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Comprehensive Analysis of the Influence of Morphological Characteristics of Algal Species and Technological Processing Parameters on the Functional and Technological Properties of K-Carrageenan

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Abstract**—** *The article examines the influence of red seaweed morphological characteristics and the technological processing parameters of the raw material on the functional and technological properties of κ-carrageenan. The study's relevance lies in the high variability in the structure and texture-forming capacity of commercial samples, which complicates the reproducible quality control of food products. The research aims to identify cause-and-effect relationships between species and strain identity, growth conditions, and post-harvest treatment, on the one hand, and the rheological characteristics of gels and solutions, on the other. The scientific novelty lies in systematising fragmented data into a unified concept of the ingredient's raw material and technological history, and in validating a specialised methodological toolkit for the quantitative assessment of its properties. It is shown that the combined action of the botanical source, geography of cultivation, methods of harvesting and washing, and drying regimes determines the molecular weight, degree of depolymerisation, 3,6-anhydrogalactose content, and gel strength, critical gelation concentration, syneresis, water-holding capacity, and plasticity of κ-carrageenan. Reproducible differences have been established between carrageenans obtained from Kappaphycus alvarezii, Eucheuma denticulatum, and Chondrus crispus in terms of the deformation behaviour profiles of their gels and their suitability for different food matrices. The diagnostic sensitivity of the test complex, which enables ranking raw-material batches by expected technological performance and substantiating expanded requirements for supplier specifications, is demonstrated. The article is intended for food technologists and product developers, quality professionals, as well as manufacturers and users of carrageenan involved in the design and standardisation of stabilising systems.*

Keywords**—** *κ-carrageenan, red seaweeds, morphological characteristics, cultivation conditions, biomass drying.*

I. Introduction

Carrageenans occupy a leading position among food hydrocolloids owing to their unique gelling, thickening, and stabilising properties [1]. The more specialized form of carrageenan kappa (κ-carrageenan) may be gelled into a firm thermoreversible gel in the presence of potassium ions (K^+) and in the presence of milk κ-casein, locust bean gum (LBG), and other polysaccharides. It is the most common form of carrageenan and is used in the dairy industry for yogurts, desserts, and curd products; in the meat industry for injection brines, canned meats, and emulsions; and in a range of food products.

However, users of κ-carrageenan frequently encounter variability of its functional properties from batch to batch and between different suppliers [2]. This instability can lead to deviations in texture, stability, and yield of the final food product.

The present work is based on the hypothesis that the leading causes of variability in the functional properties of commercial κ-carrageenan are differences in botanical source (species and strain of seaweed), geography of growth/harvesting and environmental conditions, methods of collection and, in particular, primary processing (drying) of the raw material, as well as the parameters of technological processing of seaweeds into refined carrageenan.

The study aims to systematically analyze the influence of these factors on the key functional properties of κ-carrageenan: gelation (strength, critical concentration), syneresis (moisture release), gel plasticity/elasticity, water-holding capacity, and synergy. Based on many years of experience in developing and applying specialised techniques for analysing the functional properties of carrageenans, developed with the participation of the author at the Russian University of Biotechnology (ROSBIOTECH) under the supervision of Professors N.A. In the present work, Gurova and A.I. Zharinov analyze the key factors determining the quality of κ-carrageenan.

II. Materials And Methods

The empirical and theoretical basis of the study is a body of published data on the structure and functional properties of κ-carrageenan, the botanical sources and cultivation conditions of red seaweeds, and the influence of technological processing parameters on the molecular and rheological characteristics of the polymer [1–10]. As the object base, commercial κ-carrageenans obtained mainly from Kappaphycus alvarezii and Eucheuma denticulatum of tropical origin (the Philippines, Indonesia, Tanzania) were analysed, along with samples associated with Chondrus crispus from temperate North Atlantic waters [7–9,11–13].

