

## RESEARCH ARTICLE

# Effect of Carrageenan on the Quality of Purple Sweet Potato Frozen Dough and Steamed Buns

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**Abstract:** In order to enhance the stability of purple sweet potato steamed dough and the quality of resulting steamed buns, the influence of carrageenan conditions (0%, 0.5%, 1.0%, 1.5%, 2.0%, mass fraction) on the dough's moisture distribution, freezable water content, rheological properties, microstructure, and on the specific volumes, water activity, texture, and color quality of steamed buns were studied. Adding carrageenan led to a marked reduction in the freezable water of the purple sweet potato frozen dough, preventing the loss of strongly bound water to free water, improved the modulus of elasticity  $G'$  and viscous modulus  $G''$ , and finally made the protein network structure of purple sweet potato frozen dough more continuous and denser during the freezing and storage process. In terms of quality of steamed buns, adding carrageenan reduced the hardness while enhanced the elasticity and specific volume, with no significant impact observed on color parameters. In summary, carrageenan could be served as a good quality improver for purple sweet potato frozen doughs, and achieving the best freezing protection effect on the end-product attributes of the purple sweet potato steamed buns when the addition amount was 1.5%.

**Keywords:** Purple Sweet Potato Frozen Dough, Carrageenan, Water Migration, Frozen Storage, Quality of Steamed Buns

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## Introduction

Steamed buns (Mantou), as a traditional Chinese staple food, are very popular among consumers in China. Purple sweet potato is a source of diverse phytochemicals, notably polyamines, carotenoids, anthocyanins, flavonoids and other phytochemicals that are beneficial to health [1]. Purple sweet potato steamed buns are marketable as a fermented mixed grain pasta that not only has a unique flavor, but also has potential health benefits, thereby imparting protective effects against certain chronic diseases, including obesity, diabetes, and cardiovascular disease [2]. However, the shelf-life is shorter than breads due to the higher moisture content. To enhance storage stability and prevent undesirable quality deterioration, several new technologies, such as freezing technology and the use of different additives, were introduced and applied by producers and scholars [3]. Even so, dough products are still facing quality problems such as reduced yeast viability, small volume of

the final product, reduced water holding capacity and disruption of organization in dough due to ice formation and recrystallization [4]. Therefore, it is necessary to add dough enhancement ingredients to mitigate freezing damage as well as to improve the gluten structure and quality of purple sweet potato buns.

Carrageenan, a hydrocolloid from red seaweed, is characterized by its linear molecular configuration and hydrophilic nature, which confer excellent hydration capacity. It has been extensively used in food industry as a stabilizer, gelling, thickening, and emulsifier. It was demonstrated that carrageenan was beneficial to fix moisture and inhibit the development of extensive ice crystals in compromised dough matrix, eventually improving final quality of related products, including frozen dough and gluten-free bread [5]. Raman et al. added 4% of carrageenan to the dough, and found that the bread showed superior quality in terms of the improved mineral composition and fiber content, as well as the increased volume of the bread [6]. It was confirmed by Shang et al. that the addition of 0.5% carrageenan oligosaccharides significantly improved the fermentation characteristics and viscoelasticity and extensibility of frozen dough, previous research has established that carrageenan improves dough structure and baking characteristics. [7]. However, this work has not been extended to purple sweet potato frozen dough, and its influence on the dough's freeze-thaw stability and the final steamed bun quality is still unclear.

In this study, the influences of carrageenan additions on water mobility, rheology, and microstructure changes of the purple sweet potato frozen dough, alongside the textural and color quality of steamed buns was investigated, aiming to explore carrageenan's application in frozen mixed grains dough, and expected to supply theoretical insights for controlling quality deterioration.

## Materials and Methods

### Materials

All-purpose flour (Yihai Kerry Oil and Food Industry Co., Ltd.), high sugar-tolerant active dry yeast (Lesfu Yeast (Shanghai) Co., Ltd.), granulated sugar (Taikoo Sugar Industry Co., Ltd.), purple sweet potato powder (Shanghai Fengwei Industrial Co., Ltd.) was obtained in Metro Supermarket in Yangzhou City. Carrageenan was sourced from Zhongchen Biotechnology Co., Ltd. with food grade specifications.

### Preparation of Purple Sweet Potato Frozen Dough and Steamed Buns

The purple sweet potato frozen doughs were produced according to the method reported by Gong [8]. In brief, different contents of carrageenan were added to wheat flour, and making the concentrations of carrageenan were 0.5%, 1.0%, 1.5%, and 2.0% (w/w, dry weight) in the flour. When preparing the dough, wheat flour (800 g) and purple sweet potato flour (200 g) was mixed and different contents of carrageenan was added accordingly. The water used for dough mixing contains dissolved yeast powder (3%) and white sugar (5%). Followed by kneading the dough using a dough mixer (HSE-15, Hengwei Jianyi Trading Co., Ltd., Guangzhou, China) until it becomes smooth and uniform, the dough was cut into 50 g portions. Under controlled conditions (37 °C, 80% humidity), the dough was fermented for a duration of 40 minutes using a fermentation chamber (SPC-40FP, Xinmai Machinery Co., Ltd., Wuxi, China) subsequently frozen at -38°C for 2 hours (BC/BD-106DT Meiling freezer, Changhong Meiling Co., Ltd.), and then stored at -18°C for 15 days. The aforementioned frozen stored dough was subjected to thawing at 37 °C and 80% humidity for 60 minutes, steamed for 20 minutes, and then allowed to rest for 60 minutes until reaching room temperature before testing.

### Fermentation Capability Measurement

The purple sweet potato doughs with different carrageenan dosages were thawed in the fermentation tank for 30 minutes (35°C, 75% relative humidity). Then, taking the purple sweet potato doughs out and putting them into 250 mL graduated cylinder respectively, flattening the dough to 50 mL to maintain consistency in the initial volume of awakening. Fermentation was carried out in the fermentation tank (37°C, 80% relative humidity), and the volumes of the dough were recorded every 10 minutes. The volumes in different periods of the sample are recorded, and the increase of sample volume was calculated when compared with the initial volumes.

