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Red Seaweed Carrageenan: A Comprehensive Review of Preparation in Cosmetics - An In Depth Analysis

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ABSTRACT

Carrageenan, an extract from red seaweed *(Rhodophyta*), has many uses in cosmetics, and this literature review delves into them all. Due to its superior gelling, thickening, and stabilizing properties, carrageenan, a polysaccharide with a wide range of chemical structures, has been utilized in various industries throughout history. In recent years, the cosmetics industry has shown growing interest in harnessing the potential of carrageenan, driven by the increasing demand for natural and sustainable ingredients. This review provides a comprehensive examination of the botanical background, types of carrageenan, and the most effective extraction methods for obtaining the key bioactive compounds that enhance its functionality in cosmetic formulations. The functional properties of carrageenan in cosmetics are discussed in depth, including its gelling and thickening capabilities, moisturizing effects, and stability enhancement. Additionally, its biological activities, such as antioxidant and anti-inflammatory properties, contribute to its appeal as a valuable ingredient in skincare products. Formulation considerations, including compatibility with a wide range of cosmetic ingredients and optimal concentrations, are explored to facilitate the development of effective products. The review also addresses the incorporation of carrageenan into cosmetic formulations, along with safety and regulatory aspects, ensuring a comprehensive understanding of the product's conformity with industry standards. In conclusion, the review provides an overview of current challenges, potential future research directions, and case studies showcasing the incorporation of carrageenan into cosmetic products. This review aims to serve as a valuable resource for researchers, formulators, and industry professionals interested in the innovative use of carrageenan in the evolving landscape of cosmetic science by synthesizing existing knowledge and identifying gaps in the current scientific literature.

Keywords: Carrageenan, cosmetic, red seaweed (*Rhodophyta*)

INTRODUCTION

Cosmetics, encompassing a wide variety of personal care products, constitute an essential aspect of daily grooming routines and play a crucial role in enhancing and maintaining the aesthetic appeal of the human body (Kalasariya *et al*., 2021). These products are currently undergoing a transformative shift, driven by an increasing emphasis on sustainability and consumer demand for natural alternatives (Ferreira *et al*., 2022). In addition to their role in facilitating self-expression and boosting confidence, cosmetics are also leading the way in this development.

The cosmetics industry is experiencing a surge in the utilization of bioactive compounds derived from natural sources, reflecting a broader societal trend towards environmentally friendly products (Prajaputra *et al*.,2024). Customers are becoming increasingly conscious of the environmental impact of their choices, thus seeking products aligned with their ethical principles (Khalil *et al.*, 2017). This trend is exemplified by the adoption of ingredients such as carrageenan from red seaweed (Batista *et al.*, 2020), underscoring the industry's commitment to offering aesthetically pleasing options that are both environmentally friendly and sustainable (Shi *et al.*, 2020), catering to individual well-being and ecological responsibility alike.

Carrageenan is a sulfated polysaccharide derived from various species of red seaweed (Shi *et al*., 2020). It is highly sought after in the cosmetic industry due to its excellent gelling and thickening properties (Tarman *et al*., 2020). The extraction process involves a series of meticulous steps, beginning with the collection of red seaweed, typically found in large quantities in coastal regions worldwide (Pessarrodona *et al*., 2020). Before undergoing extraction, this natural resource is meticulously cleaned and dried. The extraction process typically involves alkaline treatment or other specialized methods (Firdayanti *et al*., 2023).

Due to the abundance of red seaweed in coastal areas, carrageenan extraction is a sustainable practice that requires minimal land use and freshwater resources compared to the extraction of plant-based ingredients from terrestrial sources (Bukhari *et al*., 2023). Given the growing demand for sustainable sourcing in the cosmetics industry, carrageenan aligns well with this trend (Gerber *et al*., 1958).

Furthermore, carrageenan's appeal stems from its natural derivation and high biocompatibility, making it an ideal candidate for the production of clean and environmentally friendly beauty products sought by conscientious consumers (Hamasuna *et al*., 1994) Its versatility extends beyond gelling and thickening; carrageenan also moisturizes and conditions the skin, enhancing its desirability for use in various cosmetic formulations (He *et al*., 2019), including haircare (Ismail *et al*., 2020), skincare (Janowicz *et al*., 2023), and other personal care products (Jiménez-Escrig *et al*., 2013).

The significance of incorporating natural ingredients into cosmetic formulations cannot be emphasized enough (Jing *et al*., 2021). With a rising consumer demand for products free from synthetic additives, chemicals, and potential irritants (Ju *et al*., 2023), the allure of natural ingredients extends beyond environmental concerns (Khoobbakht *et al*., 2024). They offer unique advantages for skin health and product efficacy (Pangestuti *et al*., 2021). In this landscape, carrageenan emerges as a standout ingredient, sourced from botanical origins and boasting a versatile array of functionalities (Gerber *et al*., 1958). It presents an enticing option for formulators seeking to align with current beauty industry trends and values.

The aim of this review is to extensively examine the utilization of carrageenan extract from red seaweed in cosmetic production. By delving into extraction methods, functional properties, biological activities, formulation considerations, safety aspects, and regulatory implications associated with carrageenan, move forward to deepen understanding of its potential in the cosmetics industry. Through this investigation, the review endeavors to furnish researchers, formulators, and industry professionals with valuable insights to navigate the convergence of natural ingredients and cosmetic science more effectively.