In this work, the morphological characteristics of the raw material are operationalised through the species and strain

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identity of the seaweeds, the specific features of their cultivation (wild-grown/marine mariculture, depth, temperature–light regime, salinity, hydrodynamics) and the associated variations in the carrageenan profile (ratio of κ-, ι- and λ-fractions, potential content of 3,6-anhydrogalactose precursors, degree of sulphation) [3,7–13]. The technological block of materials is described by the dominant schemes of harvesting and primary processing of biomass (manual/mechanised collection, washing intensity, drying parameters), with emphasis on the comparison of traditional sun-drying and controlled artificial regimes that determine the degree of depolymerisation, colour, and organoleptic characteristics, as well as preservation of the functional activity of carrageenan [14,15].

Methodologically, the work represents a comprehensive comparative analysis that integrates structural–biochemical concepts of κ-carrageenan (molecular architecture, 3,6-anhydrogalactose content, ion-induced spiralisation) with data on the morphology and ecology of the source seaweeds and on the parameters of the technological chain from raw material to refined powder [1,3,5–7,10–13]. As the key toolkit, a methodological complex developed at ROSBIOTECH was used; it includes standardised tests of gelling ability (gel strength, gelation and melting temperatures, critical concentration), assessment of syneresis and water-holding capacity, analysis of structural–mechanical parameters (plasticity and elasticity of gels) and characterisation of the viscosity behaviour of solutions before gel formation, as well as investigation of synergistic effects in the systems κ-carrageenan – locust bean gum and κ-carrageenan – milk protein components [1–4].

III. Results and Discussion

The structure and functional properties of carrageenans largely depend on the species of red seaweeds from which they are obtained, as well as on the conditions of their growth. Different taxa synthesise predominant types of polysaccharide chains (κ-, ι-, λ- and hybrid forms), which leads to pronounced differences in the rheological characteristics of gels and solutions [3]. This, in turn, determines the technological suitability of carrageenans in specific food systems and explains why the raw material seaweed is selected to achieve the desired texture type, rather than adjusting the texture to a predefined raw material.

Carrageenan from Kappaphycus alvarezii belongs predominantly to the κ-type. It is characterised by the formation of rigid, brittle gels in the presence of potassium ions. Such gels exhibit pronounced syneresis, i.e., a tendency to release bound water during storage or upon mechanical impact. From a practical standpoint, this makes κ-carrageenan appropriate for systems requiring a dense, cuttable texture and high firmness, for example, in meat products, including injection brines, as well as in firm jellies. In such matrices, syneresis may be partially controllable and is not always considered a disadvantage, provided that it does not compromise product stability.

Eucheuma denticulatum (formerly known as Eucheuma spinosum) synthesises predominantly ι-carrageenan. Its gels in the presence of calcium ions are characterised by softness and elasticity, while retaining their structure after freeze–thaw cycles. This freeze–thaw stability makes ι-carrageenan particularly valuable for dairy desserts, soft cheeses, and various frozen products, where a delicate, creamy, or viscous texture is required without gel destruction under temperature fluctuations. In contrast to κ-carrageenan, the emphasis here shifts from firmness and density towards plasticity and structural stability under thermal stress [4].

Chondrus crispus produces a mixture of carrageenans in which κ- and λ-structural motifs are combined. This combination leads to high solution viscosity with relatively moderate or low propensity to form firm gels. Its technological effects are mainly related to the viscosity increase and the stabilization of emulsion systems. Due to their gelling properties, carrageenans from Chondrus crispus are used in products where a homogeneous, continuous dispersion is desired, such as chocolate milk and sauces, or as an alternative to plant milk. In these systems, carrageenan is a stabilizer and thickener, preventing phase separation and sedimentation.

Seaweeds of the genus Gigartina form more complex hybrid carrageenan structures, where κ-, ι-, and θ-fragments may be combined [4]. As a result, intermediate systems arise, allowing fine-tuning of the texture between rigid and soft gels, as well as between predominantly gel-forming and more viscosity-stable solutions. Such hybrid carrageenans are convenient for targeted modelling of food textures, particularly in vegan products that need to recreate sensory attributes similar to those of traditional dairy or meat products. The ability for such modulation through different raw material (seaweed) sources and gelation conditions renders Gigartina suitable for production of functional hydrocolloid materials.

