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Effects of Konjac glucomannan with different viscosities on the rheological and microstructural properties of dough and the performance of steamed bread

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ABSTRACT

Konjac glucomannan (KGM) is used as an additive to improve the properties of wheat products. The effects of three types of KGM on the rheological properties and microstructure of dough, as well as the performance of steamed bread were investigated in this study. Particularly, dough with KGM displayed new features such as reduced peak viscosity, breakdown and setback. As the viscosity of KGM increased, the stability of the dough structure increased, while the viscosity and fluidity of the dough decreased. More interestingly, the gluten film of dough also increased with increasing substitution level and viscosity of KGM. Consistently, KGM with higher viscosity improved the quality of steamed bread. Generally, three types of KGM have different effects on the rheological characteristics and microstructure of dough, as well as the performance of steamed bread, which provide useful information for the proper application of KGM in wheat-based foods.

1. Introduction

Steamed bread is one of the most appealing staple foods in many Asian countries because of its superior nutritional, sensorial, and textural characteristics (He, Guo, Ren, Cui, Han & Liu, 2020). It is made of wheat flour, yeast and water, followed by fermented, sheeted, shaped, proofed and then steamed (Cao et al., 2020b). However, with the development of flour milling industry, and the dietary and economic factors, et.al, wheat flour, as a staple food material, loses a significant amount of dietary fiber, vitamins and other nutrition, thus increasing the risk of chronic diseases (Luo et al., 2017a). Addition of fiber is the most effective way to increase the level of dietary fiber to provide health benefits (Luo et al., 2017a).

Dough is the first and the most important step of making steamed bread. It is attractive to design the functional materials for improving steamed bread properties (Awual, 2019a), such as physical and chemical properties, as well as biological activities. Over the last several decades, varieties of functionalized materials have been used to improve the nutritional value (Hsu, Chang & Shiau, 2019; Kou et al., 2019). Dough is a network containing wheat flour, water, and other ingredients (Peng, Li, Ding & Yang, 2017). In the process of dough formation, three-dimensional gluten network is formed through hydrogen bonding, disulfide bonds and non-covalent interactions, which wraps starch granules, fat and other ingredients inside (Li, Zhu, Yadav & Li, 2019b). The characteristics of the dough depend on the quality of the flour, for example the elasticity and stability of dough (Barak, Mudgil & Khatkar, 2014). The substitution of flour causes a decrease in gluten protein content, which affects the quality of the final product. Many types of dietary fibers have been used to improve the nutritional value of wheat flour and dough properties (Kou et al., 2019). Adding inulin was reported to significantly increase the height and specific volume of steamed bread and decrease the hardness, cohesiveness, recovery, and chewiness (Kou et al., 2019). Adding proper quantity of fermented bran improved the characteristics of the dough and the quality of the steamed bread (Abedfar, Hosseininezhad & Rafe, 2020). Huang et al. (2020) revealed that a novel water-soluble resistant dextrin greatly promoted the sensory appearance and crumb quality of baked bread. Conclusively, the addition of dietary fiber can improve the physicochemical characteristics of dough and nutritional value of final product.

As a water-soluble dietary fiber, konjac glucomannan (KGM) is a linear polysaccharide composed of blocks of β-1,4 linked D-mannosyl and D-glucosyl residues with a molar ratio of 1.6:1 and a low degree of acetyl groups at the C-6 position (Zhao, Zhou, Liu, Liang, Cheng & Nirasawa, 2017). KGM promoted gluten cross-linking and improved the

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thermal stability of the gluten network (Cui, Wu, Liu, Sui, Wang & Zhang, 2019b). Dough with the addition of KGM had good elasticity, tensile, and textural properties (Cui et al., 2019b). Furthermore, KGM stabilized the structures of gluten proteins and bound free water to form more stable complexes, retaining the rheological and tensile properties of the frozen dough (Cui, Liu, Wu, Sui & Zhang, 2019a). KGM has been reported to be useful as a fat replacer in manufacturing fat-reduced mozzarella cheese to improve its functionality and pizza baking characteristics (Dai, Jiang, Shah, & Corke, 2019). In our previous study, adding KGM increased the height and whiteness and decreased the springiness, cohesiveness, and resilience of steamed bread (He et al., 2020). Our research also showed that KGM was a very useful food additive to change the quality of frozen starch gel (Guo, Wang, Liu, & Wang, 2020). It was well known that the water-holding capacity of KGM has close relations with its viscosity. Hence, it is reasonable to hypothesize that the viscosity of KGM would affect the dough characteristics and steamed bread quality. If this is true, it would dramatically expand the application of KGM in wheat-based foods.