Chemical Composition of Seaweed

Based on the research conducted by Ghada and Armany on the chemical composition of seaweed from the Mediterranean Sea coast in Egypt, chemical analyses have been carried out to identify the elements present in various types of red seaweed sourced from different sampling locations along the Mediterranean Sea (El-said *et al*., 2013).

The study likely involved collecting samples of red seaweed from multiple locations along the Egyptian coast of the Mediterranean Sea (El-said *et al*., 2013; Lim *et al*., 2021). These samples would have been subjected to various chemical analyses to determine their elemental composition. Analytical techniques such as atomic absorption spectroscopy (AAS), inductively coupled plasma mass spectrometry (ICP-MS), or X-ray fluorescence spectroscopy (XRF) may have been employed to quantify the concentration of elements present in the seaweed samples (Lim *et al*., 2021).

The chemical composition analysis would have provided valuable insights into the elemental content of the red seaweed (Montaser *et al*., 2021; Mostafavi *et al*., 2020), including essential nutrients such as potassium, magnesium, calcium, and trace elements like iodine, selenium, and zinc as shown in Table 1. Additionally, the presence of potentially harmful elements or heavy metals may have been investigated to assess the seaweed's safety for consumption or utilization in various applications (Núñez-Santiago *et al*., 2011; Laokelis *et al*., 2022).

The research findings would contribute to our understanding of the nutritional value, environmental quality, and potential industrial applications of red seaweed from the Mediterranean Sea coast in Egypt (El-said *et al*., 2013). They could also inform future studies on seaweed utilization, marine biodiversity conservation, and sustainable resource management in coastal ecosystems.

Table 1. Distributions of selected elements and carbohydrate contents in different red seaweed species

Sample of red seaweed	Nutritional value for some seaweed (mg/g)					
	Ca	**Mg**	**Na**	**K**	**F**	**Carbohydrates**
Gracilaria compressa	3.33	1.73	29.08	4.46	40.97	116.23
Gracilaria verrucosa	0.94	0.29	22.80	8.17	113.12	111.46
Pterocladia capillacea	3.05	2.08	17.92	8.32	177.88	96.37
Hypnea musciformis	3.79	1.15	24.22	8.22	50.90	111.72

Based on the results of chemical analysis from the research, various critical elements present in seaweed contribute to its nutritional value, which varies depending on the type of seaweed and its growth conditions. Calcium, a vital mineral found in seaweed, plays a crucial role in promoting skeletal health and serves as a valuable dietary source (Al-Nahdi *et al*., 2019). It is essential for the development and maintenance of strong bones and teeth, with adequate consumption aiding in bone density and helping to prevent disorders such as osteoporosis, particularly among aging populations (Ningrum *et al*., 2021). Additionally, calcium is involved in various physiological functions, including muscular contraction, neuronal transmission, and blood coagulation (Otero *et al*., 2021).

Moving on to magnesium, another essential mineral found in seaweed, it serves as a cofactor for enzymes involved in the conversion of food into energy. Consumption of seaweed as a source of magnesium contributes to increased energy synthesis and utilization in cells, thereby aiding metabolic activities. Similar to calcium, magnesium is crucial for muscle and nerve function, assisting in muscle contraction and relaxation, which is integral for maintaining muscle health and preventing disorders such as muscle cramps (Hamzalıoğlu *et al*., 2016). Furthermore, magnesium has potential benefits for cardiovascular health, as it helps regulate blood pressure and maintain a regular heartbeat (Hong *et al*., 2021).

Sodium and potassium are also essential elements found in seaweed, playing roles in fluid balance, neuron function, and overall cellular health. Both sodium and potassium are important electrolytes involved in regulating water balance within and surrounding cells (Huang *et al*., 2022; Jönsson *et al*., 2023). Adequate intake of these components as part of a balanced diet contributes to optimal hydration levels, critical for cellular function, nutrient transport optimization, and waste disposal efficiency. Additionally, seaweed contains trace levels of fluorine, contributing to overall dietary fluorine consumption, which aids in the remineralization of dental enamel and helps maintain good oral hygiene (Kaur *et al*., 2022; Waseem *et al*., 2023).

Furthermore, seaweed has a high carbohydrate content compared to other elements, serving as a key source of energy. Polysaccharides found in seaweed, including agar and carrageenan in red seaweeds and ulvans in green seaweeds, offer sustained energy release, enhancing metabolic activity and overall vitality (Wells *et al*., 2016). Additionally, seaweed carbohydrates, particularly dietary fiber, promote intestinal health by promoting regular bowel movements, preventing constipation, and maintaining a healthy gut microbiota (Wijesinghe *et al*., 2019). Due to its complex composition, seaweed carbohydrates may also help manage blood sugar levels by allowing for a more gradual release of glucose into the system (Xu *et al*., 2023).

Optimized Methods for Extracting Carrageenan

Carrageenan is a polysaccharide extracted from red seaweed (Rhodophyta) and is widely used in various industries, including food, pharmaceuticals, cosmetics, and biotechnology, due to its gelling, thickening, and stabilizing properties (Al-Nahdi *et al*., 2019; Laokelis *et al*., 2022). There are several methods used to extract carrageenan from red seaweed, and these methods can vary based on factors such as the type of seaweed, extraction efficiency, and desired properties of the carrageenan (Ningrum *et al*., 2021). These methods can vary in terms of efficiency, yield, and the quality of carrageenan produced. Researchers often optimize these methods based on factors such as the type of seaweed, desired properties of carrageenan, and industrial scalability. Additionally, advancements in extraction technologies continue to improve efficiency and sustainability in carrageenan production (Xu *et al*., 2023).