Furcellaria lumbricalis excepts, which furcellaran produces. Furcellaran exists as a hybrid of κ- and β-carrageenans, and it is therefore characterized by a relatively low gelation temperature. This enables gel formation under milder thermal conditions than those required for classical κ-carrageenans [4]. This property is significant for jams, confectionery glazes, and other thermosensitive systems, where overheating may lead to degradation of flavour compounds, colour changes, or undesirable browning reactions. Owing to the low solution–gel transition temperature, furcellaran provides convenient processing and a gentler regime for sensitive ingredients. Carrageenan-Producing Red Seaweeds: Functional Properties and Applications is shown in Table 1.

Thus, the species identity of red seaweeds determines the predominant type of carrageenan and, consequently, the spectrum of its functional properties, ranging from rigid, syneresis-prone gels to soft, elastic structures and highly viscous stabilising solutions. This creates a broad space for targeted selection of raw materials for specific technological tasks: the formation of dense gel structures, the stabilisation of emulsions and suspensions, the creation of thermosensitive or freeze–thaw-stable products, and the design of textures for contemporary vegan and plant-based formulations.

TABLE I. Carrageenan-Producing Red Seaweeds: Functional Properties and Applications [3, 4]

Seaweed species	Carrageenan type	Key properties	Modern applications
Kappaphycus alvarezii	κ-carrageenan (kappa)	Rigid, brittle gels with K^+; strong syneresis.	Meat products (injection brines), firm jellies.
Eucheuma denticulatum (formerly *E. spinosum*)	ι-carrageenan (iota)	Soft, elastic gels with Ca^{2+}; good freeze–thaw stability.	Dairy desserts, soft cheeses, frozen foods.
Chondrus crispus	Mixed (κ/λ)	High viscosity; emulsion stabilization.	Chocolate milk, sauces, and plant-based milk alternatives.
Gigartina spp.	Hybrids (κ/ι/θ)	Intermediate properties; tunable texture.	Food texture modelling, vegan products.
Furcellaria lumbricalis	Furcellaran (κ/β hybrid)	Low gelation temperature (30–40 °C).	Jams, confectionery glazes, thermo-sensitive gels.

κ-Carrageenan is a linear polysaccharide composed of alternating residues of β-D-galactose-4-sulphate and 3,6-anhydro-α-D-galactose [5]. The polymer's composition, especially the high level of 3,6-anhydrogalactose, is responsible for its ability to form strong, elastic gels [5]. In the presence of specific cations, primarily potassium ions (K^+), κ-carrageenan macromolecules adopt an ordered helical conformation: individual chains form double helices, which then aggregate and self-organise into a spatially branched three-dimensional gel network. Thus, the gelation of κ-carrageenan can be regarded as the result of the combined influence of its molecular architecture (3,6-anhydrogalactose content and degree of sulphation) and the ionic composition of the medium in which structural organisation occurs.

The quality and functional characteristics of κ-carrageenan are initially determined by its botanical source [6]. Different species of red seaweeds synthesise carrageenans with differing κ-, ι- and λ-fraction ratios, different average molecular weights, and varying degrees of sulphation. These parameters, in turn, define the range of textural and rheological properties that can be obtained in subsequent raw-material processing. Significant is the initial content of 3,6-anhydrogalactose precursors and the potential for their conversion into 3,6-anhydrogalactose during alkaline treatment: it is at this stage that the gelation properties of κ-carrageenan are often tuned for specific food and non-food applications.

The primary commercial source of κ-carrageenan is Kappaphycus alvarezii, which accounts for the overwhelming share of global production [7]. This species is cultivated predominantly in coastal tropical regions with warm waters, good illumination, and moderate wave activity. Commercial production of the species is concentrated in the Philippine provinces of Palawan, Zamboanga and Tawi-Tawi, in the islands of Bali, Sulawesi and Maluku of Indonesia (where Makassar in Sulawesi is also a central point of trade), in the State of Sabah in Malaysia, and the islands of Zanzibar and Pemba in Tanzania. In several regions, K. alvarezii has been deliberately introduced for mariculture and in some ecosystems has become an invasive species, displacing local macrophytes, for example, in certain waters off Hawaii and Brazil. κ-Carrageenan from this species is characterised by a high κ-fraction content and pronounced gelling properties, making it particularly attractive to industry.

