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CARRAGEENAN A VERSATILE BIOPOLYMER – REVIEW OF ITS MULTIFACETED APPLICATIONS

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Abstract
The beneficial qualities of carrageenan, a polysaccharide derived from red algae, are utilized in a variety of industries, which adds to the biopolymer's growing significance from sustainable and biodegradable sources. Furthermore, carrageenans are used in food applications such as food packaging, pharmaceuticals (drug delivery systems and encapsulation of pharmacological agents for systemic targeted therapy) biotechnology (as culture media additive in bioprocesses), and cosmetics (solubilizing of lipophilic substances) due to their ability to form hydrogels and their bioactive qualities. Carrageenan may be combined with TiO_2, SiO_2, and Halloysite nano clay to create bio-nanocomposites, which are important packaging materials with enhanced mechanical, antibacterial, and barrier qualities that could extend the shelf life and quality of food.
Carrageenan-based hydrogels are also widely used in the biomedical field for applications such as wound healing, drug delivery, and environmental applications to remove pollutants.
Its natural properties make carrageenan an excellent plant-based ingredient in cosmetics and provide thickening, stabilization, and hydration.

Keywords
- Carrageenan
- Nanocomposite
- Cosmetics
- Biomedical Application

Introduction
The bulk of carrageenan is derived from Eucheuma denticulatum and Chondrus crispus, or Irish moss [1-5]. Its distinct chemical structure and useful qualities make it a vital component of many businesses, especially the food, cosmetic, and pharmaceutical sectors. The majority of red seaweeds that are a part of the phylum Rhodophyta employ carrageenan. It can be classified as iota (ι), kappa (κ), or lambda (λ) among the three most common depending on the configuration and sulfate content. The degree of these structural differences explains several functional properties, including solubility, gel formation, and molecular weight [5-7]. Cultivating seaweed genera Kappaphycus and Eucheuma has made Malaysia, especially the Sabah region, one of the largest carrageenan producers worldwide. As such, some areas within Semporna, Tawau, Lahad Datu, and Kunak are designated for cultivating these seaweeds due to their rich yield in carried geyser concentration [8-11]. This polysaccharide is commonly used in a variety of food products as a thickener and stabilizer and as an emulsifying agent. It is also widely used in the production of ice cream, sauces, and processed meat to improve the texture and stability of the products. This substance is safe for consumption and is used as a food additive under the code E407[16].
A lot of attention has been focused on the use of carrageenan in food packaging films made of biopolymers, in addition to its use in food. This feature makes carrageenan act as an eco-friendly alternative to manufactured polymers. These biopolymers decompose as a result of microbial activity

or environmental factors like sunshine, which makes them appropriate for eco-friendly packaging solutions [11–13]. These biopolymers include coffin-carrying packaging films, which are highly desirable due to their robustness, resistance to heat and UV light, and capacity to keep their fresh contents dry. Additionally, they make excellent gas barrier materials. Carrageenan has also been utilized to build films and is biodegradable, which makes it excellent for the manufacture of ozone-friendly packing materials. This is due to the growing environmental challenges. Carrageenan has a wide range of uses in the biomedical sector [12,14,15]. Because of its capacity to produce hydrogels, it can therefore be applied to tissue engineering, medication delivery, and wound healing. Because carrageenan is biocompatible, it can be used in medicine to manufacture biodegradable wound dressings that prevent healing moisture from escaping. Carrageenan is also more tempting for medicinal uses because its antiviral, antibacterial, anticoagulant, and immunomodulatory qualities have all been demonstrated [17–19].

Carrageenan-based hydrogels and composites are also being developed for use in environmental clean-ups, especially, in sewage treatment where dye and heavy metal contaminants are removed. The consideration of the material as one of the effective measures to reduce the degradation of the environment stems from its ability to capture and retain pollutants within itself [20]. Carrageenan is commonly found in cosmeceutical products, as it provides additional moisture while also thickening the texture. Among them, one can find creams, lotions, and gels. At the same time, one of the important characteristics of carrageenan is its multifunctionality, which makes it in demand in many industries: the ability to form gels, biocompatibility, and biodegradability [21]. The opportunities for research and application of carrageenan are developing in step with the emerging, growing seaweed biorefinery industry which enhances its importance in the global economy. Furthermore, it could be applicable regardless of the use – food packaging, biomedicine, environmental applications, or cosmetics – carrageenan remains one of the versatile and green biopolymers that will still be relevant for many industrial and ecological advancements [22,23].