### Low-field Nuclear Magnetic Resonance (LF-NMR) Measurement

By adopting the method of Wang et al., water distribution was examined utilizing a low-resolution NMR spectrometer (AccuFat-1050, Magmai Medical Technology Co., Ltd.) [9]. A 10.0 g dough was carefully placed into an NMR tube and

stabilized at the magnetic field center within the radio frequency coil at 35 °C. The  $T_2$  was measured using CPMG sequences, and the acquisition parameters were set following the methodology outlined by Wei et al. [10]. The parameters set for the CPMG experiment were: SW = 200 kHz, TW = 300 ms, NECH = 3000, TE = 0.18 ms, and Ns = 32.

## Measurement of Differential Scanning Calorimetry (DSC)

A differential scanning calorimeter (DSC 214 Polyma, NETZSCH, Germany) with a refrigerated cooling system was employed to quantify freezable water, based on a modified procedure from He et al. [11]. Approximately 10 mg of dough was sealed in an aluminum pan and underwent the following thermal cycle: equilibration at 20 °C, cooling to -20 °C, and subsequent heating back to 20 °C at a constant rate of 5 °C/min. The melting enthalpy ( $\Delta H$ ) was automatically calculated by the integrated analytical software. The content of freezable water ( $F_w$ ) in the sample was determined according to the formula below:

$$F_w = \Delta H / (\Delta H_0 \times W_t) \times 100 \quad (1)$$

In the equation,  $F_w$  represents freezable water (%),  $\Delta H$  represents the peak enthalpy (J/g) obtained from the endothermic peak,  $\Delta H_0$  denotes the peak enthalpy of melting of pure water (334 J/g), and  $W_t$  represents total water (%).

## Dynamic Rheological

The dynamic rheological behavior of the dough was achieved through a HAAKE rheometer (MARS III, Thermo Fisher Scientific Co., Ltd., Waltham, Massachusetts, USA). 5 g samples with various concentrations of carrageenan stored were thawed for 30 min, and subjected to dynamic rheological tests. The frequency sweep test was conducted in the oscillation mode using a 35 mm of the plate in diameter. The test was performed by loading the thawed dough between plates set to a 1.00 mm gap. The sample was then allowed to rest for 5 minutes to eliminate residual stresses prior to testing. The frequency sweep (0.1-10 Hz) was carried out at 25°C using a fixed strain of 0.1% to maintain linear viscoelastic conditions.

## Microstructure Measurement

The microstructure was investigated by SEM (S-4800 II, Hitachi Co., Ltd., Tokyo, Japan) and were lyophilized and coated with gold/ palladium prior to SEM analysis. Representative images were recorded under the operating conditions of 10 kV accelerating voltage and  $\times 2000$  magnification.

## Thawing Water Loss Measurements

The thawing water loss refers to the rate of water loss of dough during the thawing process when it is taken out of the refrigerator and placed in the fermentation chamber. The weight of dough was recorded immediately after refrigeration, and after the dough was thawed 37 °C and 80% humidity for 60 minutes from the fermentation chamber, and weighed again. The thawing loss rate was calculated as follows:

$$TWL = (m_1 - m_2) / m_1 \times 100 \quad (2)$$

Where:  $m_1$  is the weight which was achieved after refrigeration (g),  $m_2$  is the dough weight of frozen dough which was thawed in the fermentation chamber (g).

## Water Holding Capacity Measurements

The experiment was conducted according to Su's method [12]. The procedure for determining water holding capacity (WHC) was as follows: First, we collected and weighed three 3.0 g replicates from each batch of thawed dough into centrifuge tubes. Following centrifugation of all samples at 8000 r/min for 20 min, discarding the supernatant, and the pellet was then blot-dried on filter paper and re-weighed. Finally, the WHC was determined based on formula (3):

$$WHC = w_2 - w_1 \times 100\% \quad (3)$$

Where  $w_1$  and  $w_2$  represent the sample mass (g) before centrifugation and after water removal, respectively.

## Properties of Purple Sweet Potato Steamed Buns

The purple sweet potato frozen doughs were kept at 37 °C and 80% relative humidity for 60 minutes, and then the samples were steamed on a tray over boiling water for 20 minutes, followed by a 60-minute rest at room temperature before subsequent analysis.

**Texture properties:** The textural characteristics of all steamed purple sweet potato buns were performed utilizing a texture analyzer (TMS-PRO, FTC Co., Ltd. Scarsdale, NY, USA) equipped with a P/75 probe. Uniform 25 mm thick slices were obtained from central portion of each steamed bread. The texture analyzer was configured with following setting: pre-test and test speeds, 2.0 mm/s; post-test speed, 1.0 mm/s; trigger force, 0.1 N; and strain, 60%. Hardness and springiness were the parameters evaluated.

**Specific volume:** The volumes of purple sweet potato steamed buns were determined using the rapeseed displacement method [13] with the following calculation formula (4):

$$SV=V/M \quad (4)$$

In this formula, SV represents the specific volume (cm<sup>3</sup>), V represents the volume of steamed buns (cm<sup>3</sup>), M is the weight of steamed buns (g).

**Water activity:** Steamed purple sweet potato buns were sliced from the center to obtain crumb, and were determined at room temperature by rapid moisture activity analysis, and the data after equilibrium was read.

**The internal crumb appearance:** Steamed purple sweet potato buns were sliced from the center, and placed over the A4 paper. The internal crumb appearance was scanned by a camera (70D, SONY, Japan).

## Color Quality

The color parameters of the purple sweet potato steamed bun crusts were determined using a chroma meter (NH310, Sanenshi Science and Technology Medical Technology Co., Ltd., Shenzhen, China). Prior to measurement, the instrument was calibrated by white and black standard tiles. The brightness ( $L^*$ ), redness ( $a^*$ ) and yellowness ( $b^*$ ) values of the buns were measured.

## Results and Discussion

### Impact of Carrageenan on Fermentation Capability

To explore the fermentation characteristics of purple sweet potato frozen dough after the addition of carrageenan, the actual fermentation environment was simulated to determine the gas production and retention properties of yeast. The gas holding capacity of dough was positively correlated with carrageenan (shown in Table 1). The volume increment of carrageenan dough had a significant effect at 50 min when compared with the control sample, which indicated that carrageenan could lead to the improved fermentation performance in frozen purple sweet potato dough, and enhance the porosity stability and gas retention of dough. The gas-holding capacity reached the maximum with the addition of 1.5% carrageenan, it could be owing to that carrageenan could enhance the gluten network structure, alleviate the damage caused by ice crystal recrystallization to yeast cells, and eventually enhance the fermentation ability of doughs [7]. However, when the addition of carrageenan increased to 2.0%, the dough was sticky and resulting in excessive elasticity and reduced extensibility of the dough. The dough is not suitable for stretching and is prone to breakage, leading to weakened fermentation expansion force, which was not conducive to subsequent operation [14].