Another essential source is Eucheuma denticulatum, formerly known as Eucheuma spinosum [8]. It is often cultivated alongside K. alvarezii in the same regions: the Philippines, Indonesia, and Tanzania. Historically, E. denticulatum was regarded primarily as a source of ι-carrageenan; however, modern commercial strains and hybrids often contain substantial amounts of the κ-fraction or represent κ/ι-hybrid carrageenans. This altered chemical profile is determined by both selection and cultivation and processing conditions. Technologically, E. denticulatum is of interest for its greater tolerance to temperature and salinity fluctuations compared with K. alvarezii, expanding the range of possible cultivation areas and reducing the risk of biomass loss under adverse conditions.

The traditional, historically first source of carrageenan is Chondrus crispus, known as Irish moss [9]. In contrast to cultivated tropical species, it is usually collected in the wild in the northern Atlantic Ocean, off the coasts of Ireland, Canada (Nova Scotia, Newfoundland and Labrador), the USA (Maine and Massachusetts), France (Brittany), Iceland, and Norway. Carrageenan from Chondrus crispus is a mixture of κ- and λ-fractions in approximately a 1:1 ratio. To obtain a relatively pure κ-fraction, additional fractionation and purification steps are required, thereby increasing the technological cycle's complexity and cost. At the same time, gels obtained from the κ-fraction of Chondrus crispus are distinguished by high plasticity and favourable texture, which maintains interest in this species as a specific niche raw material source.

Genetic differences among Kappaphycus alvarezii, Eucheuma denticulatum, and Chondrus crispus set the fundamental framework for the chemical profile of the carrageenan they produce [10]. The κ-, ι-, and λ-component ratios vary, the average molecular weight and degree of sulphation change, and the ability of macromolecules to transition into ordered helical structures under the action of alkali and metal ions differs. For κ-carrageenan, the initial content of structural fragments capable of transforming into 3,6-anhydrogalactose during alkaline treatment is particularly significant, since this parameter determines the potential for further enhancement of gelation properties. Thus, the choice of botanical source and controlled processing of the raw material directly determine the functional characteristics of κ-carrageenan in final products. Figure 1 shows the botanical source of κ-carrageenan that should be used.

The properties of carrageenan synthesised by the same species of red seaweed depend markedly on the geographic area of growth and the specific environmental conditions. Water temperature is a key parameter: for tropical Kappaphycus and Eucheuma species, the optimal range is 25–30 °C, at which a balance is achieved between biomass growth rate and accumulation of carrageenan and 3,6-anhydrogalactose in tissues [11]. Elevated temperatures increase biomass yield but also negatively affect the most vital polysaccharide fractions. Temperate Chondrus crispus experiences seasonal temperature summer/winter-temperature fluctuations that create different biochemical compositions. Winter harvesting is better for maximizing carrageenan yield than summer harvesting. Light availability with depth of growth can alter polysaccharide as light synthesizes and structures; deep water or high turbidity impede light, so penetration of these slows down metabolism and synthesizes polysaccharide. Salinity also plays an important role; its reduction, for example, after heavy rainfall in coastal bays, causes stress in thalli and reduces the intensity of synthesis [12]. Water flow and nutrients such as nitrogen and phosphorus are also important; a good flow of water will ensure a good supply of plankton and dissolved nutrients. Fertilizers must also be used to maintain high growth rates and quality of raw materials in regions of intensive Kappaphycus mariculture, such as the Philippines and Indonesia. Seasonality is also marked in the tropics with wet and dry seasons in some areas.