Carrageenan

Hydrocolloids, in particular, agar, carrageenan, and alginate possess gelling properties and are therefore regarded as one of the main components in the preparation of food and medicinal products as well as in biotechnological processes and applications [24]. In addition, distinct chemical structures and characteristics are known to be possessed by collagen types derived from seaweeds that are economically significant, including carrageenan types. Carrageenan from red seaweed extracts is obtained in an eco-friendly and safe manner. Carrageenan finds widespread usage in both food and non-edible applications. The benefits of anti-microbial [25], anti-oxidant [19], and photoprotective [26] agents that are promoted in the cosmetics industry are somewhat to blame for this. This is because carrageenan's thickening and film-forming properties have made it a popular ingredient in cosmetic products for a long time. The specialists in the field have investigated the application of carrageenan on the human body and they found it fit for human consumption. Carrageenans are categorized into six different types kappa (κ), iota (ι), lambda (λ), mu (μ), nu (υ), and theta (Θ). The primary carrageenans are kappa (κ), iota (ι), and lambda (λ). Carrageenan is a type of polymer that contains sulfated galactan that is composed of D-galactose units which are of 1,3-linked β-D-galactose and 1,4-linked α-D-galactose [28].

Kappa carrageenan

Kappa-carrageenan contains alternating 1,3-linked galactosyl 4-sulfate and 1,4-linked 3,6-anhydro-D-galactose residues. The flora of red algae, Kappaphycus alvarezii is greedy in polysaccharides which are economically quite important. For this reason of its structure or its gelling agent nature, its special features have been valuable to many industries, more so the food and cosmetic industries [29]. Owing to the reasons above, kappa-carrageenan is very suitable for gelling, thickening, and even stabilizing functions due to its great water retention, and mechanical and biological properties. It would be these qualities that contribute to its widespread use for many kinds of items. Potassium chloride is in most cases incorporated during the extraction stage to precipitate the substance. This method encourages the formation of a rigid gel, because potassium chloride may induce the helical structures [29]. Kappa-carrageenan has been shown to produce a stronger gel in potassium chloride than in sodium chloride. The concentration of cations is a key factor in the gelling mechanism since a higher content of cations will increase the stability of the gel and facilitate the aggregation of the helices. This is due to the presence of cations which produce helices and junction zones as a result of polysaccharide chain aggregation [32].

Iota carrageenan

Iota carrageenan in many respects related to kappa carrageenan as elucidated because they have nearly similar structures. They are both linear polysaccharides with helical configuration. Iota carrageenan has a sulfate content that is in between that of kappa and lambda carrageenans, with two sulfate groups for every two galactose units [29]. Iota carrageenan reversibly swells into a soft, elastic gel in aqueous solutions containing calcium ions, the gel strength is sought to be manipulated with the help of ionic concentration of the environment. Such a solution may transform into a gel by introducing additional salt, but there is a definite yield point at which the gel is more unyielding than ever since the gel-forming point increases with the salt concentration [6]. Iota carrageenan also stays away from hydrating whenever salt is present even in room-temperature water. Iota and kappa carrageenan vary in their ability to form a gel, most importantly relating to the freeze-thaw cycles. In a case study, iota carrageenan gels showed the least tendency towards syneresis (or liquid ejection) and degradation even after several freeze-thaw cycles. A wide range of applications becomes more possible owing to these additional characteristics [30].

Lambda Carrageenan

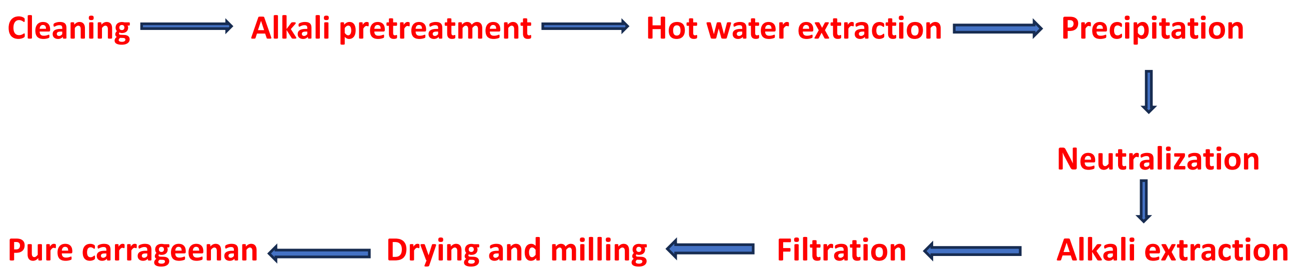
In lambda carrageenan, there are three sulfate groups for every two galactose units in the polymer with a flat structure. And unlike iota or kappa, lambda-carrageenan does not form helices, and consequently, does not form gels. Instead, due to its inadequate gelling properties, it is classified as a non-gelling polysaccharide [29]. It is also known as a thickening polysaccharide and is used as such. One of the most important factors for lambda carrageenan is the lack of requirement of any ions for viscous solution formation. This sets it apart from kappa and iota carrageenan, the gelation of which is driven by potassium and calcium ions, respectively [30]. Mechanical processing of normally plain and less viscosity solutions of lambda carrageenan renders them to be volumetric, pseudoplastic shear-thinning fluids. This feature is extraordinarily useful in food preparation as stirring makes the system less viscous. Lambda carrageenan is often used as a thickening component in products like dairy, where it helps to a creamy mouthfeel, due to its shear-thinning action [31,32].

