoconductive ceramic materials to create nanocomposite scaffolds. For example, porous kappa-carrageenan scaffolds have been successfully synthesized and characterized by incorporating calcium phosphate nanoparticles, demonstrating a structure suitable for cell infiltration and nutrient exchange crucial for tissue repair [35]. Furthermore, carrageenan has been investigated as a component in injectable bone substitutes. One notable formulation involves combining it with nano-hydroxyapatite (nHA) and collagen to produce an injectable material designed to cure *in situ* and provide mechanical support while releasing beneficial ions for bone healing [36]. This application highlights carrageenan's role not just as a structural component, but

as a key element in developing novel, minimally invasive strategies for repairing skeletal defects.

**5.2. Dental Adhesives**

Kappa-carrageenan is a sulphated polysaccharide derived from red marine algae. It exhibits pharmacological activities such as anticoagulant, antioxidant, antitumor and antimicrobial effects [37]. Its thickening and stabilizing properties have long supported its use in food and pharmaceutical products and it is recognised as safe by the FDA and WHO [38,39].

In adhesive materials, adding kappa-carrageenan may influence polymer chain mobility and plasticizer penetration, altering the formation of the polymer network. It can also act as a filler, which may increase the hardness of soft lining materials [40]. These interactions have motivated interest in incorporating kappa-carrageenan into adhesive systems or soft-tissue liners to adjust mechanical or biological behaviour.

**Table 1.** Dental applications of kappa-carrageenan: evidence

Application	Evidence Type	Key Findings	Limitations	References
Pulp regeneration (hydrogel scaffold)	In vitro, animal	Supports cell adhesion, proliferation; adaptable injectable scaffold	No validated human studies; mechanical stability unclear	[25–34]
Bone regeneration (nanocomposites)	In vivo, material studies	κ-CG with Ca-phosphate and collagen forms porous, injectable bone graft material	Limited long-term biomechanical data	[35,36]
Dental adhesives	Material studies	May alter polymer network, hardness and biological behaviour	Lack of strength testing; no comparison with standard bonding agents	[37-40]
Soft liners / provisional materials	Material studies	κ-CG acts as stabilizer or filler improving gel consistency	Clinical performance data absent	[40]
Antimicrobial components in oral products	In vitro	Reduces bacterial growth; antiviral activity relevant to oral environment	No mouthwash/toothpaste formulations tested clinically	[14-18]
Wound management	In vitro, animal	Shows wound-healing and anti-inflammatory potential	No dental wound healing trials	[33-34]

**6. LIMITATIONS**

κ-Carrageenan despite its promising bioactivity, still faces several limitations that restrict its routine use in dentistry. As a standalone material it exhibits poor mechanical strength, forming brittle gels with low tensile performance, and its behaviour is highly sensitive to ionic conditions, pH cycling and salivary enzymes, resulting in unpredictable degradation and instability in the oral environment. Long-term biocompatibility data remain limited, particularly regarding chronic inflammation, sulfate-induced irritation and sustained interactions with pulp stem cells. Its intrinsic antibacterial activity is modest and inconsistent against major oral pathogens, while its mineralization potential is significantly weaker than established bioactive materials such as calcium silicates and MTA. Additionally, chemical modifications used to enhance its performance may introduce cytotoxic residues,

and common sterilization methods can degrade its polysaccharide structure. Finally, the lack of standardization in molecular weight, sulfate content and biomedical-grade specifications contributes to batch variability and slows regulatory acceptance.

**7. FUTURE PERSPECTIVE**

Research on carrageenan-based hydrogels is progressing rapidly, yet several critical knowledge gaps continue to limit their translation into dental practice. Current evidence indicates that their mechanical integrity, bioactivity and interaction with oral tissues are strongly influenced by the polymer’s molecular architecture and the nature of chemical modifications applied. A deeper understanding of these structure–function relationships is essential before such materials can be reliably engineered for clinical dental applications. Most existing work is restricted to in-vitro models, with minimal validation in

animal studies or correlation with human clinical outcomes, creating uncertainty about their real-world performance. Key areas requiring clarification include the hydrolytic and enzymatic degradation behaviour of carrageenan in the oral environment, the kinetics of drug or ion release when used as delivery systems, and their long-term biocompatibility within pulp, periodontal and mucosal tissues.

Emerging dental applications being explored include the use of  $\kappa$ -carrageenan as a gelling or thickening component in therapeutic dental gels and desensitising pastes, incorporation into wound-healing dressings for mucosal or post-operative sites, inclusion in antimicrobial formulations such as mouthrinses or dentifrices, and as part of composite scaffold systems for restorative, regenerative or prosthetic purposes—including pulp regeneration matrices, filling materials and denture bases. While these concepts are promising, all remain at an experimental stage, and robust preclinical testing followed by well-designed clinical trials is necessary to establish their safety, stability and functional efficacy in dentistry.