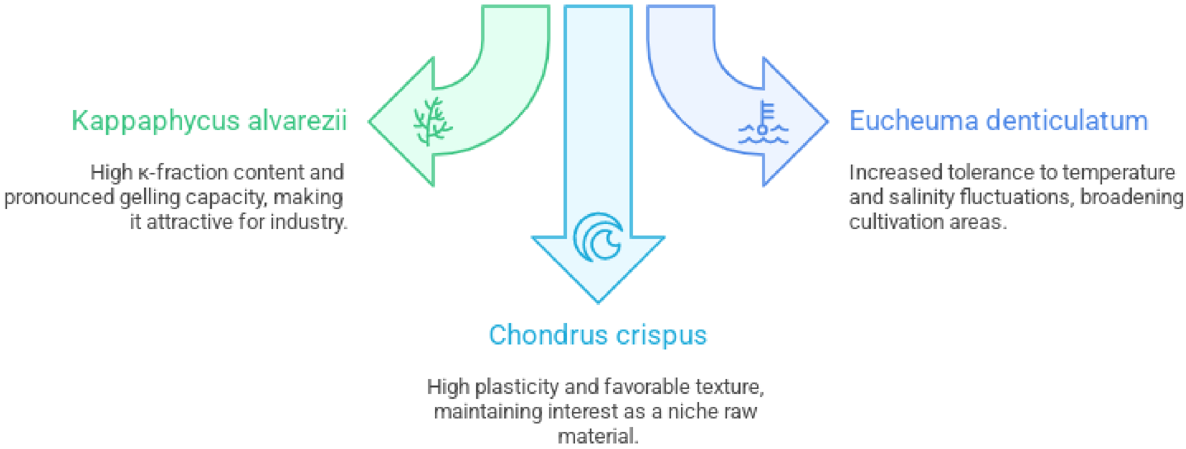

Fig. 1. Different botanical sources of kappa-carrageenan

Wild and cultivated seaweeds have different levels of property homogeneity. Natural populations of Chondrus crispus vary in proportion, depending on age of the thallus, habitat depth or local hydrology, and collected at random, the wild Chondrus crispus populations of the North Atlantic could become overharvested or severely depleted in the near future. In contrast, cultivated Kappaphycus and Eucheuma can be controlled by carefully selecting the strains, planting density and cropping cycle, as this can result in more uniform seaweed sources in the carrageenan content and fractional composition. At present, more than 90% of the world's raw material for κ-carrageenan is obtained from marine rope cultivation in tropical waters using the so-called long-line scheme, with the Philippines and Indonesia as the leading producers [7]. Rheological data confirm the relationship between cultivation conditions and polymer functions: analysis of gel strength showed that κ-carrageenan from Kappaphycus alvarezii grown in eastern Indonesia (higher average temperatures and more intense insolation) formed gels whose strength was 11.2 % lower than that of samples from the western regions of the Philippines at identical concentrations and testing conditions, which correlated with a lower 3,6-anhydrogalactose content in the Indonesian raw material [13].

Another important aspect is the method of seaweed collection and the immediate primary processing of the seaweeds after harvesting. In cultures, the seaweeds are harvested by hand from rafts or ropes. Harvesting is done by divers or from small boats. Care needs to be taken to avoid mechanical damage and the thalli need to be quickly transported ashore. For wild harvesting, the algal material can be collected underwater by hand or from material drifted ashore. The latter produces lower quality raw material due to degradation and pollution. Mechanized harvesting by dredging from the sea bed is rare as it destroys the thallus and contaminates the loads with impurities. Freshwater or seawater washing is often the first step in primary processing, and salt, sand, epiphytes, shells, and other debris are removed. Inadequate washing leads to high ash and impurities in the product which may affect its functional properties and processability.