Most groups studied the influence of one type of KGM on the characteristics of dough. There were few studies focusing on the impacts of various KGM on dough and steamed bread. The object of this study is to investigate the effects of three types of KGM on the pasting, rheological properties of wheat dough, as well as on the quality of steamed bread, which can provide research foundation for the processing of KGM-based wheat foods.

2. Materials and methods

2.1. Materials

The commercially available low-viscosity konjac glucomannan (L-KGM) powder (KM8), medium-viscosity konjac glucomannan (M-KGM) powder (KJ22), and high-viscosity konjac glucomannan (H-KGM) powder (KJ36) were purchased from Hubei Konson Konjac Technology Co., Ltd. (Hubei, China). Plain wheat flour was procured from Natural Flour Co., Ltd. (Zhumadian, Henan, China). Instant dry yeast was supplied by Angel Yeast Co., Ltd. (Yichang, Hubei, China). Analytical grade sodium chloride was obtained from Jiangsu Qiangsheng Chemical Function of Materials Co., Ltd. (Ezhou, Jiangsu, China). Deionized water was made by our lab.

2.2. Physico-chemical characteristics

2.2.1. The components of wheat flour

The protein, starch, moisture, fat, ash, and total dietary fiber contents of the plain wheat flour were 11.63%, 68.71%, 12.29%, 1.52%, 0.21% and 2.87% (dry basis, w/w), respectively, according to 920.87, 996.11, 925.10, 922.06, 923.03 and 991.43 correspondingly (AOAC International, 2000). Each group was evaluated in triplicate and the results were expressed as average.

2.2.2. The viscosity of konjac glucomannan powder

The viscosity was determined using the method formulated by Chinese GB/T 18104-2000. The samples (5.0 g) were dispersed in 495 mL deionized water, and stirred at 200 r/min for 2 h, then rested at 25 °C for 1 h. The viscosity was measured by the NDJ-1 rotating viscometer (Miqingke Industrial Co., Ltd, Minhang, Shanghai, China). Each group was evaluated in triplicate. The viscosity of konjac glucomannan powder is shown in Table S1.

2.2.3. The solubility of konjac glucomannan powder

The water solubility was determined by the method of Pan (Pan et al., 2013). The samples (W, 0.10 g) were dispersed in 24.90 g of crushed ice under an ice-water bath at 0 °C with vigorous stirring until crushed ice thawed thoroughly. Then sample solution was centrifuged at 4030×*g* for 20 min. 10.00 g of the supernatant was dried in an oven at 105 °C to constant mass (m). Each group was evaluated in triplicate. The water solubility was calculated according to formula (1).

$$\text{Water solubility}(\%) = \frac{2.5 \times \mathrm{m}}{\mathrm{W}} \times 100 \tag{1}$$

The solubility of konjac glucomannan powder is shown in Table S1.

2.2.4. The glucomannan polysaccharide content of konjac glucomannan powder

According to the method of Chinese GB/T 18104-2000, the glucomannan polysaccharide content of konjac glucomannan powder was determined by spectrophotometry. First, the standard glucose solution (1.0 mg/mL) was prepared, and the absorbance was recorded in order to generate a standard curve. Konjac glucomannan powder was dissolved in deionized water, diluted to 100 mL, kept at 35 °C for 4 h, and then cooled down to 25 °C and maintained for 2 h. The mixture was centrifuged at 4030×*g* at 25 °C for 20 min, then the supernatant was collected and mixed with 0.5 mL H_2SO_4 (3 mol/L). Later, the mixture was heated in water bath at 100 °C for 1.5 h, and cooled down to 25 °C, then mixed with 0.5 mL NaOH (6 mol/L). Finally, 1.5 mL of 3,5-dinitrosalicylic acid was added into konjac glucomannan hydrolytic solution in a 50 mL volumetric flask, then placed in a water bath at 100 °C for 5 min, then cooled down to 25 °C, and diluted with deionized water. After that, the absorbance of the sample was read at 550 nm using a visible spectrophotometer (722N, Shanghai Instrument Analysis Co., Ltd, Songjiang, Shanghai, China). Deionized water was used as the control group. Each group was evaluated in triplicate. The glucomannan polysaccharide content of konjac glucomannan powder was calculated according to formula (2).