## 8. CONCLUSION

Kappa carrageenan shows potential as a bioactive polymer for dental use. Laboratory and animal studies indicate that it can support cell activity, form stable hydrogels and contribute antibacterial, antiviral and antioxidant effects. These characteristics make it a possible candidate for regenerative scaffolds, adhesive modification and composite development. Despite these findings, evidence remains preliminary. Preparation methods differ across studies, the mechanical behaviour of carrageenan-based systems is not well established and clinical data are minimal. Future research should focus on standardised formulations, long-term stability and controlled clinical evaluation to determine whether kappa carrageenan can be incorporated into routine dental practice.

## 9. REFERENCES

- Abbass MM, El-Rashidy AA, Sadek KM, Moshy SE, Radwan IA, Rady D, Dörfer CE, Fawzy El-Sayed KM. Hydrogels and dentin–pulp complex regeneration: from the benchtop to clinical translation. *Polymers*. 2020 Dec 9;12(12):2935.
- Abraham AQ, Abdul-Fattah N. Influence of chlorhexidine diacetate salt incorporation into soft denture lining material on antifungal and mechanical properties. *J Baghdad Coll Dent*. 2017;29(1):9-15.
- Abu-Galiyun E, Huleihel M, Levy-Ontman O. Antiviral bioactivity of renewable polysaccharides against Varicella Zoster. *Cell Cycle*. 2019 Dec 17;18(24):3540-9.
- Burns BM, Keogh JB, Clifton PM. Carrageenan: a natural hydrocolloid with implications for gut health and inflammation. *Food Chem*. 2018;245:1118-1126.
- Campo VL, Kawano DF, da Silva Jr DB, Carvalho I. Carrageenans: Biological properties, chemical modifications and structural analysis—A review. *Carbohydrate polymers*. 2009 Jun 10;77(2):167-80.
- Chiu YH, Chan YL, Tsai LW, Li TL, Wu CJ. Prevention of human enterovirus 71 infection by kappa-carrageenan. *Antiviral Res*. 2012;95:128-134.
- Aslam Khan MU, Abd Razak SI, Al Arjan WS, Nazir S, Sahaya Anand TJ, Mehboob H, Amin R. Recent advances in biopolymeric composite materials for tissue engineering and regenerative medicines: a review. *Molecules*. 2021 Jan 25;26(3):619.
- Daniel-da-Silva AL, Lopes AB, Gil AM, Correia RN. Synthesis and characterization of porous  $\kappa$ -carrageenan/calcium phosphate nanocomposite scaffolds. *Journal of Materials Science*. 2007 Oct;42(20):8581-91.
- Zhu M, Ge L, Lyu Y, Zi Y, Li X, Li D, Mu C. Preparation, characterization and antibacterial activity of oxidized  $\kappa$ -carrageenan. *Carbohydrate polymers*. 2017 Oct 15;174:1051-8.
- García-Vaquero M, Rajauria G, O'Doherty JV. Antimicrobial, antioxidant and anti-inflammatory properties of carrageenan extracts from marine red algae: a review. *Food Hydrocoll*. 2020;100:105423.
- García-Vaquero M, Rajauria G, O'Doherty JV. Red seaweed polysaccharides: structure, bioactivity and applications in tissue engineering. *Trends Food Sci Technol*. 2023;138:182-196.
- Gan S, Feng Q. Preparation and characterization of a new injectable bone substitute—carrageenan/nano-hydroxyapatite/collagen. *Zhongguo Yi Xue Ke Xue Yuan Xue Bao*. 2006;28:710-713.
- Gómez-Ordoñez E, Jiménez-Escrig A, Rupérez P. Antioxidant and anticoagulant activities of carrageenan extracts from *Mastocarpus stellatus*. *J Appl Phycol*. 2012;24(3):447-456.
- Joint FAO/WHO Expert Committee on Food Additives. Evaluation of certain food additives: eighty-fourth report. Geneva: World Health Organization; 2017.
- Lai JY. Biocompatibility of chemically cross-linked gelatin hydrogels for ophthalmic use. *J Mater Sci Mater Med*. 2010;21(6):1899-1911.
- Liu J, Zhang S, Wang X, et al. Inhibitory effects of  $\kappa$ -carrageenan on enterovirus 71 infection through interference with viral attachment and replication. *Int J Biol Macromol*. 2015;72:722-728.
- Loukelis K, Machla F, Bakopoulou A, Chatzinikolaidou M.  $\kappa$ -carrageenan/chitosan/gelatin scaffolds provide a biomimetic microenvironment for dentin–pulp regeneration. *Int J Mol Sci*. 2023;24(14):11453.