Drying, which simultaneously serves as a stabilisation step for the raw material, is critical for preserving the molecular weight and structural integrity of carrageenan. The most common method in tropical regions is sun-drying: thalli are spread in a thin layer on platforms or directly on the ground [14]. Despite its low cost and simplicity, this method is highly dependent on weather conditions: prolonged rainfall and high relative humidity slow the process and promote the development of bacterial and fungal microflora, enzymatic degradation, and oxidative changes, resulting in a yellowish tint and off-odours. All these factors are accompanied by depolymerisation, a decrease in molecular weight, and deterioration of gelling properties. Artificial drying in ovens and dryers under controlled temperatures and directed air flow ensures faster and more uniform moisture removal, better preservation of the polymer chain, stable colour, and minimal risk of microbial spoilage; however, this approach is more expensive and is used more often for premium-segment raw material or in regions with unstable solar insolation. Dried raw material must be stored in dry, cool, well-ventilated, and light-protected premises to prevent rehydration and subsequent degradation. Studies of syneresis and moisture content of gels showed that κ-carrageenan from Kappaphycus alvarezii subjected to poor sun-drying under prolonged rainfall and high humidity formed gels with increased volumes of syneretic

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liquid after 24 hours and reduced water-holding capacity compared with carrageenan from raw material dried rapidly and thoroughly under stable sunny conditions or using dryers [15]. These differences directly reflect the degree of polymer chain degradation and the reduction in their hydrophilicity, emphasising the critical role of an appropriately designed post-harvest processing technology. Factors Affecting Carrageenan Quality are systematised in Figure 2.

