

## Techno-functional gelling mechanism and rheological properties of gelatin capsule-waste gel modified with kappa-carrageenan for future functional food applications

Sasina Sanprasert <sup>a</sup>, Pudthaya Kumnerdsiri <sup>a</sup>, Anusorn Seubsai <sup>b</sup>, Piyangkun Lueangjaroenkit <sup>c</sup>, Jaksuma Pongsetkul <sup>d</sup>, Tanyamon Petcharat <sup>e</sup>, Pimonpan Kaewprachu <sup>f</sup>, Samart Sai-ut <sup>g</sup>, Saroat Rawdkuen <sup>h</sup>, Narudol Teerapattarakarn <sup>i</sup>, Wanli Zhang <sup>j</sup>, Young Hoon Jung <sup>k</sup>, Passakorn Kingwascharapong <sup>a,\*</sup>

<sup>a</sup> Department of Fishery Products, Faculty of Fisheries, Kasetsart University, Bangkok 10900, Thailand

<sup>b</sup> Department of Chemical Engineering, Faculty of Engineering, Kasetsart University, Bangkok 10900, Thailand

<sup>c</sup> Department of Microbiology, Faculty of Science, Kasetsart University, Bangkok 10900, Thailand

<sup>d</sup> School of Animal Technology and Innovation, Institute of Agricultural Technology, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand

<sup>e</sup> Professional Culinary Arts Program, School of Management, Walailak University, Thasala, Nakhon Si Thammarat 80161, Thailand

<sup>f</sup> Cluster of Innovation for Sustainable Seafood Industry and Value Chain Management, Faculty of Agro-Industry, Chiang Mai University, Samut Sakhon 74000, Thailand

<sup>g</sup> Department of Food Science, Faculty of Science, Burapha University, Chonburi 20131, Thailand

<sup>h</sup> Unit of Innovative Food Packaging and Biomaterials, School of Agro-Industry, Mae Fah Luang University, Chiang Rai 57100, Thailand

<sup>i</sup> School of Medicine, Mae Fah Luang University, Chiang Rai 57100, Thailand

<sup>j</sup> School of Food Science and Engineering, Hainan University, Haikou, 570228, PR China

<sup>k</sup> School of Food Science and Biotechnology, College of Agriculture and Life Sciences, Kyungpook National University, Daegu 41566, South Korea

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### ABSTRACT

Gelatin capsule production generates large amounts of waste. Repurposing this waste into hydrogels offers a sustainable solution. This study investigated the techno-functional gelling mechanism and rheological properties of gelatin waste gel with added carrageenan, aiming to enhance the gel's potential for future functional food applications. Gelatin capsule waste (GCW) was substituted with carrageenan at different levels (0 %, 10 %, 20 %, 30 %, 40 %, or 50 % w/w). The texture profile analysis and gel strength increased with the addition of carrageenan, accompanied by changes in the spectra obtained from Synchrotron Radiation-based Fourier-Transform Infrared Spectroscopy (SR-FTIR), which identified intermolecular and intramolecular interactions between the gelatin and carrageenan. The rheological measurements revealed that the incorporation of carrageenan influenced the elastic modulus ( $G'$ ) and loss modulus ( $G''$ ) of the substituted GCW gel, as observed from the temperature sweep, which coincided with the higher gelling and melting temperatures ( $p < 0.05$ ). The substituted GCW gels had a higher turbidity than the GCW gel without substitution, as confirmed by a decreased  $L^*$  value. The water activity of the GCW gel remained stable with the addition of carrageenan. Based on the gel microstructure, the GCW gel had a looser gel network with larger voids, whereas the substituted gels had a finer network with smaller voids. However, there was a decrease in the overall likeness score for the gels substituted with carrageenan, especially at higher levels. In summary, the incorporation of carrageenan into GCW gel significantly influenced its rheological and textural properties. At an optimal substitution level, the GCW gel with carrageenan had strong potential as a functional material for food applications, particularly in soft confectionery.

### 1. Introduction

Gelatin is a denatured fibrous protein derived from collagen found in

connective tissues (Charoenchaitrakool et al., 2024). Typically, it is produced through the partial hydrolysis of materials such as animal skin, cow bones, and fish scales (Kumnerdsiri et al., 2024; Zhang et al., 2024).

\* Corresponding author.

E-mail address: [passakorn.ki@ku.th](mailto:passakorn.ki@ku.th) (P. Kingwascharapong).

Owing to its unique functional and technological properties, gelatin has been applied extensively in the food, pharmaceutical, cosmetic, and photography industries (Zhang et al., 2024). The global gelatin market, valued at USD 6.08 billion in 2022, is projected to reach USD 13.14 billion by 2030 (Charoenkool et al., 2024). According to data from Service Pack Manufacturing Company, a soft gel capsule manufacturer in Pathum Thani province, Thailand, the production process generates a large amount of gelatin waste, with around 20–30 % of the gelatin used in capsule production ending up as waste, totaling approximately 1 tonne per month (Charoenchaitrakool et al., 2024; Sanprasert et al., 2025). This gelatin waste cannot be directly reused, as the manufacturing process can alter key properties such as light and water barrier functions or solubility (Kummerdtsiri et al., 2024). However, exploring ways to utilize this waste is crucial as it provides solutions to lower disposal costs, reduce environmental pollution, and promote sustainability. Reusing, recycling, and upcycling this waste not only minimize waste management expenses and environmental harm but also support the Sustainable Development Goals (SDGs) set forth in the United Nation's 2030 agenda for achieving a "Zero Carbon Emissions" future (Kummerdtsiri et al., 2024). Thus, transforming gelatin capsule waste into valuable products presents an intriguing opportunity.

Hydrogels are cross-linked polymeric networks prepared from hydrophilic polymers, which can absorb and retain a high-water content while maintaining their three-dimensional integrity (Chen, 2020). Due to their unique properties, hydrogels have a broad range of uses, including in food processing, cosmetics, drug delivery, tissue engineering, flexible electronics, soft robotics, sensors, actuators, and thermal insulation (Ishwarya S et al., 2022). In the food industry, hydrogels are used in food formulation and are commonly found in gel-based or confectionery hydrogel products such as fluid gels (pseudo gels), soft gels (weak gels), and hard gels (strong gels) (Casas-Forero et al., 2022; Zhang et al., 2020). In addition, hydrogels are utilized in the production of food for the elderly, jelly confectionery, 3D-printed food, and fat mimetics (Garcia et al., 2024; Zhang et al., 2020; Zheng et al., 2023). Natural food proteins, particularly gelatin, are used widely in hydrogel production due to their excellent gelation properties (Liu et al., 2021; Mushtaq et al., 2022). Repurposing gelatin capsule waste for hydrogel fabrication offers a promising and sustainable approach. However, preliminary findings indicated that gels produced from gelatin capsule waste have low gelation and melting temperatures, along with weak gel strength. These limitations must be addressed to enable their effective application in food systems. Numerous modification techniques have been developed to enhance the properties of gelatin gels, including chemical (for example, phosphorylation, aldehydration, and phenolation), physical (including the addition of electrolytes or non-electrolyte substances), enzymatic methods (such as transglutaminase, tyrosinase, and laccase), and composite modifications (such as addition of polysaccharides) (Azmir et al., 2025; Cheng et al., 2022; Liu et al., 2025). Among these methods, composite modification has shown greater efficiency than the other approaches. (Liu et al., 2025). One of the polysaccharides effectively utilized to modify gelatin gels for the food industry is  $\kappa$ -carrageenan (Derkach et al., 2018).