Extraction of carrageenan

Hot alkaline extraction has long been the preferred method of carrageenan extraction followed by the more recent development of microwave-assisted extraction among other techniques [33,34]. To begin with, the collected seaweeds are washed properly to get rid of dirt and salt completely. Following centrifugation of this suspension, the resulting liquor is cleaned with water and treated with either a non-alkaline solution or an alkaline solution. Following the extraction, KCl or alcohol (ethanol or methanol) was added to cause precipitation [34-37].

The non-alkaline methods suffer from the limitation of lower yield of kappa carrageenan and the inability to remove unwanted cellular components such as cellulose or metal ions (Potassium and sodium) that can sometimes get bound to the produced kappa carrageenan. The sulfate groups of the galactose units form bonds with potassium and sodium ions thereby producing salts of the forms Na_2SO_4 or K_2SO_4 in aqueous solutions and the alkaline treatment assists in the formation of anhydrous galactose polymer through the dehydration process [38-40]. This procedure is often utilized to improve the gel strength of commercially available CG solutions. Any unstable sulfate groups were converted into 3,6-anhydro-L-galactopyranose (3,6-AG) through an alkaline pre-treatment which improved the structure of the extracted material and improved the gelling and rheological characteristics of the kappa carrageenan [42]. A pictorial representation of the various sources and processes of kappa carrageenan extraction demonstrates the ease and efficiency of these extraction methods.

FLOW CHART FOR THE EXTRACTION OF KAPPA CARRAGEENAN [41]



APPLICATIONS OF CARRAGEENAN

Biomedical Applications

Polysaccharides are ideal for synthesizing hydrogels due to their advantages, including biological functions, biocompatibility, and biodegradability, making them suitable for biomedical applications like biosensors, tissue engineering, and drug delivery. They can also form antibacterial hydrogels that inhibit bacterial growth, enhancing their appeal in biotechnology and wound healing contexts [43].

Wound Healing

According to conventional definitions, a wound is a break in the skin's surface continuity brought on by trauma. It's not always easy to heal a wound, especially for people who are ill or have other conditions that limit their capacity to heal [43]. This instance raises a third issue for reconstructive medicine practitioners to be concerned about chronic wounds from trauma, illnesses, burns, or accidents are a public health concern with financial ramifications [44,45]. To reduce the likelihood of scarring, new and improved wound dressings are therefore required. These dressings must enable faster healing, quicker closure of wounds, and faster commencement of the healing process than what is currently achievable [46].

Hydrogels derived from biopolymers, such as carrageenan (CG) systems, are becoming more and more popular as viable options for wound healing due to their high biocompatibility, capacity to draw exudates from the wound while allowing oxygen to diffuse, and ability to maintain a moist environment conducive to cell growth [46-48]. These CG hydrogels can also be used to transport and shield wounds following the injection of bioactive substances like growth factors. Consider the CG GSE SNP hydrogel film, which is made of these two ingredients: carrageenan-based hydrogel film integrating chitosan CS, sulfur nanoparticles SNP, and grapefruit seed extract GSE [47]. Its pattern outperforms the native CG films in terms of buoyancy, mechanical characteristics, and UV protection. This film is suitable as a wound-healing dressing due to its lower solubility, reduced water vapor transmission rate, and confirmed antibacterial action against Escherichia coli and Staphylococcus epidermidis [47, 48]. Excellent wound healing performance is demonstrated by this hydrogel film histological examination. In vivo investigations revealed complete regeneration of the epidermis. An important consideration in the treatment of non-healing wounds is diabetic wound infection. Using physically cross-linked CS hydrochloride, ¸κ-CG, and PVA, Sohail *et al*. created a burn wound healing hydrogel membrane [52,53]. The membrane was loaded with cefotaxime sodium, CTX, and was intended to treat diabetic patients. Solvent casting was used to create this membrane, which has been reported to have oxygen and water vapour permeabilities of 8.2 mg/ml and 20,000–25,000 g/m²/day, respectively. The hydrogel membranes demonstrated the beneficial characteristics of controlling drug release and promoting wound healing, improving the care of diabetic wounds [54]. Wound healing benefits from the use of carrageenan (CG), but because of these weaknesses, including unsatisfactory gelation ability, high rate of degradation, and low mechanical properties, it is not suitable as an effective wound dressing. To improve such properties, it is regularly combined with other materials such as polymers or pharmaceutical substances. In 2022, researchers reported the use of CG and polyethylene glycol (PEG) to produce thyme oil-loaded hydrogel membranes that shield wounds from infections while retaining moisture for speedier recovery [49].