The extraction process of carrageenan from red seaweed is meticulously executed, involving several crucial steps. Initially, seaweed is carefully harvested from coastal regions, with common species including Chondrus crispus or Eucheuma cottonii (Al-Nahdi *et al*., 2019). Following harvest, thorough cleaning is undertaken to eliminate contaminants such as sand and epiphytes. Subsequently, the seaweed may undergo pre-treatment, often involving immersion in an alkaline solution to soften cell walls for easier extraction (Liu *et al*., 2022). Careful drying follows to reduce moisture content, preparing the seaweed for the extraction phase (Entezari *et al*., 2022).

Based on Figure 1, during the extraction process, the dried seaweed undergoes an alkaline treatment, typically employing potassium hydroxide (KOH) (Ferdiansyah *et al*., 2023). This treatment dissolves the carrageenan previously present in the seaweed. Subsequently, carrageenan precipitation occurs by adding an acid, usually potassium chloride (KCl), causing the carrageenan to solidify and separate from the solution (Yuan & Song, 2005). Post-precipitation, the produced carrageenan undergoes washing to remove residual salts and impurities before being dried (Zaitseva *et al.*, 2022), yielding a purified carrageenan product ready for utilization across various industries, including cosmetics.

This extraction method is crucial to ensure the isolation of carrageenan in a form suitable for diverse applications, owing to its exceptional gelling and thickening properties as summary in Table 2.

Alkaline Extraction Method

This method involves treating the red seaweed with an alkaline solution, typically potassium hydroxide (KOH) or sodium hydroxide (NaOH), to solubilize the carrageenan. After alkaline treatment, the mixture is heated to facilitate carrageenan extraction. The carrageenan is then precipitated from the solution by adding an acid, such as hydrochloric acid (HCl) or sulfuric acid (H_2SO_4). The precipitated carrageenan is then washed and dried to obtain the final product (Loukelis *et al*., 2022)

Acid Extraction method

In this method, the red seaweed is treated with a dilute acid, such as hydrochloric acid (HCl) or sulfuric acid (H_2SO_4), to dissolve the carrageenan. The mixture is then heated to aid in the extraction process. Once the carrageenan is extracted, it is precipitated by adding a base, such as calcium carbonate ($CaCO_3$) or potassium carbonate (K_2CO_3), to neutralize the acid. The precipitated carrageenan is then washed and dried (Núñez-Santiago *et al*., 2011; Laokelis *et al*., 2022).

Hot Water Extraction Method

This method involves boiling the red seaweed in water to extract carrageenan. The mixture is then filtered to remove solid residues, and the filtrate containing carrageenan is concentrated by evaporation. Carrageenan is then precipitated by adding alcohol, such as isopropyl alcohol or ethanol, to the concentrated solution. The precipitated carrageenan is collected, washed, and dried (Liu *et al*., 2022; Entezari *et al*., 2022).

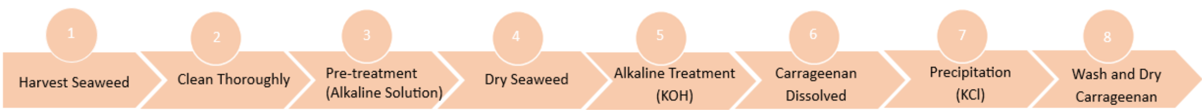

Figure 1. The eight (8) extraction process of carrageenan

Table 2. Summary of extraction carrageenan process from red seaweed

Extraction Method	Method steps	Reagent Related**	Industry Related	Applications [Ref.]
Alkaline	• Treatment with Alkaline Solution • Heating and Facilitation of Extraction • Precipitation with Acid • Washing and >Drying of Carrageenan	• Potassium hydroxide (KOH) or sodium hydroxide (NaOH) as alkaline solution • Hydrochloric acid (HCl) or sulfuric acid (H_2SO_4) as acid for precipitation	Food Industry: Carrageenan extracted via this method is commonly used as a stabilizer and thickening agent in dairy products like ice cream and chocolate milk. Pharmaceutical Industry: Utilized as a gelatinous substance in pharmaceutical formulations, including capsules and tablets.	Applied Phycology (Kaur *et al.*, 2022; Wells *et al*., 2016; Thiviya *et al*., 2022)
Acid	• Dissolution with Dilute Acid • Heating to Aid Extraction • Neutralization and Precipitation • Washing and Drying of Carrageenan	• Hydrochloric acid (HCl) or sulfuric acid (H_2SO_4) as acid for dissolution • Calcium carbonate ($CaCO_3$) or potassium carbonate (K_2CO_3) as base for precipitation	Biotechnology: Carrageenan extracted via this method finds applications in tissue engineering and drug delivery systems. Cosmetic Industry**:** Used as a thickening agent and stabilizer in lotions, creams, and shampoos.	Agricultural and Food Chemistry (Núñez-Santiago *et al*., 2011; Laokelis *et al*., 2022).
Hot Water	• Boiling and Extraction in Water • Filtration and Concentration • Precipitation with Alcohol • Washing and Drying of Carrageenan	• Water as solvent for extraction • Isopropyl alcohol or ethanol as alcohol for precipitation • Optionally, salt solutions (e.g., sodium chloride) for salting out	Biomedical Engineering: Carrageenan extracted via this method is utilized in the development of wound dressings and scaffolds for tissue regeneration. **Nutraceuticals:** Used as a dietary supplement due to its potential health benefits, including its role in promoting digestive health.	Marine Drugs (Tarman *et al*., 2020; Pangestuti *et al*., 2021; Pacheco-Quito *et al.*, 2020; El-Beltagi *et al*., 2022; López-Hortas *et al*., 2021; Peñalver *et al*., 2020; Wan-Loy *et al*., 2016)
Enzyme-Assisted	• Cell Wall Breakdown with Enzymes • Further Solubilization and Recovery • Precipitation and Processing • Washing and Drying of Carrageenan	• Specific enzymes such as cellulase or pectinase for cell wall degradation • Alkaline solution (e.g., KOH or NaOH) or acid solution (e.g., HCl or H_2SO_4) for further extraction	Biopharmaceuticals: Carrageenan extracted via this method is utilized in the formulation of controlled-release drug delivery systems. **Bioremediation:** Used in environmental applications for the removal of heavy metals from wastewater.	Biotechnology and Bioengineering (Tarman *et al*., 2020; Entezari *et al*., 2022; Kanlayavattanakul *et al*., 2015)
Microwave-Assisted	• Utilization of Microwave Irradiation • Enhanced Extraction Efficiency • Precipitation and Processing • Washing and Drying of Carrageenan	• Water or alkaline solution as solvent for extraction • Isopropyl alcohol or ethanol as alcohol for precipitation • Optionally, salt solutions (e.g., sodium chloride) for salting out	Food Packaging: Carrageenan extracted via this method is employed as a coating material for food packaging films to improve their mechanical and barrier properties. Agriculture: Utilized as a bio-stimulant in agriculture for enhancing plant growth and stress tolerance.	Chemical Technology and Biotechnology (Tarman *et al*., 2020; Entezari *et al*., 2022; Kanlayavattanakul *et al*., 2015)