$$\text{Glucomannan polysaccharide content}(\%) = \frac{0.9 \times \mathrm{T} \times 100}{\mathrm{m}} \times 100 \tag{2}$$

T is the value of glucomannan hydrolytic solution in the standard curve determined by colorimetry. m is the weight of konjac glucomannan powder (mg).

The glucomannan polysaccharide content of konjac glucomannan powder is shown in Table S1.

2.2.5. The components of konjac glucomannan powder

The protein, moisture, and ash contents of konjac glucomannan powder were measured according to approved methods of AOAC International, 2000 (methods 920.87, 925.10, and 923.03, respectively). Each group was evaluated in triplicate and the results were expressed as average. The components of konjac glucomannan powder are shown in Table S1.

2.2.6. The molecular weight of konjac glucomannan powder

The molecular weight of konjac glucomannan powder was determined by gel permeation chromatography-refractive index-multi angle laser light scattering (GPC-RI-MALLS). 5 mg konjac glucomannan powder was dissolved in 0.1 mol/L $NaNO_3$ (AR grade, Sinopharm Chemical Reagent Co., Ltd) aqueous solution containing 0.02% NaN_3 (AR grade, Sinopharm Chemical Reagent Co., Ltd) at the concentration of 1 mg/mL and filtered through 0.45 μm filter. The samples were measured on a DAWN HELEOS-II laser photometer (He-Ne laser, λ = 663.7 nm, Wyatt Technology Co., Santa Barbara, CA, USA) equipped with three tandem columns (300 × 8 mm, Shodex OH-pak SB-805, 804 and 803; Showa Denko K.K., Tokyo, Japan) which were held at 40 °C using a model column heater. The flow rate was 0.4 mL/min. A differential refractive index detector (Optilab *T*-rEX, Wyatt Technology Co., Santa Barbara, CA, USA) was simultaneously connected to give the concentration of fractions and the dn/dc value. Data were acquired and processed using ASTRA6.1 (Wyatt Technology). All the measurements were done in triplicate. The weight-average molecular weight (Mw) of L-KGM, M-KGM and H-KGM were 400.20 ± 1.90 kg/mol, 699.60 ± 9.40 kg/mol and 849.50 ± 24.80 kg/mol, respectively.

2.3. Flour blends preparation

Wheat-KGM flour (1000 g) with different proportions of flour and KGM was evenly mixed to obtain a homogenous flour blend. Based on the preliminary experimental results, the flour blend containing 0.5%, 1.0%, and 1.5% KGM (g/g, dry basis) was prepared by replacing the same amount of wheat flour with KGM, separately. The flour without KGM was taken as the control group.

2.4. Farinograph and extensograph tests

The farinograph properties of the different flour blends were tested using the Farinograph-AT device (Brabender, Duisburg, Germany) with a mixing bowl for 300 g flour according to the standard AACC Method 54-21 (2002). The dough development time, water absorption, stability time, softening degree, and farinograph quality number of the flour blends were obtained. Each group was evaluated in triplicate.

The extensograph properties of dough were conducted using an Extensograph-E device (Brabender, Duisburg, Germany) according to the standard method AACC 54-10 (2002). The dough area (energy) under the curve, extensibility, maximum resistance, and ratio of resistance to extensibility were determined. Each measurement was performed in triplicate.

2.5. Pasting properties

The pasting properties of different flour blends were detected with a Brabender viscometer (Brabender, Duisburg, Germany) by using the method of Guo et al. (2020). Thirty grams of the flour blends (14% moisture basis) were combined with appropriate deionized water, the amount of which was calculated as 15 times as the value of water absorption of flour blends obtained on the farinograph test (shown in Figs. S1-S10), then mixed in the analyzer canister to prevent lumps. The rotational speed was 75 r/min and test range was 700 cmg. The samples were heated from 30 °C to 95 °C at a rate of 3 °C/min, which were then maintained at 95 °C for 30 min, followed by cooling to 50 °C at a rate of 3 °C/min, and holding at that temperature for 30 min. Finally, the viscosity curves with temperature and time, and the dough pasting temperature, peak viscosity, trough viscosity, final viscosity, breakdown, and setback were obtained. The average of three measurements was reported.