A pH-sensitive wound dressing with κ-carrageenan (κ-CG) hydrogel membranes containing in situ prepared silver nanoparticles (Ag NPs) has been fabricated, with κ-CG working as a reducing and stabilizing agent. This hydrogel maintains excellent antimicrobial and scalable properties which provide it with full potential for utilization in wound healing therapies, and reconstruction of Ag release [50]. Another study created a thermo-reversible injectable biopolymer based on hyaluronic acid that can be used in controlled release systems and injectable foam formulations to efficiently distribute medicinal ingredients. Because of the complementary contributions of κ-CG and CS molecules to cross-linked polymeric structures, self-assembled hydrogels demonstrated enhanced mechanical characteristics. These films demonstrated favorable mechanical strength, biocompatibility with mouse fibroblasts, and anti-adhesion characteristics, indicating their possible application in full-thickness wound surgery and treatment [51].

Drug delivery

The κ form of carrageenan (κ-CG) has garnered increased interest as a possible drug carrier in recent times due to its favorable characteristics such as non-toxicity, biodegradability, biocompatibility, thermoreversible gelation, and effective drug loading [52,53]. The structural uniqueness offered by the sulfate and hydroxyl functional groups in CG can be enhanced by the addition of additional polymers in drug delivery systems. Gelatinous thermoplastic CG (photo crosslinked cellulose-gelatin composite hydrogel) in three dimensions and with a high moisture content are useful for maintaining moisture at the wound bed, which will promote healing. The body of research on κ-CG-based sustained-release medication formulations is extensive, which highlights its value in the pharmaceutical industry [54,55]. Recently, there has been a movement toward the use of CG-based hydrogels for drug delivery applications. Stimulus-responsive hydrogels have been created utilizing a variety of materials, including collagen, natural polysaccharides, and synthetic polymers. These systems serve two therapeutic purposes by allowing for the regulated release of one medicine and the inclusion of multiple drugs. For example, allopurinol, a medication prescribed to treat gout and uric acid stones because it lowers uric acid levels in circulation, was delivered using a pH-responsive hydrogel composed of fish scale collagen and CG. Synthetic anionic CG and collagen formed ionic and hydrogen bonds, which enhanced the hydrogel's mechanical strength, pH, stability, and biocompatibility [56]. Adenosine (AD), a vasodilator and antiarrhythmic medication, is similarly well-liked by drug delivery systems based on CG. Vaid and Jindal reported that the hydrogel that was created using κ-CG and tamarind kernel powder crosslinked with epichlorohydrin (ECH) was less harmful and more effective. Within the designed system, this hydrogel technology demonstrated an enhanced in vitro drug release at 37°C [57]. In a different study, they were included using pH-sensitive hydrogels of κ-CG, guar gum, and polyvinyl alcohol (PVA) with silane-based crosslinking with the uppermost layer. Cephradine, an antibiotic, was administered using the system, which allowed for a regulated release of up to 85.5% in 120 minutes. One polymer that was frequently used in CG-based hydrogels meant for distribution systems was PVA [58]. An injectable thermoresponsive-based κ-CG based hydrogel with cephradine included was introduced by Rasool *et al.* It was crosslinked using a synthetic polymer/silane APTES. Due to the ionization of CG's sulfate groups, this hydrogel's implanted pH was pH-sensitive. Still, it swelled, raising osmotic pressure and improving drug release efficiency at higher pH levels. Since the drug was administered more than 7.5 hours ago, it is possible that this biocompatible substance, which takes the shape of a hydrogel, will function as a bio container for injectable drug delivery systems [59].