$\kappa$ -Carrageenan (KC) is a negatively charged anionic polysaccharide composed of alternating  $\alpha$ -(1–3)-D-galactopyranose and  $\beta$ -(1–4)-3,6-anhydro-D-galactopyranose units, extracted from red algae (Xu et al., 2025). KC is widely used in the food industry as a thickening and stabilizing agent due to its valuable properties, including biodegradability, strong water retention, and its desirable emulsification, thickening, and gelation capabilities (Tao et al., 2025; Xu et al., 2025). Although some studies have examined the influence of  $\kappa$ -carrageenan on gelatin gel properties, research remains limited on the effects of polysaccharide addition to gelatin gels derived from gelatin capsule waste. Therefore, the current study utilized gelatin capsule waste (GCW) to prepare composite hydrogels by incorporating  $\kappa$ -carrageenan at varying concentrations. The physicochemical and functional properties of the developed gels were analyzed to enhance understanding of GCW gels,

providing insights for designing edible hydrogels with improved functionality. Additionally, this approach supports waste utilization in the nutraceutical industry, aligning with the United Nation's SDGs.

## 2. Material and methods

### 2.1. Materials

Ethanol (food grade) was purchased from the Excise Department (Bangkok, Thailand). Carrageenan 5744 (Lot no. 240,507) was purchased from Thai Food and Chemical (Samut Prakan, Thailand).

### 2.2. Preparation of gelatin capsule waste

The GCW was obtained from Service Manufacturing Co., Ltd., Thailand. The samples were placed in polyethylene bags and transported to the Department of Fishery Products, Faculty of Fisheries, Kasetsart University, Bangkok, Thailand, where they were stored at 4 °C. Upon receipt, the samples were washed three times with 95 % ethanol to remove oil residues and unwanted debris (Kummerdtsiri et al., 2024). Then, the cleaned samples were then repackaged in polyethylene bags and stored at 4 °C for further analysis.

### 2.3. Preparation of gelatin capsule-waste gel

Each sample of the washed GCW (6.67 g) was mixed with distilled water (100 g). Then, the carrageenan was added into the gelatin solution at different levels (10 %, 20 %, 30 %, 40 %, or 50 % gelatin substitution) to produce the final solid concentration of 6.67 % (w/v). Next, the mixture was stirred until it became homogeneous using a hot plate magnetic stirrer (C-MAG HS 10; IKA; Germany) at 70 °C. Subsequently, each sample solution was transferred into a cylindrical mold (3 cm diameter and 2.5 cm height) and kept at 4 °C for 24 h. Afterward, the solidified gel was removed from the mold for further analysis.

## 3. Analysis

### 3.1. Proximate analysis

The fat, protein, ash, and moisture contents of each GCW gel were determined according to the AOAC (2019) method.

### 3.2. Water activity

The water activity of each GCW gel was measured using a water activity meter (4TE; AQUALAB; USA) with the measurement repeated three times.

### 3.3. Color measurement

The color of each GCW gel was analyzed using a Hunter Lab Colorimeter (Ultra Scan VIS; Hunter Lab; USA). The L\*, a\*, and b\* color values represent brightness, redness/greenness, and yellowness/blueness, respectively. The measurements were repeated 15 times.

### 3.4. Visualization of gel stability

The stability of each GCW gel was analyzed by storing the sample at room temperature and taking a photograph every 10 min for a total of 40 min to observe the changes.

### 3.5. Syneresis

The syneresis was calculated based on a modification of the method by Petcharat et al. (2025) in which each GCW sample was mixed with distilled water and carrageenan at concentrations of 10 %, 20 %, 30 %,

40 %, or 50 % (w/v). Then, the mixture was stirred until it became homogeneous using a hot plate magnetic stirrer (C-MAG HS 10; IKA, Germany) at 70 °C. Each solution (30 mL) was poured into a 50 mL centrifuge tube and the mass ( $m_1$ ) was recorded, followed by chilling at 4 °C for 18 h. Then, it was centrifuged at 5000 rpm and 4 °C for 10 min using a refrigerated centrifuge (UNIVERSAL 32R; Hettich; Kirchlengern, Germany). After centrifugation, the water on top of the solution was wiped off, being careful not to touch the solution. The tube was weighed ( $m_2$ ). The syneresis was calculated using the equation:

$$\% \text{Syneresis} = \frac{m_1 - m_2}{m_1} \times 100$$

### 3.6. Texture profile analysis

Each GCW gel was subjected to texture profile analysis (TPA) using a texture analyzer (TA.XT Plus; Stable Micro Systems; UK) with a cylindrical aluminum probe (P/50). The measurement mode was set to TPA, with a pre-test speed of 1 mm/s, a test speed of 5 mm/s, and a post-test speed of 5 mm/s, applying 50 % strain. The parameters determined were hardness, adhesiveness, springiness, cohesiveness, gumminess, and chewiness. The measurements were repeated 15 times.

### 3.7. Gel strength determination

The gel strength of each GCW was measured using a texture analyzer (TA.XT Plus; Stable Micro Systems; UK) with a cylindrical probe (P00.5). The measurement mode was set to GMIA Gelatin Bloom, with the test speed at 1 mm/sec and a distance of 4 mm. The parameter determined was the Gel Strength/Bloom (g). The measurements were repeated 15 times.

### 3.8. Determination of gelling and melting temperatures

All sample solutions (6.67 %, w/v, 60 °C) were prepared as described previously. The gelling and melting temperatures of all samples were determined using a rheometer (MCR302; Anton Paar; Austria) according to the method of [Petcharat and Benjakul \(2017\)](#). The measuring equipment consistent of a 2.5 cm parallel plate and the gap was set at 1.0 mm. A sample was transferred to the rheometer and the measurement was performed at a scan rate of 1 °C/min, a frequency of 1 Hz, an oscillating applied strain of 1 % during cooling from 60 to 5 °C and heating from 5 to 90 °C. The elastic modulus ( $G'$ ) and the loss (viscous) modulus ( $G''$ ) were recorded. Finally, the gelling and melting temperatures were determined as the temperatures, at which  $\tan \delta$  ( $G'' / G'$ ) equaled 1 (or  $\delta = 45$ ).

### 3.9. Scanning electron microscopy (SEM)

The microstructure of each GCW gel was visualized using SEM (Quanta400; FEI; Tokyo, Japan) at an accelerating voltage of 15 kV. Prior to visualization, each sample was mounted on a brass stub and sputter-coated with gold to make it conductive.

### 3.10. Synchrotron radiation-based fourier-transform infrared spectroscopy (SR-FTIR)

The biomolecular structures of the gelatin powders were analyzed using SR-FTIR spectroscopy (Bruker Tensor 27 Infrared Spectrometer coupled with DTGS detectors (Deuterated alanine-doped Tri-Glycine Sulphate)), following the method of ([Pongsetkul et al., 2024](#)). Each treatment was replicated six times. FTIR spectra of biomolecules were acquired using a Vertex 70 spectrometer with an IR microscope (Hyperion 2000), operated using the OPUS 7.5 software (Bruker Optics Ltd.; Ettlingen, Germany). Spectra were recorded in the range 4000–400 cm<sup>-1</sup> with a resolution of 4 cm<sup>-1</sup> and 64 scans per sample. Each sample was

replicated 30 times, yielding 180 spectra per sample. The spectra were processed using the Unscrambler X (version 10.5), with second derivative and Savitzky-Golay smoothing, followed by vector normalization. Principal component analysis (PCA) was used to assess data variability. The peaks of interest in the range 900–1800 cm<sup>-1</sup>, referring to C=C bending, C—O stretching, NH bending, CH<sub>3</sub> bending, CH<sub>2</sub> wagging, CH<sub>2</sub> bending, NH bending coupled with C—N stretching, and C=O stretching, were baseline corrected, followed by curve fitting using Gaussian and Lorentzian functions in the OPUS 7.5 software. After integrating subpeak areas within this range, results were expressed as relative percentages.