** These reagents and chemicals play crucial roles in each extraction method, aiding in the solubilization, precipitation, and purification of carrageenan from red seaweed. The specific choice and concentration of these chemicals may vary depending on factors such as the seaweed species, extraction conditions, and desired properties of the extracted carrageenan.

Enzyme-Assisted Extraction Method

Enzyme-assisted extraction involves using specific enzymes, such as cellulase or pectinase, to break down cell wall components of the red seaweed and release carrageenan. After enzyme treatment, the mixture is typically subjected to further extraction steps such as alkaline or acid treatment to solubilize and recover carrageenan. The extracted carrageenan is then precipitated and processed similarly to other extraction methods (Otero *et al*., 2021).

Microwave-Assisted Extraction Method

This method utilizes microwave irradiation to enhance the extraction efficiency of carrageenan. Red seaweed is mixed with a suitable solvent, such as water or alkaline solution, and subjected to microwave irradiation. The microwave energy helps to break down cell walls and facilitate the release of carrageenan into the solvent. After extraction, carrageenan is precipitated, washed, and dried (Entezari *et al*., 2022).

Types of Carrageenan and their Properties

Carrageenan, derived from red seaweed, is categorized into three main types: kappa, iota, and lambda, each with distinct properties and applications in cosmetics.

Kappa Carrageenan: Known for its strong gelling abilities, kappa carrageenan is a key ingredient in hair styling products like gels and mousses, providing firm textures (Figure 2). It helps create stable and resilient shapes, crucial for long-lasting hold in these products.

Iota Carrageenan: This type forms soft, elastic gels, making it ideal for lotions, creams, and moisturizers. Its ability to impart a smooth, luxurious feel on the skin enhances the sensory experience of cosmetic products.

Lambda Carrageenan: Unlike kappa and iota, lambda carrageenan does not gel but significantly increases viscosity. It is widely used in creams and emulsions to improve consistency and stability without forming a gel (refer to Figure 2).

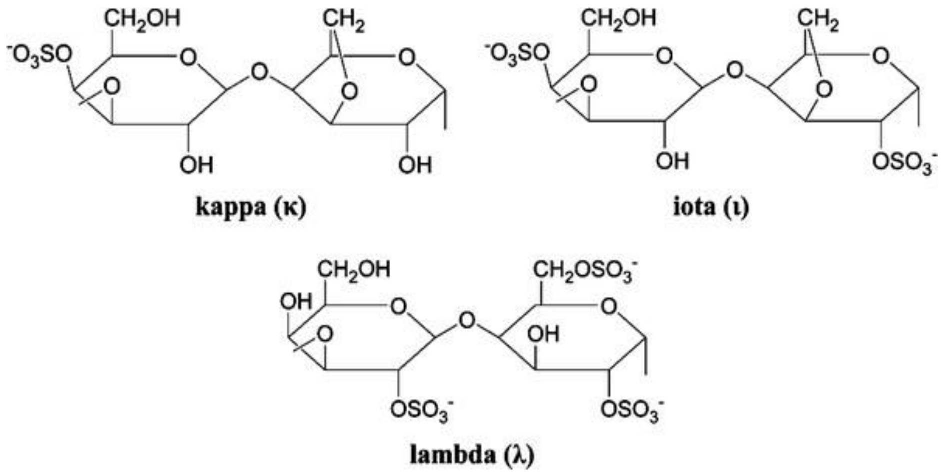

Figure 2. Chemical structure of kappa, iota and lambda carrageenans

Biological Activities

In addition to its role in enhancing texture and stability, carrageenan possesses significant biological activities that render it invaluable in cosmetic formulations (Núñez-Santiago *et al*., 2011; Bagal-Kestwal *et al*., 2019).