Searching for cutting-edge tactics like "cocktail therapy" and dual-drug delivery systems has become required due to the drawbacks of single-drug therapies (large doses, potential drug resistance, etc.). These systems are designed to treat certain diseases with low dosages and long-term release. For instance, when added to κ-CG/locust bean gum hydrogels, poly (hydroxybutyrate-co-hydroxy valerate) (PHBV) microparticles exhibit dual responsive behaviour and distribute hydrophobic medicines ketoprofen and mupirocin synergistically. Seven days after treatment, a high degree of drug release with a sustained 37 ◦ C was attained, indicating that this dual drug administration will be useful for wound healing [60]. In addition, in another investigation, scientists created biocompatible Fe_3O_4 nanoparticles that were soaked in poly (N-isopropyl acrylamide) hydrogels that were cross-linked with chitosan (CS) to allow for the prolonged release of the anticancer medication methotrexate. The pH determines how much the hydrogel swells, with an alkaline medium releasing the most medication. The hydrogel's enhanced drug loading capacity enhanced thermal stability, and the inclusion of magnetic characteristics imply that it has the potential for use as an effective anticancer drug carrier. Carrageenan hydrogels have also been created in a method that allows for the gradual, controlled release of antibiotics [61]. When abstaining from using any confining, Mahdavinia *et al.* developed a regulated medication delivery system based on κ-CG/chitosan/hydroxyapatite nanocomposite calcium. The hydrogel matrix that resulted from the cross-linking of amine groups in CS with sulfate groups in κ-CG promoted the slow release of 66% of the medication that was encapsulated, as opposed to the rapid release that was linked to the CS/κCG complex alone. The discovery of montmorillonite (MMT), which contains pH and magnetically-sensitive kappa-carrageenan/chitosan hydrogels for the regulated release of sunitinib to eliminate malignant tissues, is another advancement. This hydrogel system exhibited very prolonged drug release kinetics because of the electrostatic forces between the anionic polymer and the cationic drug which makes this hydrogel system very suitable for targeting cancers [62].

Tissue Engineering

There is an ever-growing demand for healthcare services, and this fuels the push to discover solutions that are challenging old ways of thinking in biomedical applications. At present, there is an important multidisciplinary line of research in biomaterials that brings together many experts from different areas such as the aforementioned surgeons, cardiologists and radiologists, chemists, biologists, and pharmacists; as engineers and physicists [63]. Given that material-biological interactions frequently lead to implanted devices with limited durability resulting in suboptimal long-term performance or need for revision surgeries and possibly infection, an understanding of the effects of materials on living tissue is essential. Central to tissue engineering is the ability to regenerate functional tissue by producing an artificial replacement that can be integrated within a patient. This objective is only enabled by the bioprinting of tendons using a properly engineered scaffold that mimics native environments and with proper response mechanisms, including viable cell sources and biochemical stimuli conducive to cellular adhesion, differentiation, and proliferation. The design of such scaffolds relies heavily on what is known about the properties and functions of the extracellular matrix (ECM), which supports cell growth and influences tissue formation [63,64].

For instance, the native bone ECM gives a 3D porous network consisting of both organic and inorganic materials that support cell behaviours [65,66]. The organic component is predominantly composed of collagen and numerous non-collagenous proteins, together with the group of sulfated glycosaminoglycans; in contrast, the inorganic phase consists primarily of carbonated hydroxyapatite, which provides bone with much of its structural complexity and superior mechanical properties. The design of scaffolds for tissue engineering must consider 3 aspects: (1) physical properties, such as mechanics and morphology; (2) biological factors, such as cells and growth factors; and (3) chemical features, typically the material composition and cross-linking. Together, these factors collectively impact the performance of scaffolds and their bioactivity towards tissue regeneration [65,67].

Bone injuries, mainly in the elderly and associated with different orthopaedic diseases or related to hormonal imbalances, diabetes mellitus, or surgical interventions are a common clinical concern since they cause tissue loss and impair bone's inherent ability to heal. This type of physical impairment, a common issue among the elderly is now considered as the second most common cause of disability at the global level, orthopaedic conditions and diseases. In the present era, the current modalities of treatments are prosthetic implants, allografts, and autografts which lack long-term efficacy along with their complications [63,65]. Accordingly, this area is still a critical focus for current research efforts in the field. Natural bone scaffolds are tough due to the presence of organic materials and are stiff due to the presence of inorganic materials thus, two types of materials work together to form strong structures. The artificial development of tissues requires several ingredients, including proteins, polysaccharides, carbon nanotubes as organic matter, and calcium oxide and hydroxyapatite (HAP) as inorganic matter. In addition, a scaffold ought to have a highly porous structure that is linked to allow waste, nutrients, and oxygen to be exchanged. Biological hydrogels have gained a lot of traction recently in the fields of human tissue replacement and regeneration. In bone, nerve, and heart tissue scaffolds, it has been demonstrated that specific hydrogel networks are more advantageous than surrounding hydrogel [65,67,68].