### 3.11. Sensory property

Each sample solution was poured into a tasting cup (size 30 ml) labeled with a 3-digit random number. The samples were kept at 4 °C until the sensory evaluation was performed. The 30 non-trained panelists were students and staff from the Department of Fishery Products, Faculty of Fisheries, Kasetsart University, Bangkok. All panelists were asked to assess the appearance, color, odor, flavor, taste, texture, and overall liking of each gel sample using a 9-point hedonic scale. During the testing, participants were asked to rinse their mouths with room temperature water between samples.

## 4. Statistical analysis

A completely randomized design (CRD) was used for this study. All experiments were conducted in triplicate ( $n = 3$ ). Data analysis was performed using analysis of variance (one-way ANOVA) with the SPSS software package (SPSS 23.0 for Windows, SPSS Inc.; Chicago, IL, USA). The significance of the means was determined using Duncan's multiple range test with a confidence level of 95 % ( $p < 0.05$ ). Sensory data were analyzed using a randomized complete block design (RCBD) and Duncan's multiple range test, with significance tested at the  $p < 0.05$  level.

## 5. Results and discussion

### 5.1. Proximate analysis

Proximate analysis classifies food components into five key categories: moisture, ash, protein, fat, and fiber ([Chan et al., 2013](#)). The proximate result of the GCW substituted with various levels of carrageenan substitution is shown in [Table 1](#). The control sample

**Table 1**

Proximate composition of gelatin capsule-waste gel with various levels of carrageenan substitution.

Sample	Moisture (%)	Fat (%)	Ash (%)	Protein (%)	Carbohydrate (%)
CFG	93.84 ± 0.02 <sup>d</sup>	0.05 ± 0.00 <sup>b</sup>	0.03 ± 0.01 <sup>f</sup>	5.95 ± 0.08 <sup>a</sup>	0.14 ± 0.08 <sup>e</sup>
GCW	96.08 ± 0.13 <sup>a</sup>	0.03 ± 0.01 <sup>b</sup>	0.01 ± 0.00 <sup>f</sup>	2.65 ± 0.06 <sup>b</sup>	1.24 ± 0.08 <sup>d</sup>
10 %C	95.22 ± 0.21 <sup>b</sup>	0.05 ± 0.03 <sup>ab</sup>	0.23 ± 0.03 <sup>e</sup>	2.48 ± 0.03 <sup>c</sup>	2.02 ± 0.24 <sup>c</sup>
20 %C	94.99 ± 0.30 <sup>bc</sup>	0.10 ± 0.03 <sup>a</sup>	0.38 ± 0.04 <sup>d</sup>	2.28 ± 0.05 <sup>d</sup>	2.25 ± 0.30 <sup>c</sup>
30 %C	94.70 ± 0.32 <sup>c</sup>	0.04 ± 0.03 <sup>b</sup>	0.57 ± 0.02 <sup>c</sup>	1.92 ± 0.03 <sup>e</sup>	2.78 ± 0.36 <sup>b</sup>
40 %C	93.81 ± 0.25 <sup>d</sup>	0.07 ± 0.04 <sup>ab</sup>	0.64 ± 0.02 <sup>b</sup>	1.57 ± 0.11 <sup>f</sup>	3.90 ± 0.13 <sup>a</sup>
50 %C	93.62 ± 0.24 <sup>d</sup>	0.03 ± 0.01 <sup>b</sup>	0.81 ± 0.08 <sup>a</sup>	1.39 ± 0.05 <sup>g</sup>	4.15 ± 0.22 <sup>a</sup>

Note: Commercial fish gelatin: CFG, Gelatin capsule waste: GCW, 10 % Carrageenan substitution: 10 %C, 20 % Carrageenan substitution: 20 %C, 30 % Carrageenan substitution: 30 %C, 40 % Carrageenan substitution: 40 %C, and 50 % Carrageenan substitution: 50 %C. Values (mean ± standard deviation) with different letters in same column are significantly different ( $p < 0.05$ ).

(commercial fish gelatin; CFG) had the highest protein content and the lowest carbohydrate content of all samples, perhaps due to the control sample being made from pure gelatin without any added substances. In contrast, the GCW samples could have contained additional substances, such as plasticizers used in gelatin capsule production, which could have directly altered the protein content in the gelatin gel. The increase in the carbohydrate content in the GCW treatments compared to the control might be attributed to the addition of the κ-carrageenan, a natural carbohydrate (polysaccharide) source. This results was in accordance with [Minguito \(2023\)](#), who reported that the addition of gummy κ-carrageenan in guyabano (*Annona muricata*) candy resulted in an increase in the carbohydrate content and a decrease in the fat content. Based on the current results, there was a lower moisture content in the GCW samples containing κ-carrageenan, postulated as being due to the addition of κ-carrageenan facilitating the formation of a tightly bound gel network, resulting in water being squeezed out of the gel structure. This was consistent with the higher gel strength observed at higher concentrations of κ-carrageenan. In addition, this result was consistent with the findings of [Çelebi and Erge \(2024\)](#), who reported that the addition of carrageenan to their sausage formulation decreased the moisture content compared to the control. Therefore, the addition of κ-carrageenan, especially κ-carrageenan at a high level, altered the proximate composition of the GCW gels.

## 5.2. Water activity ( $a_w$ )

Water activity is a key factor in food products, influencing their shelf life, quality, and sensory characteristics ([Gok et al., 2020](#); [Tarahi et al., 2023](#)). Based on the current results, the water activity of GCW gel with various levels of carrageenan substitution is shown in [Table 2](#). The water activity values of the gel samples were in the range 0.99–1, with no significant differences, likely due to their soft and jelly-like nature. This result was expected and was consistent with the findings of [Amin et al. \(2022\)](#), who reported that the addition of carrageenan at higher concentrations did not affect the water activity of jam made from the honey pineapple (*Ananas comosus* [L.] Merr.). In general, hydrocolloids, particularly carrageenan, have the ability to reduce the amount of free water and bind large quantities of water molecules ( $H_2O$ ) due to the presence of free hydroxyl (OH) groups, thereby lowering the water activity in food products ([Udo et al., 2023](#)). However, the gel derived from GCW is classified as a high-water-content product; therefore, the incorporation of a lower amount of carrageenan as a substitution agent

**Table 2**  
Chemical properties and physicochemical properties of gelatin capsule-waste gel with various levels of carrageenan substitution.

Sample	$a_w$	Syneresis (%)	Color		
			$L^*$	$a^*$	$b^*$
CFG	1.00 ± 0.00 <sup>a</sup>	0.27 ± 0.08 <sup>ab</sup>	31.98 ± 2.27 <sup>b</sup>	-1.18 ± 0.13 <sup>d</sup>	1.01 ± 0.42 <sup>d</sup>
	0.99 ± 0.00 <sup>b</sup>	0.32 ± 0.02 <sup>a</sup>	35.37 ± 1.56 <sup>a</sup>	-1.47 ± 0.07 <sup>e</sup>	4.13 ± 0.44 <sup>c</sup>
10 %C	1.00 ± 0.00 <sup>ab</sup>	0.26 ± 0.01 <sup>ab</sup>	34.72 ± 3.61 <sup>a</sup>	-1.11 ± 0.15 <sup>d</sup>	6.09 ± 0.35 <sup>b</sup>
	1.00 ± 0.00 <sup>a</sup>	0.23 ± 0.02 <sup>bc</sup>	28.03 ± 1.55 <sup>c</sup>	-0.46 ± 0.17 <sup>c</sup>	6.91 ± 1.15 <sup>ab</sup>
20 %C	1.00 ± 0.00 <sup>a</sup>	0.18 ± 0.00 <sup>c</sup>	29.62 ± 4.17 <sup>bc</sup>	-0.27 ± 0.16 <sup>b</sup>	7.31 ± 1.34 <sup>a</sup>
	1.00 ± 0.00 <sup>a</sup>	0.17 ± 0.05 <sup>c</sup>	28.11 ± 2.46 <sup>c</sup>	-0.23 ± 0.22 <sup>b</sup>	6.44 ± 1.62 <sup>ab</sup>
30 %C	1.00 ± 0.00 <sup>a</sup>	0.09 ± 0.01 <sup>d</sup>	27.67 ± 1.82 <sup>c</sup>	0.12 ± 0.20 <sup>a</sup>	6.85 ± 1.48 <sup>ab</sup>
	1.00 ± 0.00 <sup>a</sup>	0.09 ± 0.01 <sup>d</sup>	27.67 ± 1.82 <sup>c</sup>	0.12 ± 0.20 <sup>a</sup>	6.85 ± 1.48 <sup>ab</sup>