The inherent properties of this polysaccharide make it a highly sought-after addition to personal care and skincare products. Renowned for its antioxidant properties, carrageenan plays a pivotal role in combating oxidative stress on the skin (Wang *et al*., 2024) Antioxidants aid in neutralizing free radicals and mitigating damage caused by environmental factors, making them particularly relevant in cosmetics designed for anti-aging or protective purposes (El-Beltagi *et al*., 2022; Pinheiro *et al*., 2023).

Furthermore, carrageenan exhibits anti-inflammatory properties, making it an excellent choice for soothing and calming irritated or sensitive skin (Obafemi *et al*., 2021; Fransiska *et al*., 2021). These anti-inflammatory attributes align with the increasing demand for skincare products tailored to address conditions such as inflammation or redness. Moreover, carrageenan serves as a humectant, facilitating skin moisture retention and contributing to hydration (Kanlayavattanakul *et al*., 2015). As such, it holds importance as a key component in moisturizers and formulations intended to hydrate the skin (Liu *et al*., 2023), thereby enhancing the overall skin-conditioning performance of cosmetic products.

Given its diverse biological activities, carrageenan transcends its role as a mere texturizing agent; it emerges as an active ingredient with positive implications for skin health and the overall effectiveness of cosmetic products within the industry.

Protein

Seaweeds are renowned for being rich sources of protein, with the concentration varying depending on factors such as species, seasonal cycle, and environmental fluctuations. These proteins encompass essential amino acids, along with glycine, alanine, proline, arginine, glutamic acid, and aspartic acid (McKim *et al*., 2019). Among the three main types of seaweeds - green, red, and brown - red seaweeds boast the highest protein concentration, reaching up to 47%. In comparison, brown seaweeds typically contain protein concentrations ranging from 24% to 35%, while green seaweeds fall within a similar range (Míšková *et al*., 2021; Morais *et al*., 2021). Interestingly, the protein concentration of red seaweeds rivals that of other protein-rich foods such as soybeans, cereals, eggs, and fish.

Lipid

Seaweeds harbor lipids, albeit with a low concentration ranging from 0.5% to 5.0% of dry weight samples as shown in Table 3 (Peñalver *et al*., 2020). Despite this modest concentration, seaweeds are esteemed as rich sources of lipids, notably containing a high proportion of unsaturated fatty acids, including Eicosapentaenoic acid (as n-3 PUFAs) and Arachidonic acid (as n-6 PUFAs) (Petikirige *et al*., 2022)

Further examination from Table 3 reveals that red seaweeds exhibit the lowest lipid content (0.64-5.0) %, followed by brown (0.38-11.91) % and green seaweeds (1.57-13.04) %. The variation in total lipid content can be attributed to factors such as geographic location, temperature, light intensity, seasonal changes, salinity, and species interactions (Priyadarshi *et al*., 2022).

Seaweeds are rich reservoirs of beneficial lipids, including a diverse array of sterols such as cholesterol and clionasterol (Rioux *et al*., 2017). These sterols are renowned for their bioactivity, offering numerous health benefits including cancer prevention, weight management, antioxidant effects, and protection against tumors (Yuan and Song, 2021), viruses, and cardiovascular diseases (Roohinejad *et al*., 2017). Fucosterol and isofucosterol emerge as prominent players among these seaweed sterols (Shannon E *et al*., 2022; Safwa *et al*., 2023).

Table 3. Chemical composition of seaweeds based on different species

Species	Chemical composition of seaweed (% dry weight)		
	Protein	Lipid	Ash
Green seaweed	32.70-3.30	13.04-1.57	27.50-19.59
Brown seaweed	25.70-5.40	11.91-0.38	39.30-20.71
Red seaweed	47.0-2.30	5.0-0.64	44.03-17.50

Vitamins

Seaweeds boast a diverse array of vitamins, including fat-soluble vitamins such as vitamin A, vitamin D, vitamin E, and provitamin A, as well as water-soluble vitamins like vitamin C, various B vitamins (including vitamin B12, vitamin B6, vitamin B3, vitamin B2, and vitamin B), pantothenic acid, niacin, riboflavin, and folic acid (Chauhan *et al*., 2016; Obafemi *et al*., 2021). However, the levels of vitamins in seaweeds may vary depending on the species, with some seaweeds exhibiting lower levels of certain vitamins (Lim *et al*., 2021).

Different types of seaweeds-green, red, and brown-each possess their own unique strengths when it comes to vitamins. Green seaweeds are particularly rich in vitamin E, while red seaweeds excel in providing vitamin C. Brown seaweeds stand out for their contribution of essential vitamin B3 (Rioux *et al*., 2017). Interestingly, seaweeds also contain vitamin B12, a nutrient often scarce in plant-based foods, with various seaweed families containing differing amounts of this vital vitamin (Salido *et al*., 2024).

Pigments

Pigments play a crucial role in controlling photosynthesis, as well as the growth and development of plants (Shannon E *et al*., 2022). There are three main types of pigments: chlorophylls, carotenoids, and phycobilins. Chlorophylls, particularly chlorophyll a, are essential elements in photosynthesis, with green seaweeds containing the highest quantity of chlorophyll. Carotenoids and phycobilins serve as accessory pigments, transferring energy to chlorophyll a. Brown macrophytes are distinguished by their fucoxanthin content, while red ones are renowned for their phycobilins (Smyth *et al*., 2021).