According to recent studies, natural sulfated polysaccharide-based scaffolds, such as carrageenan, are very interesting options in a variety of tissue engineering domains because they mimic the properties of extracellular matrix, can hold onto growth factors, and have a porous shape. Furthermore, carrageenan's sulfate function groups enhance the transport and activity of ins proteins while providing functionalization for calcium phosphate minerals [63,69,70]. For example, it has been discovered that κ-carrageenan (κ-CG) improves the biocompatibility and compressive strength of collagen-hydroxyapatite (COL-HAP) composites, which are useful for bone regeneration. Carrageenan's mechanical, physical, and physiological qualities will be enhanced by adding more polymeric materials and inorganic fillers, like calcium silicate, which will boost the material's bioactivity and mechanical qualities [71].

Ternary systems based on gum Arabic, kappa-carrageenan, and nano-hydroxyapatite have demonstrated good mechanical performance and apatite formation in simulated body fluid in recent breakthroughs in scaffold fabrication. These systems are ideal candidates for application in bone tissue creation because they have some degree of advantageous antibacterial property, protein absorption capability, and biodegradability [72]. Carrageenan is suitable as an injectable hydrogel for tissue regeneration because of its thixotropic qualities and gelling behavior at physiological temperatures. Research has demonstrated that the incorporation of gold nanoparticles (Au NPs) into hydrogels based on κ-carrageenan and gelatin enhances their electrical conductivity, cell proliferation, and attachment, particularly in the context of bone tissue engineering [73].

κ-CG/methacrylate (MA) hydrogels are an additional innovation that has a composition that improves various mechanical characteristics, keeps its lower value when subjected to degradation, and raises the adhesion level. In addition to being tissue-appropriate and light-activated, these hydrogels promote the healing of soft tissues and skin [74]. Furthermore, they created double-network (DN) hydrogels with κ-CG and polyacrylamide (PAM), which have shown to have highly beneficial mechanical qualities, the capacity to heal on their own, and biocompatibility—possibly finding utility in the creation of artificial cartilage, diaphragms, and tendons. Among these are the microwave-synthesized methacrylated κ-CG hydrogels (Mw-κCG-MA), which have a higher resistance to degradation and are better suited for three-dimensional bioprinting. They also enhance cell viability and promote chondrogenesis, which is very helpful in the regeneration of cartilage tissue [75].

Application in food packaging

Carrageenan is a naturally occurring polysaccharide that possesses several therapeutic properties including anti-inflammatory, antitumor, anti-hyperlipidaemic, and anticoagulant properties. In addition, it has a potential for strong antioxidative free radical scavenging activity. Its functional properties of thickening, emulsification, stabilization, and gelling make it favourable in the food industry for applications like use as stabilizer in dairy products and binders in meat processing [76,77]. In addition, carrageenan can be used as an oxygen barrier in meat and meat products, pet food, baby food, and beverages. While food applications are dominant, carrageenan can be found in non-food applications such as fire extinguishing foam, shoe polish, air conditioner cleaning agents, etc. As well, due to its viscoelasticity and strength, it can make a good candidate as a tablet excipient for sustained-release formulations [78-80].

Packaging material compositions such as bio-nanocomposite film based on carrageenan have been reported to possess better properties than those of single-use polymers [81]. For example, covalent incorporation of CuS to films made of carrageenan dramatically improves tensile strength, thermal stability, and light-blocking ability, whereas carrageenan/agar/ TiO_2 films exhibit enhanced tensile strength and water barrier properties at certain concentrations of nano- TiO_2 [82,83]. The addition of silicon dioxide could improve the mechanical performance of the composite films without compromising clarity. Furthermore, the carrageenan/melanin nanoparticle-containing films possessed adjustable photonic features as adding more melanin decreased the tensile ability [85]. Carrageenan has emerged as a biomaterial for pharmaceutical and packaging use in bio-nanocomposites in the past two decades due to its multifunctional properties. Metal oxides like titanium dioxide (TiO_2) have also been added to biopolymer films to improve their functional properties such as anti-microbial and anti-radiation activities [86]. The TiO_2, which is widely used as a food enhancer & colorant, is safe, economically viable, and photostable within a certain dose that has been prescribed [87]. For the last few decades, this particular additive, TiO_2, has also been reported to enhance the tensile characteristics of the biopolymer film compositions while concurrently lowering the transmittance of light in the visible, UVA, and UVB regions. Apart from that, when treated with UV light, TiO_2 nanoparticles can degrade organic substances such as ozone and therefore are useful in preventing the oxidation of foods packed in packages that are exposed to light [88]. Other studies have also added TiO_2 nanoparticles into AG/CA nanocomposite films using a thermal casting method with incorporated materials that contain varying amounts of TiO_2 (0.5 to 2 grams in 100 grams of the matrix), which has the potential to improve packaging applications [84].