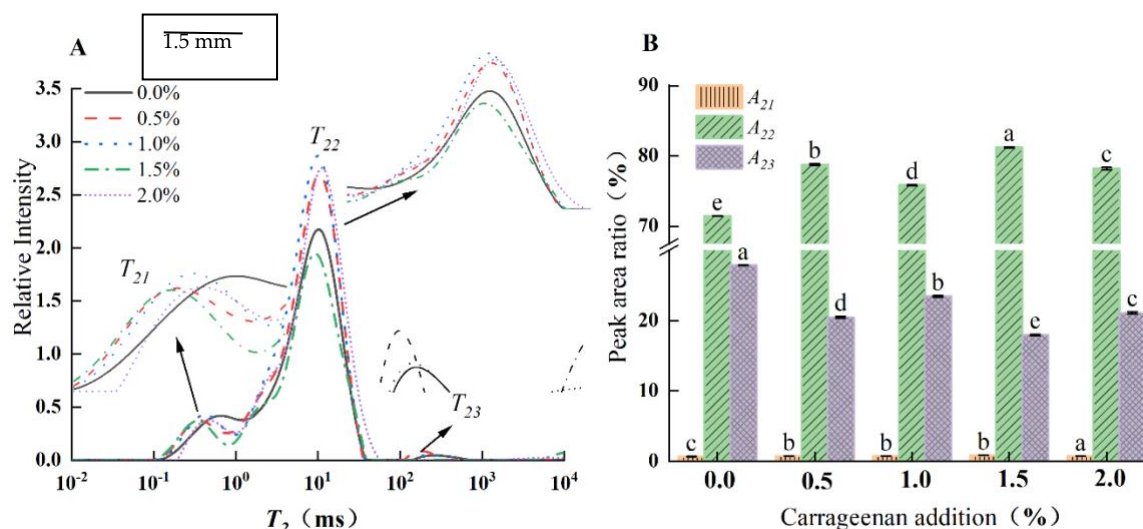
**Table 1: Effect of carrageenan content on fermentation capability of purple sweet potato frozen dough**

Carrageenan addition (%)	30	40	50	60
0.0	4.67±0.58 <sup>c</sup>	6.33±0.58 <sup>d</sup>	8.33±0.42 <sup>d</sup>	8.33±0.58 <sup>d</sup>
0.5	5.17±0.76 <sup>c</sup>	10.33±0.58 <sup>bc</sup>	11.77±0.32 <sup>c</sup>	11.77±0.38 <sup>c</sup>
1.0	7.83±1.26 <sup>bc</sup>	9.83±0.29 <sup>c</sup>	12.50±0.50 <sup>bc</sup>	12.50±0.50 <sup>bc</sup>
1.5	9.17±0.41 <sup>a</sup>	11.69±0.53 <sup>a</sup>	13.33±0.58 <sup>a</sup>	13.33±0.50 <sup>a</sup>
2.0	8.51±0.36 <sup>b</sup>	9.90±1.01 <sup>c</sup>	11.83±0.29 <sup>c</sup>	11.83±0.29 <sup>c</sup>

All the experiments were in triplicate and data were expressed as mean value ± SD (n=3). Different superscript letters (a, b, c, d, e) in the same column are significantly different ( $p < 0.05$ )

## Impact of Carrageenan on Water Mobility

Figure 1A presents the relaxation curves of frozen dough with various doses of carrageenan. Three protons are reflected in the relaxation signal:  $T_{21}$ ,  $T_{22}$  and  $T_{23}$  represents strongly bound water, immobilized water and free water, respectively [15]. Figure 1B shows dough's moisture state throughout freezing and storage periods, with the corresponding peak areas labeled as  $A_{21}$ ,  $A_{22}$  and  $A_{23}$ . Compared with the control sample with no carrageenan addition, a distinct difference in moisture mobility was achieved in the carrageenan-added group, and the contents of  $A_{21}$  and  $A_{22}$  are the lowest, which is because the disruption of gluten cross-linking by ice recrystallization during frozen storage led to a decline in its water-binding ability, thereby facilitating water redistribution to less tightly bound states [16].



**Fig. 1: Effect of carrageenan content on the water distribution of purple sweet potato frozen dough. (A) relaxation curve, (B) moisture parameter**

With the increased concentration of carrageenan addition, the  $A_{21}$  and  $A_{22}$  contents also changed significantly, especially the  $A_{21}$  and  $A_{22}$  contents in samples with 1.5% and 2.0% carrageenan addition doughs were higher than other samples, which may be attributed to the fact that the carrageenan contains abundant hydrophilic groups, which exhibited strong water-absorption properties, and forming gluten protein-water-carrageenan complex network that effectively inhibited ice recrystallization, preserving the gluten network structure, consequently decreasing migration and loss of moisture during frozen storage [17]. The values of  $A_{23}$  in the doughs with 0.5%, 1.0%, 1.5%, and 2.0% carrageenan addition decreased by 26.57%, 15.85%, 35.59%, and 24.34%, respectively, indicating that by driving the redistribution of free water to bound water, the free hydroxyl groups in carrageenan consequently limited ice crystal formation [7].

## Impact of Carrageenan on the Content of Freezable Water

The onset and termination temperatures in doughs treated with different doses of carrageenan were studied (Table 2). The onset and termination temperatures exhibited a decreasing trend with the increased dose of carrageenan. This phenomenon might be owing to the fact that carrageenan could bind water molecules to its hydroxyl groups through hydrogen bonding, thus lowering the freezing point of water. The increased concentration of solute in the doughs improved the growth inhibition of ice crystal, thus preventing the destruction to the dough from ice crystal [8]. A comparative reduction in  $\Delta H$  values was observed in all frozen dough formulations containing carrageenan relative to the control, and when 1.5% carrageenan was added, the  $\Delta H$  value decreased by 33.25% with a minimum value of 23.34 J/g, when compared with the control sample. The elevated freezable water (Fw) content observed in the control sample may originate from gluten network disruption after the addition of carrageenan. Such structural breakdown promotes water migration from the gluten-starch complex, and consequently increases freezable water [18]. The carrageenan-treated doughs showed significantly less freezable water ( $p < 0.05$ ). This protective effect is consequently ascribed to carrageenan's molecular structure; its hydroxyl groups restrict water mobility and inhibit proton exchange under high humidity, enhancing its water-absorption capacity [19].