18. Mano JF, Silva GA, Azevedo HS, Malafaya PB, Sousa RA, Silva SS, et al. Natural origin biodegradable systems in tissue engineering and regenerative medicine. *J R Soc Interface*. 2007;4(17):999-1030.
19. Mishra A, Singh S, Chandra A.  $\kappa$ -carrageenan-based composite scaffolds for dental pulp regeneration: in-vitro evaluation of stem cell differentiation and mineralization. *J Biomater Appl*. 2023;38(5):712-725.
20. Mokhtari H, Tavakoli S, Safarpour F, Kharaziha M, Bakhsheshi-Rad HR, Ramakrishna S, et al. Recent advances in chemically modified and hybrid carrageenan-based platforms for drug delivery, wound healing and tissue engineering. *Polymers (Basel)*. 2021;13(11):1749.
21. Necas J, Bartosikova L. Carrageenan: a review. *Vet Med (Praha)*. 2013;58(4):187-205.
22. Nguyen HTT, Trung DT, Trang VTD, Thinh PD, Thuy TTT, Hung LD. Carboxymethyl- $\kappa$ -carrageenan derivatives synthesized from *Kappaphycus striatus*: characterization, structure and biological activity. *J Appl Phycol*. 2024;37:527-537.
23. Nishimura F, Terranova VP, Brauer DS. Biological evaluation of polysaccharide-based materials in pulp tissue repair. *J Dent Res*. 1988;67(10):1354-1359.
24. Popa EG, Carvalho PP, Dias AF, Santos TC, Santo VE, Marques AP, et al. In-vitro and in-vivo biocompatibility of carrageenan-based hydrogels. *J Biomed Mater Res A*. 2014;102(11):4087-4097.
25. Rasool A, Ata S, Islam A, Khan RU. Carrageenan-based stimuli-responsive injectable hydrogels for controlled cephadrine release. *RSC Adv*. 2019;9(22):12282-12290.
26. Schmalz G, Galler KM. Biocompatibility of dental biomaterials—lessons learned and future considerations. *Dent Mater*. 2011;27(1):18-30.
27. Silva RM, Rosales-Leal JI, Dalby MJ. Biomaterials approach to dentin–pulp complex regeneration. *J Dent*. 2013;41(7):507-516.
28. Santo VE, Frias AM, Carida M, Cancedda R, Gomes ME, Mano JF. Carrageenan-based hydrogels for controlled delivery of PDGF-BB in bone tissue engineering. *Biomacromolecules*. 2009;10(6):1392-1401.
29. Souza MP, Vaz AFM, Costa TB, Cerqueira MA, Castro CMMB, Vicente AA. Biocompatible antioxidant multilayer coating of  $\kappa$ -carrageenan and quercetin nanoparticles. *Food Bioprocess Technol*. 2018;11(5):1197-1208.
30. Torabinejad M, Faras H. Regenerative endodontic procedures: clinical and histological evaluation in animal models. *J Endod*. 2012;38(9):1195-1203.
31. US Food and Drug Administration. Overview of food ingredients, additives and colors. Silver Spring (MD): FDA; 2013.
32. Vermonden T, Censi R, Hennink WE. Hydrogels for protein delivery. *Chem Rev*. 2012;112(5):2853-2888.
33. Wang Q, Chen Y, Liu Y, Zhang J. Bioactive hydrogel scaffolds in regenerative endodontics: role of polysaccharides. *Front Bioeng Biotechnol*. 2023;11:1245783.
34. Weiner ML. Carrageenan: update on regulatory status. *Toxicol Mech Methods*. 2018;28(3):200-208.
35. Yegappan R, Selvaprithiviraj V, Amirthalingam S, Jayakumar R. Carrageenan-based hydrogels for drug delivery, tissue engineering and wound healing. *Carbohydr Polym*. 2018;198:385-400.
36. Yuan H, Song J, Li X, Li N, Liu S. Carrageenan-based biomaterials for tissue engineering. *Carbohydr Polym*. 2020;241:116137.
37. Yuan Z, Nie H, Wang S, Lee CH, Li A, Fu SY, et al. Biomaterial selection for tooth regeneration. *Tissue Eng Part B Rev*. 2011;17(5):373-388.
38. Zhang L, Chen H, Li Y. Antibacterial activity of  $\kappa$ -carrageenan oligosaccharides. *Appl Mech Mater*. 2011;108:194-198.
39. Zhang X, Li Y, Sun H. Antibacterial and immunomodulatory potential of marine polysaccharides: focus on  $\kappa$ -carrageenan. *Mar Drugs*. 2024;22(1):58.
40. Zong X, Li Y, Zhang L, Chen H, Wang J. Chemical derivatives of  $\kappa$ -carrageenan and applications in antitumor therapy and drug delivery. *Int J Biol Macromol*. 2018;115:156-167.