In the realm of food, color is a vital aspect, with pigments playing a crucial role. Primarily, pigments are utilized as natural dyes, reflecting a growing consumer preference for health-conscious choices. Natural pigments are regarded as health-promoting ingredients, offering numerous beneficial functions and serving as promising alternatives to synthetic dyes and ingredients. Additionally, due to their nutraceutical properties, pigments exhibit biological activities that significantly impact human health (Qin, 2018; Thiviya *et al*., 2022).

Metals and Iodine

Given seaweeds' propensity for bioaccumulating metals, their consumption raises concerns regarding the potential transfer of high-risk metals to humans in relation to chemical pollution. Thus, it is imperative to comprehend the metal concentrations present in seaweed. Various factors, such as the seaweed's habitat and the surrounding water quality, influence the levels of metals within them. Typically, green macrophytes exhibit higher metal bioaccumulation compared to red and brown macrophytes (Jia *et al* 2014; Sanjeewa *et al.*, 2016). In Europe, the European Union Recommendation has proposed regulations for controlling the presence of arsenic, cadmium, iodine, lead, and mercury in seaweed, halophilic plants, and seaweed-based products.

Of particular importance is iodine, as some seaweed species contain elevated levels of this element. While excessive iodine intake may contribute to thyroid diseases, it is essential for the synthesis of thyroid hormones. Studies conducted by the Spanish Agency for Food Safety and Nutrition (AESAN) have revealed that processing methods, such as freezing or drying, can affect the iodine content of seaweeds. In France, a maximum iodine content of 2000 mg kg^{-1} DW is recommended for all seaweed species. However, pregnant women, individuals with heart or renal conditions, and those with thyroid disorders (especially those taking iodine-related medications) should exercise caution when consuming iodine or iodine-derived products (Otero *et al*.,2021).

Application and Formulation Considerations

The application and formulation considerations of carrageenan in cosmetic products underscore its versatile role in achieving specific textural and performance characteristics while meeting formulation requirements. Thanks to its unique gelling properties, carrageenan proves to be a valuable ingredient across a range of cosmetic products, including lotions, creams, and gels, where it imparts desired smoothness and consistency. Its ability to form and stabilize gels enhances both the tactile experience and visual appeal of the final product.

Furthermore, carrageenan demonstrates compatibility with a wide array of cosmetic ingredients, affording formulators the flexibility to create diverse formulations without compromising stability or efficacy. Its compatibility extends to formulations based on either water or oil (Fransiska *et al.*, 2021), rendering it suitable for use in various cosmetic products.

Formulation considerations for carrageenan involve optimizing its concentration according to the specific requirements of the cosmetic product to achieve optimal results. Formulators can manipulate carrageenan concentration to attain desired texture, viscosity, and stability without negatively affecting the performance of other ingredients (Shannon *et al*., 2022; Safwa *et al*., 2023). Its versatility makes it an ideal candidate for combination with other natural ingredients commonly used in cosmetics, enabling the creation of holistic formulations that align with consumer demand for clean and environmentally friendly beauty products.

Beyond its role as a texturizing agent, carrageenan contributes to the overall sensorial experience provided by cosmetic products (Rioux *et al*., 2017; Salido *et al*., 2024). Enhancing spread ability and absorbability, it not only improves product effectiveness but also enhances customer satisfaction (Liu *et al*., 2023). Formulators can leverage carrageenan to create aesthetically pleasing products that resonate with market trends emphasizing functionality and a natural, environmentally conscious appeal.

Specific Chemical Content

Red seaweed, like other types of seaweed, contains a variety of bioactive compounds that offer benefits for cosmetic applications. While the specific chemical content may vary between different species of seaweed, red seaweed is known for containing unique compounds that contribute to its skincare properties as shown in Figure 3. Here are some of the key chemicals found in red seaweed, along with their cosmetic benefits.

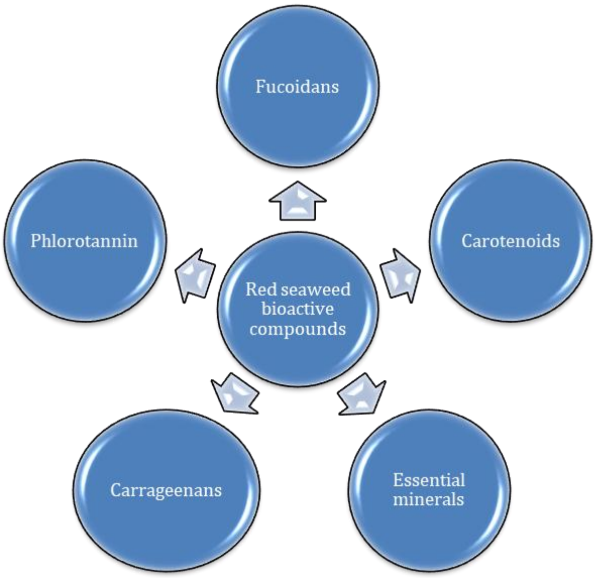

Figure 3. Several of chemicals found in red seaweed, along with their cosmetic benefits

Carrageenans

Red seaweed is rich in carrageenans, a type of sulfated polysaccharide. Carrageenans have excellent emollient properties, making them valuable in moisturizing creams, lotions, and masks. They form a protective barrier on the skin, helping to retain moisture and prevent dryness. Additionally, carrageenans have a soothing effect on the skin, making them suitable for calming irritated or inflamed skin.

Fucoidans

Fucoidans are another type of polysaccharide found in red seaweed. They have antioxidant and anti-inflammatory properties, which can help protect the skin from environmental damage and reduce redness and inflammation. Fucoidans also promote collagen synthesis and skin regeneration, making them beneficial for anti-aging and wound healing formulations.