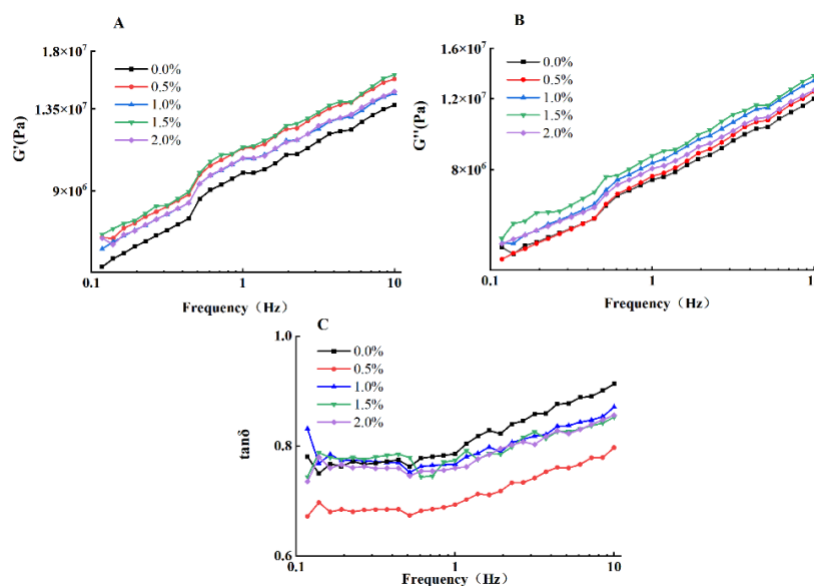
**Table 2: Effect of carrageenan content on gelatinization parameters of purple sweet potato frozen dough**

Carrageenan addition (%)	To (°C)	Tf (°C)	$\Delta H$ (J/g)	Fw(%)
0.0	-0.42±0.01 <sup>a</sup>	3.63±0.01 <sup>a</sup>	34.96±0.07 <sup>a</sup>	20.94±0.04 <sup>a</sup>
0.5	-3.44±0.10 <sup>b</sup>	2.93±0.01 <sup>b</sup>	24.25±2.08 <sup>b</sup>	14.52±1.25 <sup>b</sup>
1.0	-3.73±0.01 <sup>c</sup>	1.82±0.02 <sup>d</sup>	23.97±0.10 <sup>b</sup>	14.35±0.06 <sup>b</sup>
1.5	-3.53±0.01 <sup>b</sup>	2.41±0.03 <sup>c</sup>	23.34±0.06 <sup>b</sup>	13.98±0.03 <sup>b</sup>
2.0	-4.13±0.01 <sup>d</sup>	1.49±0.04 <sup>e</sup>	26.24±0.12 <sup>b</sup>	15.71±0.07 <sup>b</sup>

All the experiments were in triplicate and data were expressed as mean value ± SD (n=3). Different superscript letters (a, b, c, d, e) in the same column are significantly different ( $p < 0.05$ ). To: the onset temperature of melting; Tf: the conclusion temperature of melting;  $\Delta H$ : the enthalpy of the endothermic peak of the melting curve; Fw: the freezable water content

### Impact of Carrageenan on the Dynamic Rheological Properties

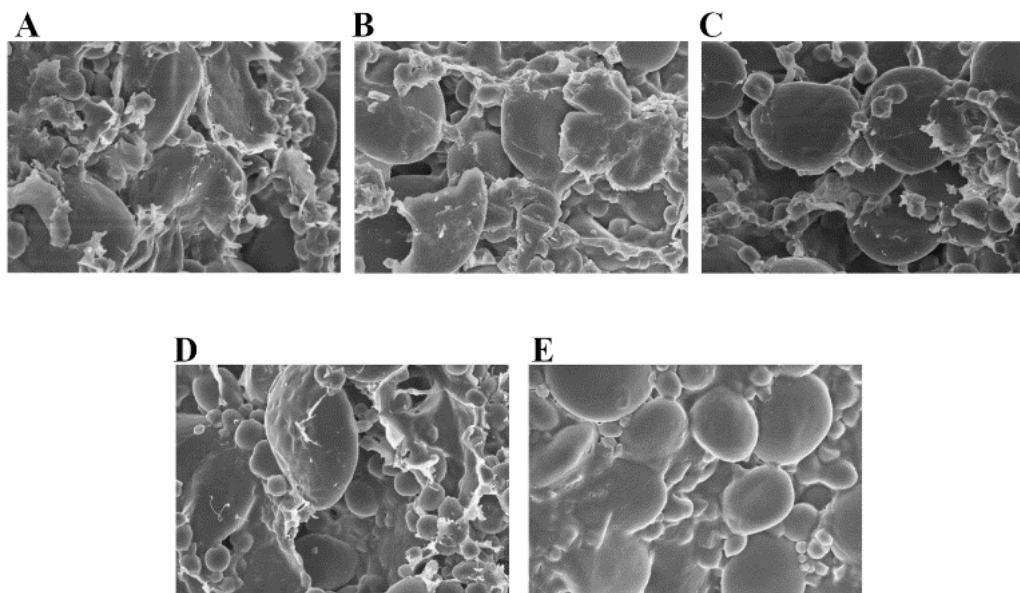
Figure 2 presents the dynamic rheological spectra of frozen purple sweet potato doughs with different contents of carrageenan, where Figure 2A, 2B and 2C shows the variation of elastic modulus, viscous modulus and loss  $\tan\delta$  ( $\tan\delta=G''/G'$ ), respectively. As shown in Figure 2A, the doughs with varying concentrations of carrageenan exhibited higher  $G'$  values compared to the control dough within the 0.0-10.0 Hz. It may be attributed to carrageenan reinforcing the gel network by forming intermolecular cross-links with starch chains, thereby securing water more effectively [20]. The dough with 1.5% carrageenan addition exhibited the largest  $G'$  value, followed by the dough samples with 0.5% carrageenan addition. The higher values of  $G'$  and  $G''$  indicated the enhanced elastic and viscous properties. Through its capacity to bind free water, adding carrageenan restricted large ice crystal growth, consequently preserving the gluten network in frozen dough [21]. In Figure 2B, the relatively higher values of  $G''$  were obtained in the doughs treated with 1.5% and 0.5% carrageenan, followed by 2.0% and 1.0% carrageenan, these results suggested that the carrageenan's high-water affinity altered the water distribution within the dough, consequently increasing the  $G''$  values. As depicted in Figure 2C, the  $\tan\delta$  of all dough is always less than 1, which indicated that the dough is always a viscoelastic system. Within the range of 0.1-1 Hz, the  $\tan\delta$  decreased initially at low frequency but followed by a steady increase as frequency rose. This trend signifies the development of a stronger, more solid-like structure [22]. Moreover, as a key indicator of dough quality, a lower  $\tan\delta$  value corresponds to more elastic and less viscous behavior, and a more stable network structure. The smaller  $\tan\delta$  value represents more polymers and greater polymerization within the dough. It was shown in Figure 2C that the  $\tan\delta$  values in carrageenan-treated samples between 1-10 Hz were significantly lower than that of the blank sample. It was inferred that the addition of carrageenan could increase polymerization's degree in polymers (glucose). In conclusion, appropriate dose of carrageenan could result in a more compact structure and improved viscoelasticity of the dough.