Note: Commercial fish gelatin: CFG, Gelatin capsule waste: GCW, 10 % Carrageenan: 10 %C, 20 % Carrageenan: 20 %C, 30 % Carrageenan: 30 %C, 40 % Carrageenan: 40 %C, 50 % Carrageenan: 50 %C.

Values (mean ± standard deviation) with different letters in same column are significantly different ( $p < 0.05$ ).

did not significantly reduce its water activity. Although the GCW gel samples had high water activity, they remain promising for further development as a jelly product. In general, the water activity of soft confectionery, such as jellies, gummies and candy, varies depending on the product type, production technology, and composition ([Atalar et al., 2025](#)). Thus, the addition of carrageenan did not substantially affect the water activity of the GCW gels.

## 5.3. Color

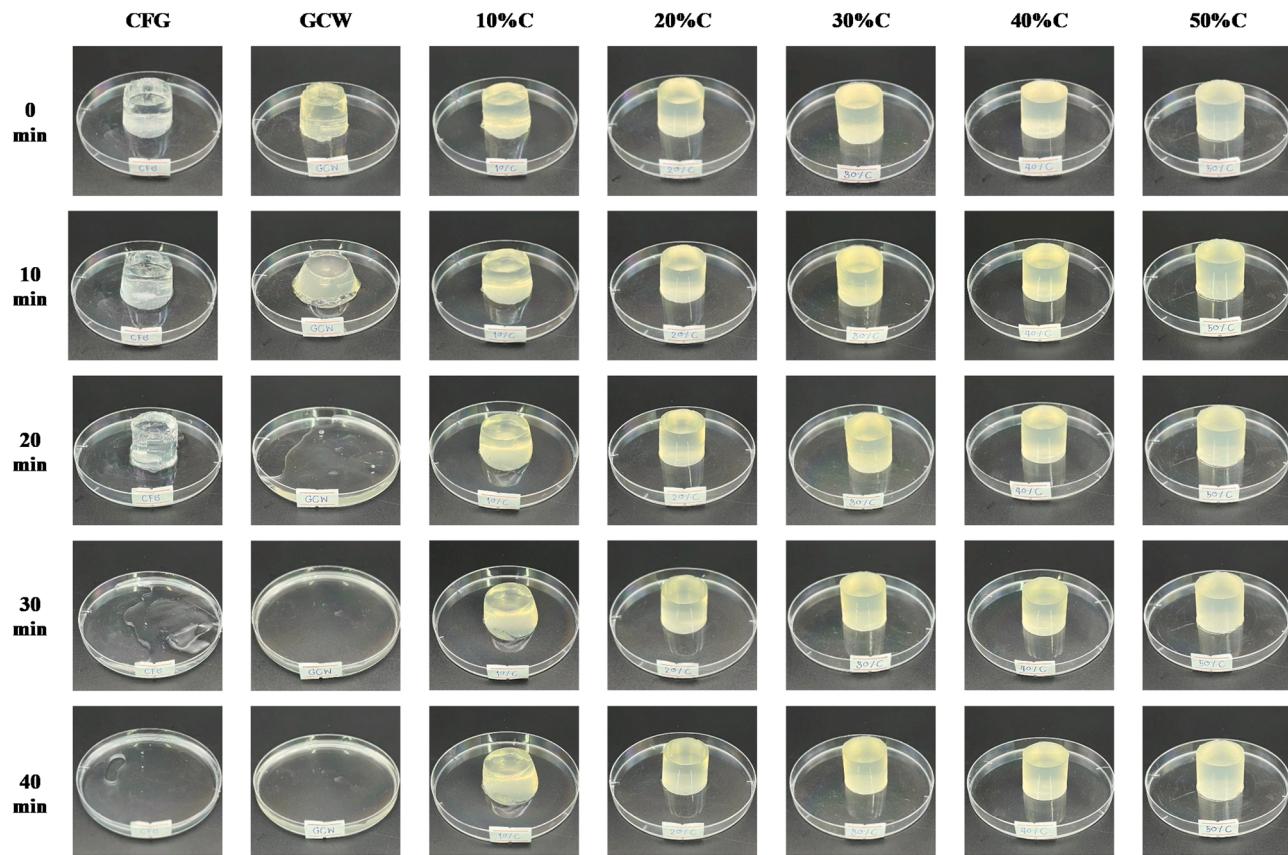
Color is considered as one of the most important quality attributes used for the evaluation of food quality. The color parameters ( $L^*$ ,  $a^*$ , and  $b^*$ ) and the physical appearance of the GCW gels with varying levels of carrageenan substitution are presented in [Table 2](#) and [Fig. 1](#), respectively. The CFG had the highest lightness ( $L^*$ ), lowest redness ( $a^*$ ) and yellowness ( $b^*$ ) values of all gel samples. The lightness ( $L^*$ ) of the GCW gels decreased significantly with increasing levels of carrageenan substitution. This coincided with the increased opaqueness of the gels ([Fig. 1](#)). These results suggested there had been a heterogeneous interaction between polymers, where the formation of aggregates may have contributed to light scattering, resulting in increased turbidity ([Sinthusamran and Benjakul, 2018](#)). [Sinthusamran et al. \(2017\)](#) reported that the color of hydrocolloids, as well as their dispersion and interaction, influences the overall appearance of a mixed gel. Furthermore, in the current study, there was significantly higher yellowness in the GCW gel and those substituted with carrageenan at all levels compared to the control gel (CFG). This could be attributed to the naturally yellowish color of GCW. Additionally, during the gelation process of GCW at high temperatures, free amino acids may be more exposed and could react with the lipids and sugars present in the GCW, potentially leading to the formation of yellow pigments through the Maillard reaction. Thus, based on the results of the current study, the incorporation of carrageenan directly influenced the color and appearance of the GCW gels.

## 5.4. Visualization of gel stability

The appearance of GCW gel substituted with various levels of carrageenan is shown in [Fig. 1](#). The GCW gel without carrageenan substitution had the lowest stability of all the gels. The commercial fish gelatin (CFG) gel had slightly greater stability than GCW. The presence of carrageenan within the gel network led to the formation of opaque or turbid gels, which was consistent with the report from [Zampouni et al. \(2023\)](#). This action was due to the formation of a more compact structure resulting from the interaction between the oppositely charged chains of gelatin and carrageenan ([Zampouni et al., 2023](#)). Therefore, the appearance of the GCW gels was affected by the level of carrageenan substitution.