Phlorotannins

Phlorotannins are polyphenolic compounds found in red seaweed that possess strong antioxidant properties. They help neutralize free radicals generated by UV radiation and other environmental stressors, thereby protecting the skin from premature aging and oxidative damage. Phlorotannins also have skin-brightening effects, making them useful in formulations targeting hyperpigmentation and uneven skin tone.

Carotenoids

Red seaweed contains carotenoids, including β-carotene and astaxanthin, which are responsible for its red coloration. Carotenoids have potent antioxidant properties and help protect the skin from UV-induced damage. They also contribute to the skin's natural radiance and can enhance the appearance of dull or tired skin. Figure 4 show the chemicals structure of β-Carotene.

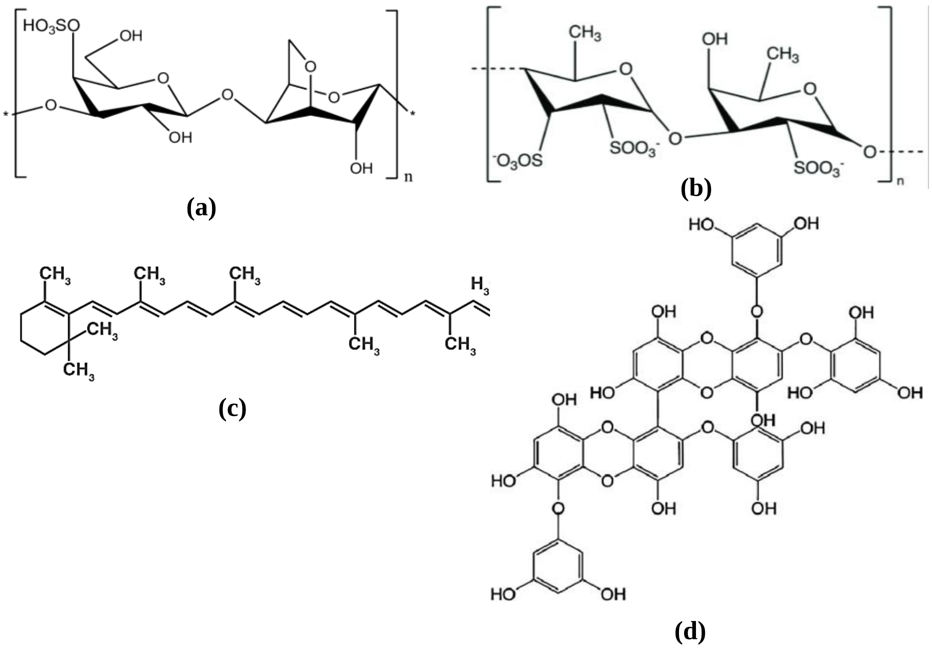

Figure 4. Chemical structures of; (a) Kappa - carrageenan; (b) Fucoidan; (c) Phlorotannin; (2,7'-phloroglucinol-6,6'-biecckol) and (d) β-carotene

Essential Minerals

Red seaweed is a rich source of essential minerals such as calcium, magnesium, potassium, and iron. These minerals play crucial roles in maintaining skin health and function. Calcium helps regulate skin cell turnover and hydration, magnesium supports enzymatic processes involved in collagen synthesis, potassium (Núñez-Santiago *et al*., 2011; Laokelis *et al*., 2022) helps maintain electrolyte balance in skin cells, and iron contributes to oxygen transport and energy metabolism in the skin.

Compared to other types of seaweed, red seaweed is particularly prized in cosmetics for its high content of carrageenans, fucoidans, and phlorotannins, which offer unique benefits such as enhanced moisturization, anti-inflammatory effects, and antioxidant protection. However, it's worth noting that the specific chemical composition and concentrations of bioactive compounds can vary between different species of red seaweed and even within the same species due to factors like geographical location, environmental conditions, and harvesting methods.

Natural and Sustainable Sourcing

With growing consumer demand for natural and sustainable skincare ingredients, red seaweed extracts offer an attractive option for cosmetic manufacturers. Seaweed cultivation is environmentally friendly and requires minimal land and freshwater resources compared to traditional agricultural crops. Table 4 shows the summary of cosmetic application based on the bioactive compound in the red seaweeds.

Table 4. Cosmetic application, bioactive and elements present in the red seaweeds