**Fig. 2: Effect of carrageenan content on rheological properties of purple sweet potato frozen dough. (A) Elastic modulus  $G'$ , (B) viscous modulus  $G''$  and (C) loss  $\tan\delta$**

## Impact of Carrageenan on the Microstructure

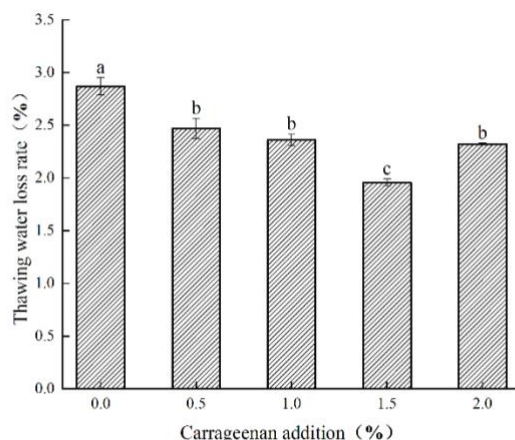
The microstructure of freeze-dried purple sweet potato frozen dough was characterized using SEM (Figure 3). The control sample showed poorer continuity of the gluten matrix, the overall structure disintegrated, appearing to have become detached from the starch granules (Fig. 3A) after freeze-drying for one week. This phenomenon was due to freezing storage inducing the aggregation of adjacent small ice crystals within the dough into larger ones through recrystallization. Consequently, the gluten protein network underwent compression and disruption, leading to its rupture, shrinkage, and denaturation, with starch granules detaching from the disintegrated network [23]. The sample with 0.5% carrageenan addition did not form more gluten film compared with no-addition sample, the gluten film provided incomplete encapsulation of the starch granules, and some of the starch granules were broken. The dough with 1.0% carrageenan addition showed a porous structure and broken gluten fragments could be observed, the decreased quality of the network of the samples might have a bearing on the decrease of wet gluten and the stability of the flour in the process of freezing and storage [24]. In contrast, the 1.5% carrageenan-treated dough retained the gluten network to a large extent, and there were fewer cases of gluten chain breakage (Fig. 3D), which was because 1.5% carrageenan in the dough acting to inhibit water migration, resulting in the prevention of forming large ice crystals while creating a more continuous overall gluten network structure [25]. A 2.0% carrageenan dose yielded a particularly compact structure, where starch granules were firmly integrated. The structural integrity of gluten network was preserved after frozen storage, as evidenced by continuous gluten membranes (Figure 3E). In summary, adding 1.5% and 2.0% carrageenan effectively suppressed the production of large ice crystals, protecting the gluten structure from water-mediated damage and leading to a measurable improvement in the quality of the frozen dough.



**Fig. 3: Effect of carrageenan content on microstructure of purple sweet potato frozen dough. A, B, C, D, and E stand are for 0, 0.5%, 1.0%, 1.5% and 2.0% carrageenan addition dough samples after frozen treatment, respectively**

## Impact of Carrageenan on the Thawing Water Loss

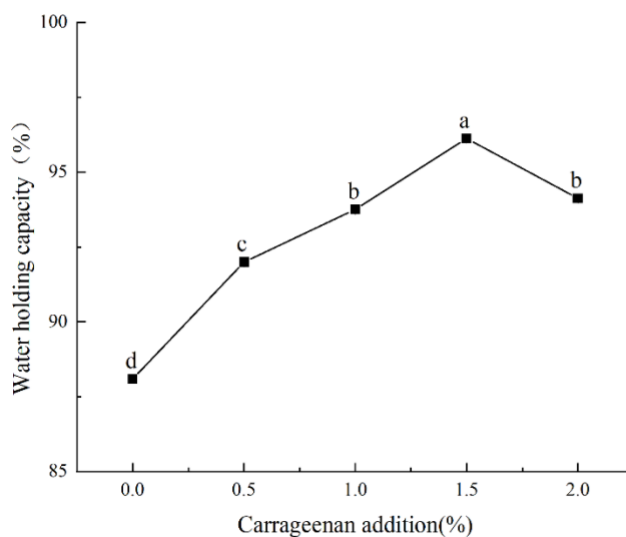
Carrageenan significantly ( $p < 0.05$ ) improved the water holding ability within all doughs (Figure 4). The thawing loss of purple sweet potato dough with 1.5% carrageenan addition was the lowest, which was related to uniformity of moisture distribution and reduction in freezable water. Compared with the control, the gluten structure was damaged during freezing and was unable to encapsulate the thawed water, resulting in water loss and thus leading to the highest thawing water loss. Additionally, the increase in carrageenan content also had an effect on the water-holding capacity. It was because hydroxyl groups of the hydrocolloid structure allowed more water to interact by hydrogen bonding, forming a dense structure that prevented water molecules loss. Consequently, a notable improvement was achieved in the freeze-thaw stability of the frozen dough. [26].