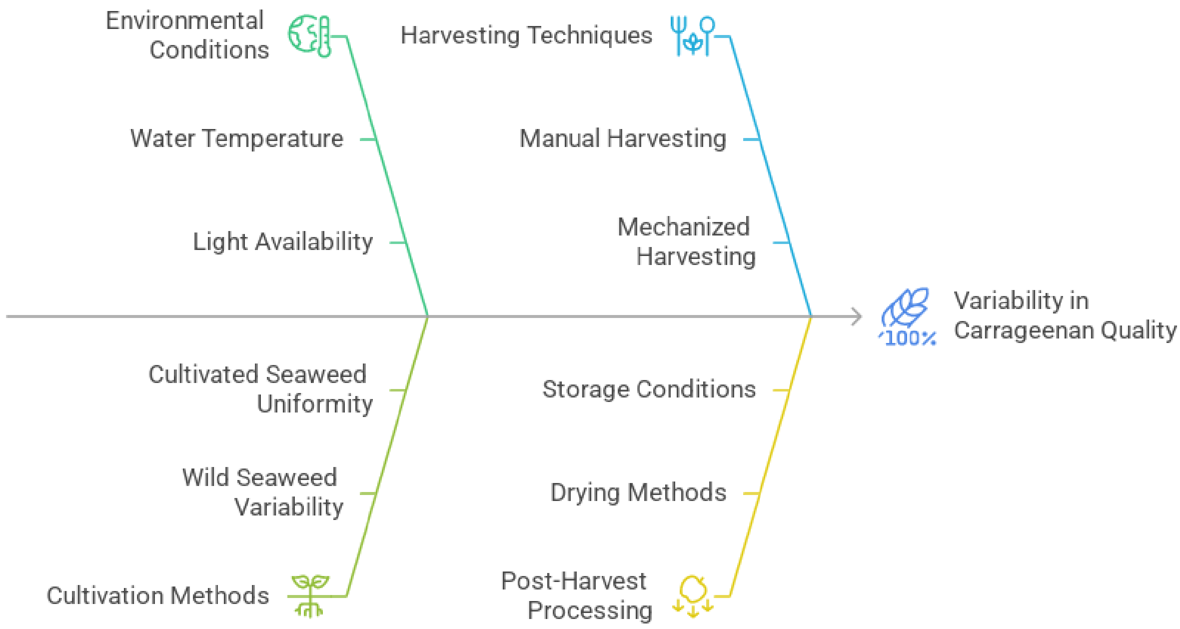

Fig. 2. Factors Affecting Carrageenan Quality

For an objective assessment of the influence of different factors on the quality of κ-carrageenan, it is necessary to rely on reliable, reproducible methodologies that allow quantitative description of the polymer's key functional parameters. A set of practical methods has been developed and tested, aimed at a comprehensive characterisation of gelling ability, critical gelation concentration, syneresis, water-holding capacity, structural–mechanical properties of gels, and the viscosity of solutions before gel formation. In the present context, gelling ability is understood as the ability of a system to form a stable gel at specified carrageenan concentrations and defined temperature regimes; it is evaluated by gel strength (in grams per square centimetre or in newtons), as well as gelation and melting temperatures. Critical gelation concentration is the minimum polysaccharide concentration above which the system transitions from a sol to a stable gel. Syneresis, i.e., the spontaneous separation of liquid from the gel matrix, serves as a sensitive indicator of structural stability and is particularly important in the development of yogurts, desserts, and other products in which visual and textural quality is directly linked to serum retention. Water-holding capacity is essentially the inverse of syneresis and reflects the gel's ability to retain bound water within its three-dimensional network.

Special attention in the developed methodological complex is paid to describing the structural–mechanical properties of gels, such as plasticity and elasticity, since these parameters determine the subjectively perceived texture in the mouth. An elastic gel can restore its shape after load removal and exhibits predominantly reversible deformation, whereas a plastic gel undergoes irreversible flow and deforms irreversibly. In addition, the viscosity of solutions before gelation is evaluated, which is essential for predicting system behaviour during technological stages such as mixing, heating, and container filling. The study of synergistic effects is significant when κ-carrageenan is combined with other hydrocolloids and proteins. For example, interaction with locust bean gum enhances gelation, increases elasticity, and reduces syneresis. In contrast, association with milk κ-casein stabilises protein micelles and promotes the formation of a more stable structure in dairy systems. This approach enables the design of compositions in which carrageenan properties are not considered in isolation but are evaluated within the system of other formulation components.

These methods have been widely applied in research and in industry because they are practical, relatively easy to implement, and do not require expensive or complicated equipment. Reproducibility is good and results are quantitative and mutually comparable. In most cases, the analysis is not excessively time-consuming, except for extended syneresis tests, which require long-term monitoring of moisture release. The most important advantage of the complex lies in its direct relevance to real food systems: precisely those characteristics that determine the product's consumer properties are measured, gel strength, propensity to serum separation, texture, and mouthfeel. It was by means of the gel plasticity estimation method that the authors of the present paper established that the structural-mechanical behavior of the κ-carrageenans isolated from different botanical sources was different qualitatively: gels obtained from the carrageenan of Kappaphycus alvarezii growing in the Philippines differed from the rest of the gels by elastic deformation behavior, high elasticity and low plasticity, that is, were more brittle and easily fractured structures. Conversely, the gels of the κ-fraction of the Norwegian carrageenan (Chondrus crispus harvested off the Canadian coast) were much more plastic (i.e. they were much more able to flow at low yield stresses and much softer in their structure). These differences clearly illustrate the sensitivity of the proposed methods to subtle variations in polymer structure and confirm their practical value for raw-material selection and optimisation.

IV. Conclusion

The results of the study allow a coherent scientific conclusion regarding the nature of variability in the functional and technological properties of commercial κ-carrageenan. It is demonstrated that the observed differences are not random or exclusively batch-related but are caused by a complex, nonlinear interaction of factors of raw-material origin (species and strain of seaweeds, geography, and conditions of growth/harvesting) and parameters of primary technological processing, primarily drying regimes. In this way, the initial hypothesis on the critical role of the entire property-formation chain, from the morphological characteristics of the seaweed to the final powdered product, is confirmed.

From a technological point of view, it is therefore more appropriate for the food industry to consider κ-carrageenan as a product with a specific raw material and technological history, and require additional specification (e.g. seaweed species, geographical area of origin, etc.), adaptation of its technological regime, and strict testing in the relevant model systems, instead of relying on generic passport data or the standard viscosity/gel strength tests used to characterize most other hydrocolloids.

The developed methods for assessing key functional parameters (critical gelation concentration, syneresis, moisture content, water-holding capacity, and gel plasticity) demonstrate robust practical and diagnostic performance. They provide a reproducible foundation for objective quality control of raw materials and finished products, for comparing samples of different origins, and for predicting the behaviour of κ-carrageenan in complex food matrices, which is a necessary condition for targeted control of its technological properties.

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