2.6. Rheological properties

The rheological properties of the dough were determined by model DHR-2 rotational rheometer (TA Instruments, New Castle, DE, USA) with parallel plate geometry (40 mm diameter) and a 2 mm gap, according to the reported method (Peng et al., 2017). The flour blends were mixed with deionized water in a kneader (model HM740, Hauswirt Co., Ltd, Zhongshan, Guangdong, China), and the dough was kneaded for 7 min, where water absorption was optimized to make the consistency at the end of mixing centered 500 FU. The dough was then placed between plates and allowed to rest for 10 min for relaxation. A thin layer of mineral oil was applied to prevent the drying of the dough during testing. The temperature was kept constant at 25 °C with a frequency of 0.1–20 Hz under a 1% strain (within the linear viscoelastic region) (Guo et al., 2020). The storage modulus (G′), loss modulus (G″), and loss tangent ($\tan \delta = G''/G'$) were obtained. All measurements were performed in triplicate.

2.7. Scanning electron microscopy (SEM)

To observe the changes in the wheat dough structure directly, SEM was carried out as described by Tang et al (Tang et al., 2019). Doughs were processed in the same manner as given in section 2.6. Doughs were cut into 10 mm cubes, which were dried at −80 °C by vacuum freeze drying. Then, freeze-dried wheat dough powders were coated with gold. The microstructures were observed by a scanning electron microscope (TM3000, Hitachi Corp., Mito, Japan) with an accelerating voltage of 15 kV.

2.8. Preparation of steamed bread

The steamed bread was produced as previously described (Luo et al., 2017b). The dough formulation consisted of 100 g flour blends, 1 g dry yeast, and the appropriate volume of water. The flour blends were added to a kneader (HM740, Hauswirt Co., Ltd, Zhongshan, Guangdong, China). The yeast was dissolved in 30 °C deionized water before used. The dough was evenly divided, molded, and placed in a fermentation room (Oumeijia Co., Ltd, Shenchuan, Hebei, China) at 30 °C and 80% relative humidity for 40 min. The dough was then molded and steamed for 20 min using boiling water.

2.9. Specific volume of steamed bread

The specific volume of steamed bread was examined according to the reported method (Luo, Liang, Xu, Kou, et al., 2017 a). The steamed bread was weighed after cooling for 1 h and the specific volume was obtained. The average of three measurements was reported.

2.10. Spread ratio of steamed bread

The spread ratio of steamed bread was determined using the method formulated by Ayo-Omogie (2020) with a slight modification. The heights and bottom widths of steamed bread were measured at three different locations with a ruler. The spread ratio (height/diameter) was calculated. Measurements were done in triplicate.

2.11. Textural properties of steamed bread

The textural properties of steamed bread were measured by a method (Luo et al., 2017a) with some modifications. The center crumb sample ($2 \times 2 \times 2$ cm^3) was removed by cutting and measured with a SMS TA. XT express enhanced texture analyzer (Stable Micro Systems Co., Ltd. Surrey, UK). The testing speed was 1 mm/s, the trigger force was 3 g, and the degree of compression was 60%. The hardness, springiness, cohesiveness, chewiness, and resilience were evaluated. All measurements were performed in triplicate.

2.12. Sensory evaluation of steamed bread

The sensory analysis of steamed bread (SB) was performed based on Chinese GB/T 35991-2018. A questionnaire survey was conducted among 14 people (six males and eight females, 21–55 years of age) who ate steamed bread as their staple food. Seven attributes of different SB samples were scored: specific volume, appearance, color, structure, toughness, stickiness, and flavor. The seven parameters contribute respectively to 20%, 15%, 10%, 20%, 15%, 15% and 5% of the total score. An overall score of 10 points was used to assess the general performance of steamed bread.