## 5.5. Syneresis

Syneresis is an important phenomenon in aqueous physical gels that impacts flavor release and various food applications. It refers to the leakage of liquid from solid products such as jellies, jams, and dairy products ([Zahedi et al., 2024](#)). Syneresis associated with the GCW gel with various levels of carrageenan substitution is shown [Table 2](#). The level of syneresis was higher in the GCW gel compared to the control (CFG) gel. This increased syneresis may have been due to a weaker gel network that was unable to retain water within its structure. When carrageenan was added to GCW, the syneresis level decreased, irrespective of the concentration used. The lowest syneresis was in 50 %C, which could have been due to the interaction between gelatin and carrageenan through hydrogen bonding, hydrophobic interactions, and electrostatic forces ([Liu et al., 2025](#)). As a result, the more compact structure had less space for water entrapment. Therefore, carrageenan played an important role in the water holding capacity of the GCW gel.



**Fig. 1.** Appearance of gelatin capsule-waste gel substituted with various levels of carrageenan during storage at 30 °C for 40 min. Note: Commercial fish gelatin: CFG, Gelatin capsule waste: GCW, 10 % Carrageenan: 10 %C, 20 % Carrageenan: 20 %C, 30 % Carrageenan: 30 %C, 40 % Carrageenan: 40 %C, 50 % Carrageenan: 50 %C.

### 5.6. Texture properties

Texture is an important quality attribute that affected the palatability, mouthfeel and swallowing properties of gel food (Lyu et al., 2023). The results of the texture profile analysis of the GCW gel substituted with various levels of carrageenan is shown in Table 3. Hardness is defined as the force required to compress a material between the teeth or between the tongue and palate, typically measured by the maximum peak force (Lyu et al., 2023). The GCW gel had the lowest hardness, likely due to the presence of plasticizer agents, such as glycerol and other active compounds, which may have reduced the gel's hardness. As the carrageenan content increased, there was an increasing trend in the hardness of the gels. The significantly highest hardness was in the 50 %C sample, because electrostatic interactions existed between the GCW and carrageenan, where the negatively charged sulfated groups on carrageenan could interact with the positively charged amino

groups on proteins (-OSO<sub>3</sub>-NH<sub>3</sub><sup>+</sup>) (Lu et al., 2023). This trend was similar for gel strength and was consistent with the findings from other studies such as fish gelatin gel (Geng et al., 2024; Wang et al., 2023a) and plant-based egg systems (Lu et al., 2022). Springiness refers to the ability of a food product to return to its undeformed state after being stretched (Lyu et al., 2023). The significantly highest springiness was in the GCW gel, because the plasticizer localized within the GCW gel matrix may have enhanced the gel's elastic properties, resulting in increased springiness. As the carrageenan content increased, the springiness of the GCW gels consistently decreased. The decreased springiness indicated the brittle characteristics of the GCW gel. Typically, carrageenan gels are less springy and are broken easily during compressive testing (Sinthusamran et al., 2017). Petcharat and Benjakul (2017) reported that fish gelatin gel became more brittle (lower springiness) when gellan gum was added. Furthermore, in the current study, the addition of κ-carrageenan resulted in increased cohesiveness, chewiness, and

**Table 3**

Texture profile analysis and gel strength of gelatin capsule-waste gel substituted with various levels of carrageenan.

Sample	Texture profile analysis						Gel strength/ Bloom value (g)
	Hardness (N)	Adhesiveness (N.sec)	Springiness (cm)	Cohesiveness	Gumminess (N)	Chewiness (N.cm)	
CFG	18.75 ± 1.94 <sup>c</sup>	-1.00 ± 0.50 <sup>c</sup>	0.95 ± 0.02 <sup>b</sup>	0.91 ± 0.02 <sup>a</sup>	17.09 ± 1.64 <sup>b</sup>	16.32 ± 1.64 <sup>b</sup>	123.90 ± 7.85 <sup>e</sup>
GCW	3.77 ± 0.42 <sup>d</sup>	-0.02 ± 0.05 <sup>a</sup>	1.74 ± 0.78 <sup>a</sup>	0.91 ± 0.01 <sup>a</sup>	3.41 ± 0.40 <sup>c</sup>	5.96 ± 2.76 <sup>c</sup>	25.03 ± 1.48 g
10 %C	10.71 ± 0.91 <sup>cd</sup>	-0.60 ± 0.23 <sup>b</sup>	0.94 ± 0.02 <sup>b</sup>	0.78 ± 0.00 <sup>de</sup>	3.16 ± 0.95 <sup>c</sup>	3.20 ± 1.19 <sup>c</sup>	50.37 ± 4.10 <sup>f</sup>
20 %C	19.78 ± 2.85 <sup>c</sup>	-0.91 ± 0.65 <sup>bc</sup>	0.89 ± 0.04 <sup>b</sup>	0.21 ± 0.02 <sup>de</sup>	8.36 ± 0.73 <sup>c</sup>	7.84 ± 0.83 <sup>c</sup>	151.98 ± 13.34 d
30 %C	41.53 ± 2.92 <sup>b</sup>	-0.65 ± 0.66 <sup>b</sup>	0.87 ± 0.02 <sup>b</sup>	0.23 ± 0.02 <sup>d</sup>	10.15 ± 1.33 <sup>bc</sup>	8.52 ± 0.77 <sup>c</sup>	374.06 ± 35.67 c
40 %C	42.90 ± 15.21 <sup>b</sup>	-0.58 ± 0.51 <sup>bc</sup>	0.78 ± 0.06 <sup>b</sup>	0.18 ± 0.06 <sup>e</sup>	11.39 ± 3.60 <sup>bc</sup>	8.89 ± 2.86 <sup>c</sup>	535.65 ± 47.81 b
50 %C	86.26 ± 35.42 <sup>a</sup>	-0.37 ± 0.23 <sup>ab</sup>	0.76 ± 0.03 <sup>b</sup>	0.41 ± 0.09 <sup>c</sup>	38.25 ± 19.92 <sup>a</sup>	9.03 ± 15.02 <sup>a</sup>	676.11 ± 17.85 <sup>a</sup>

Commercial fish gelatin: CFG, Gelatin capsule waste: GCW, 10 % Carrageenan: 10 %C, 20 % Carrageenan: 20 %C, 30 % Carrageenan: 30 %C, 40 % Carrageenan: 40 %C, 50 % Carrageenan: 50 %C.

Values (mean ± standard deviation) with different letters in same column are significantly different ( $p < 0.05$ ).

gumminess, which may be attributed to the formation of a more compact gel structure, as previously discussed. This finding was consistent with the study by [Saengsuk et al. \(2022\)](#), who reported similar effects when using  $\kappa$ -carrageenan in restructured pork steak. Therefore, the carrageenan level was a major factor influencing the texture of the GCW gels.

### 5.7. Gel strength

Gel strength is one of the crucial factors in the assessment of the gelling properties of gelatin ([Geng et al., 2024](#)). The gel strength in the current study of the GCW gel substituted with various levels of carrageenan is shown in [Table 3](#). The GCW had the lowest gel strength (~25 g), while CFG had a significantly higher gel strength (~123 g). The gel strength of the GCW mixed gels increased with a higher carrageenan content, reaching a maximum (~676 g) at the highest carrageenan level (50 %C). The increase in the gel strength of GCW substituted with carrageenan might have been due to the interaction between the negatively charged sulphate groups of carrageenan and the positively charged chains of GCW ([Qiao et al., 2024; Saengsuk et al., 2022; Wang et al., 2023a](#)). Therefore, the incorporation of carrageenan enhanced the gel strength of GCW in a dose-dependent manner.