The halloysite nanotubes, commonly referred to as HNTs, are multi-walled alumino-silicate nanotubes that have been used more recently as reinforcing fillers in nanocomposite films owing to their thermal and mechanical stability [89,90]. One way in which their efficiency can be increased is by surface modifications or by including antibacterial constituents on their inner lumen. They contain small silver nanoparticles (AgNPs) that have excellent antibacterial properties due to the properties of silver. HNT-AgNP nanoparticles incorporated in the films improved the UV-barrier properties and the mechanical properties of the films when chemically synthesized nanoparticles were added to them as fillers and also imparted potent antibacterial activity against the food crash pathogens E. coli and L. monocytogenes [91]. It is also reported that these nanocomposites can be further improved using ionic surfactants such as sodium dodecyl sulfate (SDS) which improve the distribution of these nanoparticles in the carrageenan matrix and consequently its mechanical strength, clarity, and anti-microbial activity of the nanocomposite films [91]. Novel improvement by incorporating antibacterial nanoparticles like CuO, Ag, ZnO, and TiO_2 leads to the production of bio nanocomposite films that provide certain key functional properties such as thermal stability, mechanical stability, and antibacterial properties [92-96]. Testing of these nanocomposite films in an antibacterial test for 10 h where profound bactericidal activity was exhibited, many tested however failed to exhibit good antibacterial properties against the Gram-Positive bacteria. Some layers applied the Li et al. [97] used NIR (Near-infrared irradiation) with the rationale to provoke a photo-thermal effect that enhanced further the bacterial activity towards the CG /CuS film against various food samples. The CG/CuS film on the other hand is more transparent but has less mechanical strength and thermal resistance as opposed to the CG/CuS film [97].

Bentonite is a clay that consists largely of montmorillonite and comprises two silicate tetrahedral sheets with an octahedral sheet sandwiched in between, interlayered with exchangeable cations. Because of its plate-like structure, bentonite has good sorption and swelling properties. Despite this relative impurity because of the incorporation of other clay and non-clay minerals, montmorillonite which is the main unit of this rock can find many uses. Dogaru *et al.* have studied the preparation of nanocomposite films based on κ-carrageenan and bentonite nano clay [98]. These films were expected to be different for moisture reduction, decreased swelling, and moisture sorption capacity, and therefore, have been designed for moisture-sensitive applications. Out of all man-made nanomaterials, silica is probably the most widely used in several industries, such as food additives, anti-foaming agents, adhesives, coatings, and polymers due to its ability to act as barrier properties against moisture and oxygen. In the U.S. FDA regulation on food, it has been stipulated that silica may be incorporated into a product not exceeding 2% by weight. However, the Use of such materials in food for export to the EU is restricted to only E551 anti-caking agent, permitted to a level of 5% by the UK Food Standards Agency [99]. Similar works by Aji *et al* have worked on the development of bio-composite films derived from bio-nanocomposite films from semi-refined iota carrageenan and Silica (SiO_2) which had improved mechanical and optical properties. Incorporation of SiO_2 in κ-carrageenan films consequently enhanced the tensile properties, and reduced water solubility and moisture absorption of the films without impacting film thickness [100].

Application in cosmetics

Carrageenan is a natural polysaccharide that finds application in the cosmetic industry due to its properties of thickening, gelling, and moisturizing among others. It has been studied and incorporated into other products like toothbrushes, twist-on tops of sunscreens, and many more with the claimed benefits of improved texture and performance. Such includes Maddukuri *et al.* [101] who designed an anti-acne gel composed of carrageenan, niacinamide, and calendula oil where carrageenan was the gelling agent and tested for antimicrobial activity where pathogenic bacteria causing acne were the target. There was more than one supporting evidence that enhanced the performance of the gel including carrageenan gelling retention capabilities and its adverse effect on tissue disorders. Wahyuni *et al.* [102] on the other hand incorporated activated carrageenan from Eucheuma in soap making and claimed it had moisturizing effects. This study showed that carrageenan use induces the skin while the soaps are moist, avoiding the disadvantages of propylene glycol. Carrageenan serves largely the role of a stabilizer and a gelling agent in toothpaste compositions such that it enhances the product composition and prevents the products from becoming lumpy under different temperature conditions. Joshi *et al.* [103] during their investigations on the addition of 2%g carrageenan in toothpaste found out that the proper gelling structure and viscosity which ensures constancy and improved physiological attributes of the oral care products were obtained.