**Fig. 4: Effect of carrageenan content on thawing loss of purple sweet potato frozen doughs**

### Impact of Carrageenan on the Water Holding Capacity

Figure 5 illustrates there was a significant difference in water holding ability of purple sweet potato frozen doughs by adding carrageenan with different doses. Adding carrageenan notably increased the WHC ( $p < 0.05$ ) of doughs, with the highest WHC when adding 1.5% carrageenan, because the addition of 1.5% carrageenan could reduce the collapse phenomenon of gluten network caused by semi bound water freezing into ice crystals, maintain the gluten network and the internal water content, improve the binding force between water molecules and proteins, and even strengthen the gluten network structure, thereby enhance water holding capacity [27]. However, when the addition of carrageenan increased to 2.0%, excessive carrageenan may compete for water with gluten protein, therefore impeding the hydration of gluten and weakening gluten strength, and eventually leading to a loose structure and finally compromising the quality of final product [28].



**Fig. 5: Effect of carrageenan content on water holding capacity of purple sweet potato frozen doughs**

### Impact of Carrageenan on the Characteristics

Carrageenan incorporation effectively declined the hardness value of the purple sweet potato steamed buns ( $p < 0.05$ , listed in Table 3), the purple sweet potato steamed buns with 1.5% carrageenan had the softest texture followed by samples with 2.0% and 1.0% addition. This textural softening is likely due to carrageenan impeding the retrogradation of amylose and amylopectin by competing for water and therefore decreased the hardness of the steamed buns [29]. The results of elasticity test exhibited that the elasticity values of purple sweet potato steamed buns with carrageenan addition were significantly

higher than no-addition sample. It interacts synergistically with wheat proteins and starch through hydrophilic bonds, forming a denser gel matrix that enhances dough elasticity and ultimately improves the final product's texture.

**Table 3: Effects of carrageenan content on characteristics of purple sweet potato steamed buns**

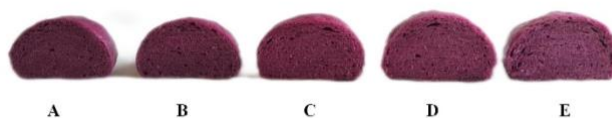
Carrageenan addition (%)	Hardness (N)	Springiness (mm)	SV/(mL/g)	Aw
0.0	25.69±0.21 <sup>a</sup>	5.22±0.22 <sup>b</sup>	2.30±0.02 <sup>c</sup>	0.941 <sup>a</sup>
0.5	25.55±0.76 <sup>a</sup>	5.79±0.31 <sup>ab</sup>	2.34±0.01 <sup>c</sup>	0.936 <sup>b</sup>
1.0	21.14±0.7b <sup>c</sup>	5.80±0.31 <sup>a</sup>	2.47±0.04 <sup>b</sup>	0.931 <sup>a</sup>
1.5	20.38±0.37 <sup>c</sup>	5.83±0.09 <sup>a</sup>	2.58±0.03 <sup>a</sup>	0.918 <sup>d</sup>
2.0	22.92±0.17 <sup>bc</sup>	5.25±0.20 <sup>b</sup>	2.50±0.01 <sup>ab</sup>	0.927 <sup>c</sup>

All the experiments were in triplicate and data were expressed as mean value ± SD (n=3). Different superscript letters (a, b, c, d, e) in the same column are significantly different (p < 0.05). SV: the volumes of purple sweet potato steamed buns; Aw: the water activity of purple sweet potato steamed buns

Steamed bun's specific volume reflected the degree of volume expansion of the dough during processing and was directly correlated with the external texture, internal structure and taste characteristics. The values improved notably (p < 0.05, listed in Table 2) with the improved carrageenan addition content, and the highest value was obtained with 1.5% carrageenan addition, followed by 2.0%, 1.0% and 0.5% carrageenan addition, which may be attributed to the fact that carrageenan could strengthen the network structure of the dough, thus increasing the retention of carbon dioxide during fermentation and contributing to the well-shaped appearance of the purple sweet potato steamed buns [30]. This indicated that the addition of carrageenan made the internal structure of purple sweet potato steamed buns softer, elastic and larger.

The purple sweet potato steamed buns with carrageenan addition exhibited lower water activity when compared with the control sample. Higher water activity was related to the release of bound water resulting from interactions among gluten proteins, starch and the dough, which increased free water content and elevated water activity. Furthermore, the texture and mouthfeel of the purple sweet potato steamed buns were influenced by changes in moisture content and water activity, driven by moisture redistribution both within the steamed buns, and between the steamed buns and its environment [31].

The internal crumb structures of steamed buns with varied carrageenan additions were depicted in Figure 6. From the perspective of internal structure, the control sample exhibited tightly packed pores with insufficient fluffiness. However, the pore structure of the purple sweet potato steamed buns showed significant improvement after adding 1.0% carrageenan. The purple sweet potato steamed bread with 1.5% carrageenan addition exhibited a more uniform pore distribution and size in its internal structure. However, when the carrageenan content was increased to 2.0%, both the diameter and height of the steamed buns decreased compared to those with 1.5% carrageenan. Therefore, the addition of 1.5% carrageenan was optimal for enhancing the fluffiness and height of purple sweet potato steamed buns, which was consistent with the above results for hardness and specific volume.



**Fig. 6: Purple sweet potato steamed buns internal crumb appearances with (A) 0%, (B) 0.5%, (C) 1%, (D) 1.5%, (E) 2.0% carrageenan addition**

### Impact of Carrageenan on the Color Quality

The color quality of steamed buns treated by different contents of carrageenan after freezing was studied (Table 4). The sample with 1.5% carrageenan addition exhibited the highest  $L^*$  value, followed by those with 2.0% and 1.0% carrageenan addition. This was attributed to that carrageenan could enhance gluten quality, improve extensibility, elasticity, and gas-holding capacity of the doughs. During steaming, it resulted in a more uniform distribution of moisture and gas within the steamed buns, along with optimized size and stability of air bubbles. These effects collectively enhanced brightness (higher  $L^*$  value), which correlated with superior color quality [32]. In this table, the  $a^*$  value was the lowest in the control sample (4.35), while the purple sweet potato steamed buns with 2.0% carrageenan addition had the highest  $a^*$  value (4.76). A higher  $a^*$  value indicated a stronger red hue in the steamed buns, was primarily driven by the darker color of the purple sweet potato flour.