### 5.8. Rheological behavior

The changes in the rheological properties of the blended system were determined by measuring the storage modulus ( $G'$ ) and loss modulus ( $G''$ ) and are presented in [Supplementary Fig. S1](#) and [S2](#). Upon cooling the solution to 5 °C, the values of both  $G'$  and  $G''$  in all gel samples increased rapidly, indicating that gelation occurred through the aggregation of molecular helices within the solution ([Cheng et al., 2022](#)). The crossover of  $G'$  and  $G''$  marks the transition from sol to gel, with this point corresponding to the gel temperature ([Zhou et al., 2023](#)). At the cross-over point, gelatin molecules transitioned from a random coil to a helical conformation (rigid form), resulting in the entrapment of water within the gel matrix ([Sinthusamran et al., 2017](#)). [Table 4](#) shows that the gelling point of control was  $19.72 \pm 0.33$  °C, similar to the typical gelling point of fish gelatin (8–25 °C) ([Zhao et al., 2021](#)). Notably, in the current study, GCW had the significantly lowest gelation point, perhaps due to the plasticizer and other substances interfering with hydrogen bond formation, which weakened the gel network. The gelling point for all gel samples increased with the increase in the carrageenan substitution level; in addition, the melting temperature increased. The gelling point and melting point followed the order: 50 %C > 40 %C > 30 %C > 20 %C > 10 %C > CFG > GCW, which was generally consistent with the observed trend in gel strength. These results were in accordance with [Wang et al. \(2023b\)](#), who reported that the gelling temperature of the blended gelatin and carrageenan systems increased with an increase in the carrageenan concentration and that the melting temperature also

**Table 4**

Gelling and melting temperatures of gelatin capsule-waste gel substituted with various levels of carrageenan.

Sample	Gelling temperature ( °C )	Melting temperature ( °C )
CFG	$19.72 \pm 0.33^f$	$26.40 \pm 0.26^b$
GCW	$15.47 \pm 0.35^g$	$24.70 \pm 0.36^c$
10 %C	$29.57 \pm 0.45^e$	$26.87 \pm 0.25^b$
20 %C	$36.70 \pm 0.61^d$	$33.93 \pm 0.06^a$
30 %C	$40.53 \pm 0.55^c$	>60
40 %C	$46.50 \pm 0.46^b$	>60
50 %C	$55.00 \pm 0.30^a$	>60

Note: Commercial fish gelatin: CFG, Gelatin capsule waste: GCW, 10 % Carrageenan: 10 %C, 20 % Carrageenan: 20 %C, 30 % Carrageenan: 30 %C, 40 % Carrageenan: 40 %C, 50 % Carrageenan: 50 %C.

Values (mean  $\pm$  standard deviation) with different letters in same column are significantly different ( $p < 0.05$ ).

increased. The highest gelling point was in the 50 %C sample. The presence of carrageenan promoted intramolecular and intermolecular interactions in the mixed gel, facilitating the formation of a network through the transition of gelatin chains from a single strand to a triple-helix structure via ionic interactions, hydrogen bonding, van der Waals forces, and hydrophobic associations ([Zhao et al., 2021](#)). On subsequent reheating, both  $G'$  and  $G''$  rapidly decreased, which was defined as the gel melting temperature ( $T_m$ ) ([Luo et al., 2023](#)). The  $T_m$  value is related to the energy required to break the cross-linked junction zones ([Derkach et al., 2018](#)). Therefore, the increase in the thermostability of gels may have resulted from either the formation of stronger junction zones or an increase in the number of junction zones ([Derkach et al., 2018](#)). The substitution of carrageenan into the GCW gel at levels higher than 30 % resulted in a melting temperature exceeding 60 °C ([Table 5](#)). Therefore, the substitution of carrageenan directly affected the GCW gel structure, especially at high concentrations.

### 5.9. SR-FTIR characteristics

The FTIR spectra in the fingerprint region (2000–800 cm<sup>-1</sup>) of GCW gel substituted with various levels of carrageenan are shown in [Supplementary Figs](#). The dominant bands in the product ([Supplementary Fig. S3](#)) were: C = C bending (900–950 cm<sup>-1</sup>), C–O stretching (950–1180 cm<sup>-1</sup>), N–H bending (1180–1300 cm<sup>-1</sup>), CH<sub>3</sub> bending and CH<sub>2</sub> wagging (1350–1420 cm<sup>-1</sup>), CH<sub>2</sub> bending (1430–1500 cm<sup>-1</sup>), N–H bending coupled with C–N stretching (1500–1590 cm<sup>-1</sup>), and C = O stretching (1600–1750 cm<sup>-1</sup>). Seven spectral clusters were clearly visualized in the PCA score plot ([Supplementary Fig. S4](#)), which explained about 28 % of the total variability of all data. PC1, retaining about 19 % of data variation, provided the major contribution of separating the samples according to the level of carrageenan used in the GCW gelling properties. The loading ([Supplementary Fig. S5](#)) and correlation loading ([Supplementary Fig. S6](#)) plots revealed some crucial spectra of biomolecules that could be used to differentiate among samples. Of the differentiated spectra, those in the range 950–1180 cm<sup>-1</sup> (including 923, 1001, 1038, 1069, 1092, and 1128 cm<sup>-1</sup>) corresponded to C–O stretching. This might be explained by the addition of carrageenan, which contributed to the C–O–C stretching vibration of 3,6-anhydro-D-galactose and the C–O–S stretching of galactose-4-sulfate ([Lyu et al., 2023](#)). To quantify changes in the most crucial spectra, the peaks in the range 800–2000 cm<sup>-1</sup> were subjected to curve-fitting analysis to evaluate the proportions of the secondary structures, as shown in [Supplementary Fig. S7](#). The integrated areas (%) are provided in [Table 5](#). As shown in [Table 5](#), the integral areas (%) of the C = C bending and C = O stretching followed an increasing trend with higher carrageenan concentrations, suggesting an interaction between the positively charged amide groups in the polypeptide chains of gelatin and the negatively charged sulfate groups in  $\kappa$ -carrageenan, leading to the formation of (bio)polyelectrolyte complexes ([Cheng et al., 2022; de Alcântara et al., 2020](#)). In general, the band observed around 920 cm<sup>-1</sup> corresponded to the C = O stretching vibration of 3,6-anhydro-D-galactose ([Cheng et al., 2022](#)), which may explain the higher integral areas (%) found in the gels containing carrageenan. Considering the functional group corresponding to Amide I (C = O stretching), the integral area (%) tended to decrease with increasing levels of carrageenan, suggesting the occurrence of electrostatic interactions between the gelatin and  $\kappa$ -carrageenan molecules ([Zampouni et al., 2023](#)). This result was consistent with [Zampouni et al. \(2023\)](#), who reported that the incorporation of  $\kappa$ -carrageenan into gelatin hydrogels resulted in decreased intensities of the Amide I (1635 cm<sup>-1</sup>) and Amide II (1564 cm<sup>-1</sup>) peaks. Overall, it was clear that the presence of carrageenan modified the structure of GCW.

### 5.10. Microstructure analysis

Images of the microstructure of the GCW gels substituted with various levels of carrageenan are provided in [Fig. 2](#). The GCW gel had a

**Table 5**

Integral area of functional groups of gelatins after curve fitting.