To enhance and thicken the emulsion suspension in sunscreens, Carrageenan has also been used as demonstrated in the work undertaken by Purwaningsih *et al*. [104] where in combination with black mangrove fruit Ekstrak, Kappaphycus alvarezii – derived carrageenan as an emulsifier enhanced emulsion water resistance. In terms of the percentage of the active agent, at a concentration of 0.5%, carrageenan did not adversely affect moisture content, while the humectant properties assured moisture retention and binding in the final formulation. Moreover, in hair care shampoos it is possible to demonstrate that carrageenan has thickening as a beneficial property useful for enhancing viscosity and expanding the usability of the products. In one study conducted by Zięba *et al*. [105] it has been proven that carrageenan is superior to many other natural polymers in terms of viscosity, which is an important feature affecting the efficiency of the product at low shear rate conditions suitable for shampoo formulations. Carrageenan in cosmetics is not limited to gelling and thickening, this ingredient expands the horizons for the development of moisture and stability retaining green cosmetics. Furthermore, as it is not only motion pictures with natural products or with synthetic products, it is more useful that it can be put into skin care, hair care, and oral care products, which makes a better solution in the cosmetic field**.**

Environmental Application

The significance of human-caused environmental pollution, particularly water pollution, has grown in recent years, necessitating a key focus on the removal of pollutants like dyes and drug residues. Hydrogels have been used as adsorbents because they are very effective at removing contaminants from water. They are biocompatible and non-toxic polysaccharides that have shown excellent performance as adsorbents for environmental cleanup [106-108]. Because polyacrylate contains non-sulfate-carrying supporting groups, its salt sensitivity has been reduced, which facilitates the production of adsorbents for a variety of pollutants [109]. It is now simpler to remove the contaminant from water thanks to the development of CG and nano modifications such as carbon nanotubes, graphene oxide (GO), and metal-organic frameworks [110]. Duman et al. created agar/ κ- CG hydrogel composite material that is employed for the removal of methylene blue (MB) dye from the solution and adjusted contact time, pH, and temperature conditions, for 37 ° C and pH 7 obtaining a maximum adsorption of 242.3 mg/g [111]. Similarly, the κ-CG grafted polyacrylic acid and TiO_2 nanocomposite hydrogels showed a broad range of malachite green adsorption capabilities, from 666 to 833 mg/g [112].

The usage of CG-based hydrogels has also extended towards heavy metal sequestration. For instance, the nanocrystalline cellulose/sodium alginate/κ-CG composite hydrogel has demonstrated the highest Pb (II) ion sorption capacity of 351 04mg/g with adsorption of Lead after five cycles of recycles [113]. Moreover, graphene oxide and CG-based aerogels have been able to remove MB dye which shows that the material is good for the removal of cationic pollutants [114]. In the studies related to drug contamination, CG-based hydrogels have been used for removing drugs such as ciprofloxacin hydrochloride (CIP). It was also found that the adsorption pH affected the interaction with the polymers, where electrostatic interactions were dominant at low pH values [115]. Drug adsorption studies using magnetic carrageenan nanocomposites have also been performed and showed excellent recoveries and removals of contaminants such as CIP [116]. Last but not least, CG-based hydrogels have also been applied to remove bacteria and endotoxins from the system. In particular, CS-κCG hydrogels could elicit enhanced anticoagulation effects and clear out 63 3% of endotoxins and a large quantity of E. coli and S. Aureus bacteria during hemoperfusion procedures [117]. These examples highlight the growing importance of CG-based hydrogels in environmental cleanup, from dye and drug adsorption to removing heavy metals and bacterial contaminants, illustrating their broad potential for sustainable water treatment solutions.

Conclusion

Carrageenan (CG) is a natural polysaccharide widely used in various fields due to its versatility. It serves as a stabilizer, thickener, drug delivery agent, and matrix for thin film preparation in the food industry and packaging materials. CG also has a high adsorption capacity, making it useful for environmental pollutant removal. While CG lacks inherent antibacterial properties, incorporating metal nanoparticles enhances its antimicrobial capabilities, making it ideal for antibacterial coatings in food packaging. CG hydrogels are widely applied in biomedical fields, such as tissue engineering, wound healing, and drug delivery. Researchers are exploring new formulations, including composites with natural and synthetic polymers, but scaling up production remains a challenge. CG-based hydrogels have shown potential for environmental cleanup beyond water pollution, such as in soil and air remediation. CG's thermoresponsive hydrogels are under research for drug delivery systems. In cosmetics, CG has antioxidant and anti-photoaging properties, offering eco-friendly alternatives to chemical ingredients. Future research will focus on enhancing CG's mechanical properties and broadening its use in packaging, biomedical applications, and other innovative fields like biosensors and solar cells.

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