The  $b^*$  values were all negative, which meant no yellow tones in any of the steamed bun samples. Overall, the color quality of the final product remained largely unaffected with the incorporation of carrageenan.

**Table 4: Effect of carrageenan content on color of purple sweet potato steamed buns**

Carrageenan addition (%)	$L^*$	$a^*$	$b^*$
0.0	32.68±0.50 <sup>a</sup>	4.35±0.08 <sup>a</sup>	-0.43±0.08 <sup>a</sup>
0.5	33.21±0.44 <sup>a</sup>	4.70±0.38 <sup>a</sup>	-0.74±0.22 <sup>a</sup>
1.0	33.81±1.34 <sup>a</sup>	4.49±0.05 <sup>a</sup>	-0.72±0.44 <sup>a</sup>
1.5	34.27±1.01 <sup>a</sup>	4.69±0.01 <sup>a</sup>	-0.76±0.26 <sup>a</sup>
2.0	33.86±0.93 <sup>a</sup>	4.76±0.03 <sup>a</sup>	-0.82±0.10 <sup>a</sup>

All the experiments were in triplicate and data were expressed as mean value ± SD (n=3). Different superscript letters (a, b, c, d) in the same column are significantly different ( $p < 0.05$ ).

## Conclusion

The effects of varying additions of carrageenan on the freezing storage stability of purple sweet potato frozen and final steamed buns quality were systematically examined. Results indicated that carrageenan exerted a significant influence on water mobility, viscoelasticity, freezable water content, microstructure and hardness of purple sweet potato frozen dough. The water migration analysis revealed that carrageenan exhibited strong water-binding capacity, which effectively inhibited the damage caused by ice recrystallization within the dough, and significantly slowed water migration rates in the dough system, preserved the structural integrity of the final product. Thermal and rheological studies indicated that carrageenan addition lowered freezable water content, minimized ice crystal formation, and preserved gluten network integrity, thereby enhanced storage modulus ( $G'$ ) and loss modulus ( $G''$ ). Adding 1.5% carrageenan resulted in a denser and more homogeneous dough microstructure, as well as a reduction in thawing losses and an increase in water-holding capacity. Quality assessments confirmed that carrageenan improved the texture of purple sweet potato steamed bread, reduced hardness, enhanced elasticity, and significantly increased specific volume. Thus, a marked improvement in comprehensive quality of both the frozen dough and steamed buns was obtained at the 1.5% carrageenan addition level.

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## Ethics

The authors declare no competing financial interests or personal relationships.

## Author's Contributions

Qiuyu Wang: Formal analysis, investigation, project administration, conceptualization, written-original drafted.

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Lei Wu: Methodology, software.

Junjuan Yu: Data-analysis.

Guangrong Sun: Writing-review and editing, project administration.