Sample	C = C bending	C-O stretching	NH bending	CH <sub>3</sub> bending wagging	CH <sub>2</sub> bending	NH bending coupled with C—N stretching	C = O stretching
<b>T1</b>	0.003 ± 0.0015 <sup>b</sup>	0.120 ± 0.0474 <sup>c</sup>	0.201 ± 0.0264 <sup>b</sup>	0.056 ± 0.0495 <sup>ab</sup>	0.187 ± 0.0255 <sup>a</sup>	1.711 ± 0.2707 <sup>a</sup>	8.983 ± 0.4948 <sup>a</sup>
							9.031 ± 0.3501 <sup>a</sup>
<b>T2</b>	0.008 ± 0.0083 <sup>b</sup>	0.281 ± 0.0323 <sup>d</sup>	0.063 ± 0.0024 <sup>c</sup>	0.000 ± 0.0000 <sup>b</sup>	0.052 ± 0.0374 <sup>b</sup>	0.849 ± 0.1314 <sup>c</sup>	9.058 ± 0.3501 <sup>a</sup>
							7.978 ± 0.4956 <sup>b</sup>
<b>T3</b>	0.001 ± 0.0017 <sup>b</sup>	1.009 ± 0.3400 <sup>b</sup>	0.085 ± 0.0422 <sup>c</sup>	0.023 ± 0.0332 <sup>b</sup>	0.039 ± 0.0671 <sup>b</sup>	0.512 ± 0.2441 <sup>c</sup>	9.058 ± 0.3714 <sup>a</sup>
							7.963 ± 0.5192 <sup>b</sup>
<b>T4</b>	0.004 ± 0.0018 <sup>b</sup>	0.171 ± 0.0237 <sup>d</sup>	0.038 ± 0.0139 <sup>c</sup>	0.022 ± 0.0057 <sup>b</sup>	0.021 ± 0.0101 <sup>b</sup>	0.742 ± 0.1915 <sup>c</sup>	8.128 ± 0.4116 <sup>b</sup>
							7.790 ± 0.6702 <sup>b</sup>
<b>T5</b>	0.022 ± 0.0224 <sup>b</sup>	0.290 ± 0.0957 <sup>d</sup>	0.075 ± 0.0653 <sup>c</sup>	0.000 ± 0.0000 <sup>b</sup>	0.000 ± 0.0000 <sup>b</sup>	0.549 ± 0.2114 <sup>c</sup>	7.963 ± 0.5192 <sup>b</sup>
							7.963 ± 0.5192 <sup>b</sup>
<b>T6</b>	0.060 ± 0.0068 <sup>b</sup>	0.741 ± 0.0885 <sup>c</sup>	0.223 ± 0.0183 <sup>b</sup>	0.037 ± 0.0116 <sup>b</sup>	0.003 ± 0.0059 <sup>b</sup>	0.728 ± 0.0922 <sup>c</sup>	7.963 ± 0.5192 <sup>b</sup>
							7.963 ± 0.5192 <sup>b</sup>
<b>T7</b>	0.135 ± 0.0255 <sup>a</sup>	1.737 ± 0.2115 <sup>a</sup>	0.426 ± 0.0594 <sup>a</sup>	0.176 ± 0.1080 <sup>a</sup>	0.062 ± 0.0190 <sup>b</sup>	1.108 ± 0.1454 <sup>b</sup>	8.128 ± 0.4116 <sup>b</sup>
							7.963 ± 0.5192 <sup>b</sup>

Note: T1 = commercial fish gelatin (CFG); T2 = gelatin capsule waste (GCW); T3 = GCW with 10% carrageenan (10%C); T4 = GCW with 20% carrageenan (20%C); T5 = GCW with 30% carrageenan (30%C); T6 = GCW with 40% carrageenan (40%C); T7 = GCW with 50% carrageenan (50%C).

Values (mean ± standard deviation) with different letters in same column are significantly different ( $p < 0.05$ ).

coarser network with larger voids or cavities. With increasing levels of carrageenan substitution, the network became finer with smaller voids. These changes could have been due to the sulfate group of carrageenan reacting with the positively charged areas of fish gelatin through ionic interactions (Geng et al., 2024). In addition, the intramolecular and intermolecular hydrogen bonding interactions might have resulted in a dense gel structure. Liu et al. (2025) reported that carrageenan could disperse within gelatin solutions and serve as a filler, leading to the formation of macromolecular polymers. This was in accordance with the current results of the increases in gel strength and gelling point of the mixed gels substituted with higher carrageenan concentrations. Cheng et al. (2022) reported that incorporating carrageenan led to smaller pores in the composite gels, likely because the carrageenan acted as a filler, integrating into the gelatin network and resulting in a denser gel structure. Thus, the levels of carrageenan had a marked influence on the gel network, which was associated with the textural properties of the gel.

### 5.11. Sensory evaluation

Sensory evaluation plays a crucial role in assessing the effectiveness of ingredients in enhancing food formulations and determining the acceptability of the final products (Ozcan et al., 2024). The sensory properties of the gelatin gel substituted with various levels of carrageenan on consumer acceptance are presented in Table 6. In general, the control had significantly higher likeness scores for all attributes tested than any of the GCW gels substituted with carrageenan. Furthermore, increasing the level of carrageenan resulted in a significant decrease in the overall likeness score. This might have been related to the gel's physical characteristics, likely the brittleness and compactness. Generally, carrageenan-derived gels have a brittle texture, whereas protein-based gels tend to form a softer structure (Khalilian-Movahhed et al., 2023). The decreases in the appearance and color likeness scores might have been associated with increasing gel turbidity (reduced transparency) caused by the presence of carrageenan in the gel matrix. These results correlated with the decrease in lightness (Table 2) as well as the increased opaqueness (Fig. 1). Furthermore, the GCW gels, both with and without carrageenan, received lower taste likeness scores than the control, perhaps due to the presence of various substances in the GCW that contributed to its distinct flavor profile and influenced the overall taste of the gel. Therefore, incorporating carrageenan at an optimal level could enhance the sensory properties of the GCW gel.

## 6. Conclusion

The influence was investigated of different level of carrageenan substitution on gelatin capsule waste (GCW) gels. The results showed that the addition of carrageenan altered the gelling and melting temperatures, as well as the elastic modulus and loss modulus of the substituted gels. Incorporating carrageenan into GCW enhanced the intermolecular interactions between gelatin and carrageenan, increasing the texture profile (hardness, gumminess, chewiness) and gel strength of the resulting gels, with the 50 % carrageenan substitution having the highest gel strength and hardness. Additionally, the presence of carrageenan had no significant effect on the water activity of the gels. At higher concentrations of carrageenan, higher carbohydrate and lower protein contents were observed. A finer, denser network was formed with carrageenan incorporation. The substitution of carrageenan also affected the gel's visible appearance, increasing its opaqueness and turbidity. However, the more compact structure caused by carrageenan addition resulted in lower sensory acceptance. Thus, carrageenan can be used to improve the physicochemical and functional properties of GCW, offering potential for designing edible hydrogels. Nevertheless, the substitution concentration should be carefully considered in future applications.