Cosmetic Application [Ref.]	Bioactive	Bioactive Compounds	Chemicals/ Elements
Moisturizing Properties (Zaitseva *et al*., 2022; Pinheiro *et al*., 2023)	• Red seaweed extracts are known for their hydrating and moisturizing effects on the skin. • Studies have identified polysaccharides and peptides in red seaweed that help improve skin hydration by forming a protective barrier, reducing transepidermal water loss, and enhancing skin elasticity.	Polysaccharides (e.g,carrageenans, agarans), peptides	Sulfur-containing compounds, such as sulfated polysaccharides
Anti-Aging Effects (Janowicz *et al*., 2023; Pangestuti *et al.*, 2021; Waseem *et al*., 2023; Priyadarshi *et al.*, 2022)	• Certain compounds found in red seaweed, such as phlorotannins and carotenoids, possess antioxidant properties. • These antioxidants help neutralize free radicals, which are known to cause oxidative stress and contribute to skin aging. • Research suggests that incorporating red seaweed extracts into cosmetic formulations may help reduce the appearance of wrinkles, fine lines, and other signs of aging.	Phlorotannins, carotenoids	Polyphenols, fucoxanthin, astaxanthin
Anti-Inflammatory and Soothing Properties (Obafemi *et al.*, 2021)	• Red seaweed extracts contain bioactive compounds like fucoidans and sulfated polysaccharides, which exhibit anti-inflammatory properties. • These compounds can help soothe irritated skin, reduce redness, and alleviate symptoms of conditions like eczema and psoriasis. • Cosmetics containing red seaweed extracts may therefore be beneficial for individuals with sensitive or inflamed skin.	Fucoidans, sulfated polysaccharides	Fucose, galactose, sulfate esters
Skin Brightening and Pigmentation Reduction (Pangestuti *et al.*, 2021; Montaser *et al*., 2021; Liu *et al.*, 2023)	• Some studies have explored the potential of red seaweed extracts in skin brightening formulations. • Certain compounds in red seaweed, such as arbutin and phycobiliproteins, have been found to inhibit melanin production and reduce hyperpigmentation, leading to a more even skin tone.	Arbutin, phycobiliprotein	Phenolic compounds, bilirubin-like pigments
Wound Healing and Regenerative Effects (Batista *et al.*, 2020; Jing *et al.*, 2021; Montaser *et al*., 2021)	• Red seaweed extracts have been investigated for their wound healing properties. • Compounds like carrageenan and fucoidans promote the proliferation of skin cells, accelerate wound closure, and stimulate collagen synthesis, thereby aiding in tissue repair and regeneration.	Carrageenans, fucoidans	Carrageenan oligosaccharides, fucose-containing sulfated polysaccharides
UV Protection (Gerber *et al.*, 1958)	• Certain red seaweed species produce compounds like mycosporine-like amino acids (MAAs), which have UV-absorbing properties. • Incorporating these compounds into cosmetic formulations may help provide additional protection against UV-induced skin damage, including sunburn and photoaging.	Mycosporine-like amino acids	Amino acids (e.g., glycine, glutamine), imino acids

Safety, Regulatory Aspects & Challenges

When integrating carrageenan into cosmetic formulations, considerations regarding safety, regulatory compliance, and related challenges are imperative to ensure the quality of the final product and the well-being of its users. Initially, carrageenan is generally regarded as safe for use in cosmetics, with numerous studies affirming its safety within specified concentrations. However, concerns arise regarding its potential degradation into smaller molecules, known as poligeenan, under specific conditions (McKim *et al*., 2019). This raises safety concerns, particularly at higher concentrations or when formulated in certain ways. To ensure the safe and effective use of carrageenan in cosmetics, regulatory bodies such as the Food and Drug Administration (FDA) in the United States, the European Commission, and similar agencies worldwide have established limits and specifications for its usage (Morais *et al*., 2021).

In the cosmetics industry, challenges associated with carrageenan include potential interactions with other components, leading to formulation instability or decreased product effectiveness (Shannon *et al*., 2019). With consumer awareness regarding ingredients on the rise, there's a growing demand for transparent labeling and communication regarding the presence of carrageenan in cosmetic products (Smyth *et al*., 2021). Despite its benefits, significant obstacles persist in utilizing carrageenan in cosmetic formulations. These hurdles encompass compliance with evolving regulations, addressing consumer concerns regarding safety and sustainability, and ongoing research to validate its efficacy and safety.

A comprehensive approach is necessary, giving equal weight to consumer safety and product innovation, to navigate these challenges and leverage the benefits carrageenan offers in the cosmetics industry, such as its natural origin, versatility, and advantageous properties (Thiviya *et al*., 2022). This entails striking a delicate balance between addressing regulatory requirements, meeting consumer expectations, and harnessing carrageenan's potential in cosmetic formulations effectively.

With regard to carrageenan, formulation considerations, safety aspects, and regulatory dynamics underscore the importance of maintaining a balanced approach. While enhancing product texture and stability, carrageenan also contributes to the broader narrative of environmentally conscious beauty (Wan-Loy *et al*., 2016). As the cosmetics industry continues to evolve, carrageenan emerges as a promising and innovative component, aligning with sustainability demands and consumer expectations (Pimentel *et al*., 2017).

To navigate carrageenan's future in the cosmetics industry effectively, ongoing research, collaboration between regulatory bodies and industry stakeholders, and transparent communication with consumers are essential (Qin *et al*., 2018). Commitment to rigorous safety assessments and continuous monitoring of industry practices is crucial to address challenges such as degradation and formulation interactions. Carrageenan plays a pivotal role in formulating products that not only meet stringent safety standards but also resonate with evolving beauty consumer values and preferences.

CONCLUSION

In conclusion, the utilization of carrageenan extract derived from red seaweed in cosmetic product production exemplifies the dynamic intersection of natural ingredients and the advancement of cosmetic science. Through a comprehensive examination of its types, biological activities, and extraction methods, it becomes evident that carrageenan holds multifaceted potential within the cosmetics sector. Among the various extraction techniques, the optimal method for obtaining the most important bioactive compounds has been identified, which maximizes its effectiveness in cosmetic applications. Its versatility in gelling, thickening, and providing skin benefits aligns well with the increasing consumer preference for clean and environmentally friendly beauty products. Given the dynamic landscape of the cosmetic industry driven by sustainability and natural ingredient trends, carrageenan stands poised to significantly influence the development of future beauty formulations that are both clean and efficacious. As the cosmetics industry embraces innovation and sustainability, carrageenan's role is set to expand, making it a key player in shaping the future of clean and effective beauty products.

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