## References

1. Liu, X., Yang, L., Zhao, S., & Zhang, H. (2020). Characterization of the dough rheological and steamed bread fortified with extruded purple sweet potato flour. *International Journal of Food Properties*, 23(1), 765-776. <https://doi.org/10.1080/10942912.2020.1733600>
2. Elisabeth, D., Yulifanti, R., & Ginting, E. (2020). Production of Chinese bun from sweet potato and its financial feasibility analysis. *IOP Conf. Series: Earth and Environmental Science*, 475, 012043. <https://doi.org/10.1088/1755-1315/475/1/012043>
3. Hejrani, T., Sheikholeslami, Z., Mortazavi, A., & Davoodi, M.G. (2017). The properties of part baked frozen bread with guar and xanthan gums. *Food Hydrocolloids*, 71, 252-257. <https://doi.org/10.1016/j.foodhyd.2016.04.012>
4. Omedi, J.O., Huang, W., Zhang, B., Li Z., & Zheng, J. (2019). Advances in present-day frozen dough technology and its improver and novel biotech ingredients development trends-a review. *Cereal Chemistry*, 96(1), 34-56. <https://doi.org/10.1002/cche.10122>
5. Ishaq, A., Nadeem, M., & Ahmad, R. (2024). Recent advances in applications of marine hydrocolloids for improving bread quality. *Food hydrocolloids*, 148, 109424. <https://doi.org/10.1016/j.foodhyd.2023.109424>
6. Raman, M., Dinakaran, A., Ravindran, A., Sankar, T. V., & Gopal, T. (2019). Dietary supplementation of κ-carrageenan to improve the physio-chemical and functional properties of white bread. *Food and Nutrition Sciences*, 10(8), 997-1010. <https://doi.org/10.4236/fns.2019.108071>
7. Shang, S., Yu, S., Zang, L., Jiang, P., Song, S., Wen, C., Qi, L., & Fu, B. (2023). Effects of trehalose and carrageenan oligosaccharides on the stability and baking characteristics of frozen dough. *Food and Fermentation Industries (In Chinese)*, 49(11), 207-216. <https://doi.org/10.13995/j.cnki.11-1802/ts.034218>
8. Gong, S., Yang, D., Wu, Q., Wang, S., Fang, Z., Li, Y., Xu, F., Wang, Z., & Wu, J. (2019). Evaluation of the antifreeze effects and its related mechanism of sericin peptides on the frozen dough of steamed potato bread. *Journal of Food Processing and Preservation*, 43(8), e14053. <https://doi.org/10.1111/jfpp.14053>
9. Wang, Q., Zhang, H., Zhu, W., Li, C., Xu, Y., Ding, X., & Zhou, X. (2022). Physicochemical properties and nutritional quality of pre-fermented red bean steamed buns as affected by freeze-thaw cycling. *International Journal of Food Properties*, 25(1), 748-763. <https://doi.org/10.1080/10942912.2022.2060252>
10. Wei, Q., Zhang, G., & Xie, J. (2025). Modulatory effects of carboxymethyl chitosan on the textural and quality attributes of frozen rice dough and corresponding rice bread. *Food Hydrocolloids*, 162, 111021. <https://doi.org/10.1016/j.foodhyd.2024.111021>
11. He, Y., Guo, J., Ren, G., Cui, G., & Liu, J. (2020). Effects of konjac glucomannan on the water distribution of frozen dough and corresponding steamed bread quality. *Food Chemistry*, 330, 127243. <https://doi.org/10.1016/j.foodchem.2020.127243>
12. Su, T.C., Du, W.K., Deng, B.Y., Gao, H.Y., Zhou, H.X., Li, G.L., Zhang, H., Gong, Y.M., Zhang, J.Y. (2023). Effects of sodium carboxymethyl cellulose on storage stability and qualities of different frozen dough. *Heliyon*, 9(8), e18545. <https://doi.org/10.1016/j.heliyon.2023.e18545>
13. Zhang, S., Zhang, Z., Wang, M., Jia, J., & Wu, Q. (2024a). Effects of rice bran soluble dietary fiber on the physicochemical properties of frozen dough and the quality of steamed bread. *LWT*, 214, 117120. <https://doi.org/10.1016/j.lwt.2024.117120>
14. Liu, K., Guan, E., Li, M., Liu, Y., Bian, K. (2023). Effects of okra polysaccharide on storage stability of frozen dough. *Food and Fermentation Industries (In Chinese)*, 49(6), 92-97. <https://doi.org/10.13995/j.cnki.11-1802/ts.030133>
15. Meng, X., Li, T., Zhao, J., Fan, M., Qian, H., Li, Y., & Wang, L. (2023). Effects of different bran pretreatments on rheological and functional properties of triticale whole-wheat flour. *Food & Bioprocess Technology*, 16(3), 576-588. <https://doi.org/10.1007/s11947-022-02959-1>
16. Xin, C., Nie, L., Chen, H., Li, J., & Li, B. (2018). Effect of degree of substitution of carboxymethyl cellulose sodium on the state of water, rheological and baking performance of frozen bread dough. *Food Hydrocolloids*, 80, 8-14. <https://doi.org/10.1016/j.foodhyd.2018.01.030>
17. Yu, N. (2017). Effect of carrageenan on baking quality of frozen dough during freeze-thaw cycles.
18. Zhang, X., Ren, G., Liu, W., Li, L., Cao, W., Wang, L., & Duan, X. (2024b). Effects of freeze-thaw cycles on the quality of a novel mixed grain composite dough and its product (potato-oat yu): Hybridization of potatoes and oats. *ACS Omega*, 9(16), 18449-18457. <https://doi.org/10.1021/acsomega.4c00294>
19. Thommes, M., Ely, D.R., & Kleinebudde, P. (2009). The water binding behavior of kappa-carrageenan determined by three different methods. *Pharmaceutical Development and Technology*, 14(3), 249-258. <https://doi.org/10.1080/10837450802572359>
20. Silva, E., Birkenhake, M., Scholten, E., Sagis, L., & Linden, E. (2013). Controlling rheology and structure of sweet potato starch noodles with high broccoli powder content by hydrocolloids. *Food Hydrocolloids*, 30(1), 42-52. <https://doi.org/10.1016/j.foodhyd.2012.05.002>
21. Li, Y., Zhang, C., Jiang, X., Gao, M., Yao, X., Liu, H., Wang, J., Zhang, H., & Zhang C. (2019). The effects of different additives on the physical properties of dumpling wrapper. *Journal of Food Measurement and Characterization*, 13(4), 3077-3085. <https://doi.org/10.1007/s11694-019-00230-4>
22. Peng, B., Li, Y., Ding, S., Yang, J. (2017). Characterization of textural, rheological, thermal, microstructural, and water mobility in wheat flour dough and bread affected by trehalose. *Food Chemistry*, 233, 369-377. <http://dx.doi.org/10.1016/j.foodchem.2017.04.108>
23. Yang, C., Xie, C., Chen, G., & Cao, Z. (2024). Effects of different reheating methods on the physicochemical properties, microstructure and sensory quality of frozen buns. *Journal of Researches on Dietetic Science and Culture (In Chinese)*, 41(3), 64-71. <https://doi.org/10.19913/j.cnki.2095-8730msyj.2024.03.10>
24. Correa, M.J., Anon, M.C., Perez, G.T., & Ferrero, C. (2010). Effect of modified celluloses on dough rheology and microstructure. *Food Research International*, 43(3), 780-787. <https://doi.org/10.1016/j.foodres.2009.11.016>
25. Sharadant, R., & Khan, K. (2006). Effect of hydrophilic gums on the quality of frozen dough: electron microscopy, protein solubility, and electrophoresis studies. *Cereal Chemistry*, 83(4), 411-417. <https://doi.org/10.1094/CC-83-0411>

26. Tan, H.L., Tan, T.C., Easa, A.M. (2018). The use of selected hydrocolloids to enhance cooking quality and hardness of zero-salt noodles. *International Journal of Food Science & Technology*, 53(7), 1603-1610. <https://doi.org/10.1111/ijfs.13742>
27. Xu, H.N., Huang, W., Jia, C., Kim, Y., Liu, H. (2009). Evaluation of water holding capacity and breadmaking properties for frozen dough containing ice structuring proteins from winter wheat. *Journal of Cereal Science*, 49(2), 250-253. <https://doi.org/10.1016/j.jcs.2008.10.009>
28. Li, H.M., Ruan, C.Q., Li, Z.J., Tang, H.C., Ding, Z.Y. (2025). Research progress on the effect of resistant starch on dough characteristic and quality of flour products. *Journal of the China Cereals and Oils Association (In Chinese)*, 40 (04), 225-234. <https://doi.org/10.20048/j.cnki.issn.1003-0174.000979>
29. Israr, T., Rakha, A., Rashid, S., Shehzad, Aamir., Ahmed, Waqas., & Sohail, M. (2017). Effect of basil seed gum on physico-chemical and rheological properties of bread. *Journal of Food Processing and Preservation*, 41(5), e13128. <https://doi.org/10.1111/jfpp.13128>
30. Yang, Q., Guo, J., Zhang, F., Zhao, F., & Zhang, G. (2024). Inulin with different degrees of polymerization as a functional ingredient: evaluation of flour, dough, and steamed bread characteristics during freezing. *Food Chemistry: X*, 22, 101431. <https://doi.org/10.1016/j.fochx.2024.101431>
31. Wang, L. (2018). Study on the effect of mixing dough's process to steamed bread quality and dough.
32. Wang, P., Tao, H., Jin, Z., & Xu, X. (2016). Impact of water extractable arabinoxylan from rye bran on the frozen steamed bread dough quality. *Food Chemistry*, 200, 117-124. <https://doi.org/10.1016/j.foodchem.2016.01.027>