## Funding

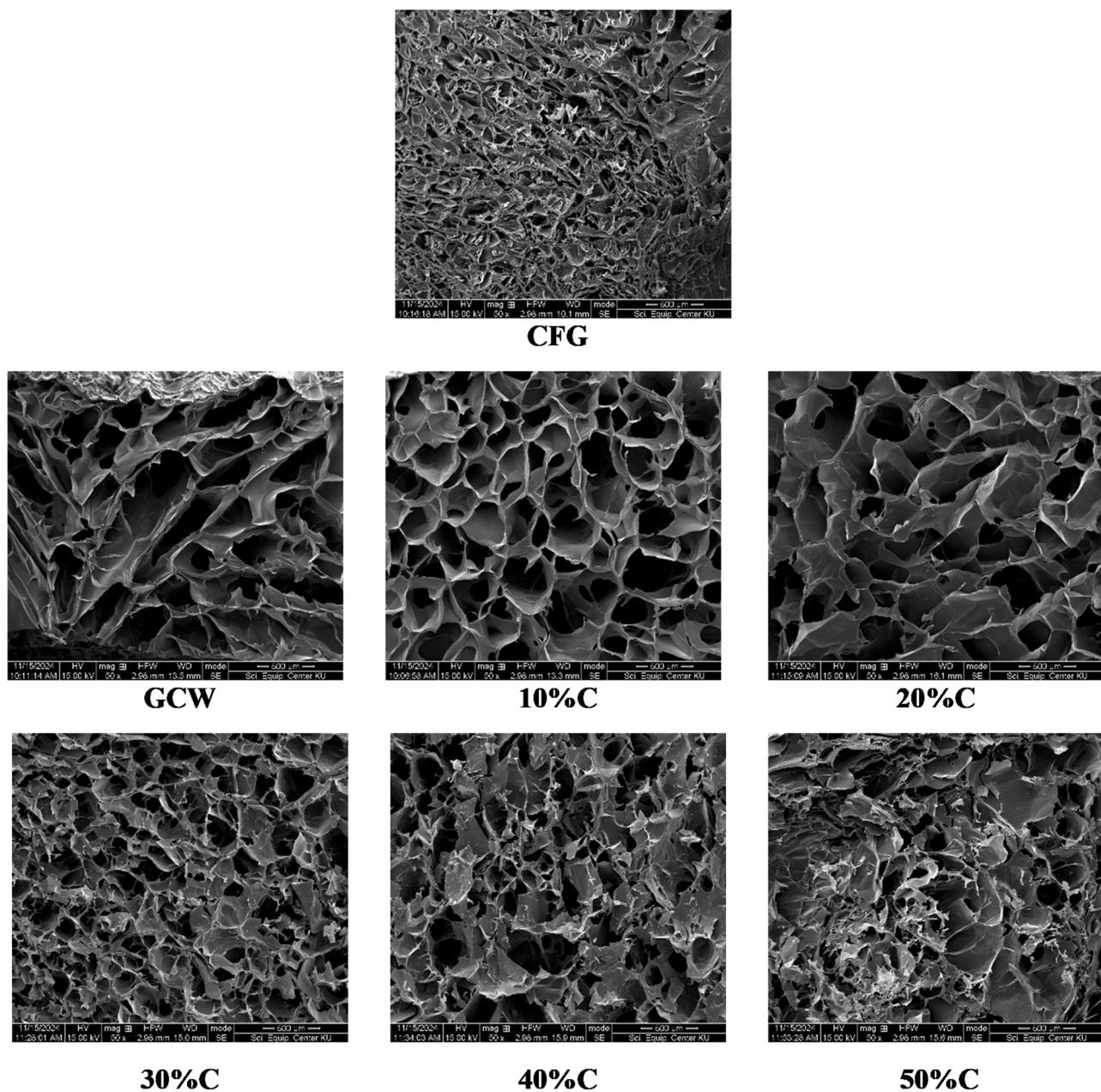
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## Certificate of exemption

The Kasetsart University Research Ethics Committee has exempted the following study which is to be carried out in compliance with the International guidelines for human research protection as Declaration of Helsinki, The Belmont Report, CIOMS Guideline, International Conference on Harmonization in Good Clinical Practice (ICH-GCP) and 45CFR 46.101(b)

## CRediT authorship contribution statement

**Sasina Sanprasert:** Methodology, Investigation, Formal analysis,



**Fig. 2.** Microstructure of gelatin capsule-waste gel substituted with various levels of carrageenan. Magnification: 50 × . Note: Commercial fish gelatin: CFG, Gelatin capsule waste: GCW, 10 % Carrageenan: 10 %C, 20 % Carrageenan: 20 %C, 30 % Carrageenan: 30 %C, 40 % Carrageenan: 40 %C, 50 % Carrageenan: 50 %C.

**Table 6**

Effect of gelatin capsule-waste gel substituted with various levels of carrageenan on consumer acceptance.

Sample	Appearance	Color	Odor	Flavor	Taste	Texture	Overall liking
CFG	8.42 ± 0.67 <sup>a</sup>	8.33 ± 0.98 <sup>a</sup>	8.50 ± 1.00 <sup>a</sup>	8.33 ± 1.37 <sup>a</sup>	8.42 ± 0.90 <sup>a</sup>	8.83 ± 0.39 <sup>a</sup>	8.55 ± 0.52 <sup>a</sup>
GCW	7.17 ± 1.64 <sup>abc</sup>	7.08 ± 1.44 <sup>bcd</sup>	5.67 ± 2.50 <sup>b</sup>	5.58 ± 1.44 <sup>b</sup>	5.08 ± 1.78 <sup>b</sup>	6.08 ± 2.47 <sup>b</sup>	5.91 ± 1.87 <sup>b</sup>
10 %C	7.75 ± .42 <sup>ab</sup>	7.33 ± 1.61 <sup>ab</sup>	5.42 ± 1.44 <sup>b</sup>	5.17 ± 1.47 <sup>bc</sup>	5.00 ± 1.60 <sup>b</sup>	6.17 ± 3.10 <sup>b</sup>	6.09 ± 2.02 <sup>b</sup>
20 %C	6.83 ± 1.47 <sup>bc</sup>	6.58 ± 1.73 <sup>bcd</sup>	5.08 ± 2.27 <sup>b</sup>	5.75 ± 1.29 <sup>b</sup>	5.33 ± 1.56 <sup>b</sup>	6.00 ± 1.86 <sup>b</sup>	5.91 ± 1.58 <sup>b</sup>
30 %C	6.33 ± 1.37 <sup>cde</sup>	6.50 ± 1.57 <sup>bcd</sup>	4.67 ± 2.06 <sup>b</sup>	5.58 ± 1.16 <sup>b</sup>	5.25 ± 1.54 <sup>b</sup>	5.08 ± 1.98 <sup>bc</sup>	5.27 ± 1.56 <sup>b</sup>
40 %C	5.25 ± 1.82 <sup>d</sup>	5.92 ± 1.16 <sup>cde</sup>	4.58 ± 2.15 <sup>b</sup>	4.83 ± 0.72 <sup>bc</sup>	4.75 ± 1.36 <sup>b</sup>	4.42 ± 2.02 <sup>bc</sup>	3.91 ± 1.30 <sup>c</sup>
50 %C	5.50 ± 1.62 <sup>d</sup>	5.33 ± 1.30 <sup>d</sup>	3.92 ± 2.15 <sup>b</sup>	4.33 ± 1.44 <sup>c</sup>	4.08 ± 1.78 <sup>b</sup>	4.00 ± 1.60 <sup>c</sup>	3.55 ± 1.63 <sup>c</sup>

Note: Commercial fish gelatin: CFG, Gelatin capsule waste: GCW, 10 % Carrageenan: 10 %C, 20 % Carrageenan: 20 %C, 30 % Carrageenan: 30 %C, 40 % Carrageenan: 40 %C, 50 % Carrageenan: 50 %C.

Values (mean ± standard deviation) with different letters in same column are significantly different ( $p < 0.05$ ).

**Data curation. Pudthaya Kumnerdsiri:** Methodology, Investigation, Formal analysis, Data curation. **Anusorn Seubsa:** Resources. **Piyang-kun Lueangjaroenkit:** Visualization, Supervision, Resources, Methodology, Investigation. **Jaksumma Pongsetkul:** Supervision, Resources, Methodology, Investigation. **Tanyamon Petcharat:** Supervision, Resources, Methodology, Investigation. **Pimonpan Kaewprachu:** Visualization, Supervision, Methodology, Conceptualization. **Samart Sai-ut:** Supervision, Resources, Methodology, Investigation. **Saroat Rawdkuen:** Visualization, Supervision, Resources, Funding acquisition. **Narudol Teerapattarakarn:** Visualization, Supervision. **Wanli Zhang:** Writing – review & editing, Supervision. **Young Hoon Jung:** Writing – review & editing, Supervision. **Passakorn Kingwascharapong:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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### Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.fufo.2025.100723](https://doi.org/10.1016/j.fufo.2025.100723).

### Data availability

No data was used for the research described in the article.

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