2.13. X-ray diffraction patterns

The X-ray diffraction (XRD) patterns of steamed bread during storage were tested based on the method from Kou et al. (2019) with a little modification. Samples taken from steamed bread core for X-ray tests were freeze-dried and then ground into powder, and passed through a 200-mesh screen. The sample powder was analyzed using a diffractometer (D-8 Advance, BRUKER-AXS) with an operating current of 27 mA and voltage of 50 kV. The scan rate was 4°/min and the scan range of the diffraction angle (2θ) was 5–50°. The X-ray diffraction patterns were analyzed by Jade 6.0.

2.14. Statistical analysis

Origin software 2018 and Macromedia Fireworks were used for the data processing and graphics drawing. Statistical analyses were performed using the SPSS package (version 19.0 for Windows, IBM Inc., Armonk, NY, USA). All statistical analyses were performed by independent sample T-test analysis. $P < 0.05$ was considered as statistically significant.

3. Results and discussion

3.1. Farinograph properties of flour blends

The farinographic properties of flours fortified with the different substitution levels of the three types of KGM were determined. The farinograph curves of dough prepared with different KGMs are presented in Figs. S1-S10, and the farinograph analysis of wheat flours are presented in Table 1. After adding KGM, the farinograph properties of dough changed significantly. The water absorption (WA) of dough increased with increasing substitution level and viscosity of KGM. When the substitution levels of L-KGM, M-KGM, and H-KGM increased from 0.5% to 1.5%, the WA of dough increased by 8.90%, 9.97%, and 8.20%, respectively. When the substitution levels of L-KGM, M-KGM, and H-KGM were 1.5%, the WA of the dough increased by 11.36%, 12.80%, and 12.70%, respectively, compared with that of the control group. This result was similar to that of Yu et al (2019), who revealed that an increasing gelation level gave rise to an increase in the capacity of water absorption in the dough. This is because there are multiple hydroxyl groups in the KGM structure, promoting its interactions with water via hydrogen bonding (Guo et al., 2020).

Dough development time (DDT) reveals the formation and stability of gluten network (Li et al., 2019b). Adding KGM increased the DDT of dough (Table 1). Increasing the substitution levels from 0.5% to 1.5% for L-KGM, M-KGM, and H-KGM increased the DDT of dough by 0.19, 3.07, and 4.22 min, respectively. When the substitution levels of L-KGM, M-KGM, and H-KGM were 1.5%, the DDT of dough increased by 70.83%, 340.28%, and 336.81%, respectively, compared with that of the control dough. This was also observed by Li et al (2019b), who suggested that the polysaccharide possessed higher hydration capacity, and the increase in DDT indicated that hydrocolloid competed with gluten proteins for water during the mixing process, and therefore affected the development of gluten network due to the swelling of hydrocolloids. The DDT of the dough significantly correlated with the added amount of KGM ($P < 0.05$). With the viscosity of KGM increasing from 8031 to 36,017 mPa·s, the DDT of dough significantly increased by 1.00, 3.24, and 3.88 min for added KGM levels of 0.5%, 1.0%, and 1.5%, respectively. This could be attributed to the higher viscosity of M-KGM and H-KGM, which have both a stronger resistance to the formation of a typical gluten matrix and a stronger water-binding ability than gluten molecules (Li, Hu, Xu, Liu, Zhang & Zhang, 2019c).

The stability time (ST) of dough is an indicator of the kneading resistance of dough and the dough strength, a higher ST means a stronger dough (Yu et al., 2019). ST displayed a declining trend after the addition of KGM (Table 1). Under 1.5% of L-KGM, M-KGM, or H-KGM, the ST decreased by 193.13%, 3.42%, and 2.63%, respectively, compared with that of the control. So, the ST in M-KGM and H-KGM blends were higher than that in L-KGM blends. It was described that a decreased ST of dough was directly proportional to an increased level of KGM (Mironeasa, Iuga, Zaharia & Mironeasa, 2019). Li et al. (2019b) also showed that the ST of dough was negatively correlated with the substitution level of KGM, which was consistent with our study. The positive correlation of ST with dough toughness and processing properties indicated that the addition of KGM decreased the toughness of the dough.

The softening degree (SD) reflects the stability and strength of the dough. SD showed an upward trend with an increase in the amount of L-KGM. SD increased by 159.25% when the substitution level of L-KGM was 1.5% compared with that of the control. In contrast, SD had a downward trend when the percentage of M-KGM and H-KGM were increased, reaching only 18.33 and 20.67 FU, which reduced the SD by 87.29% and 66.09%, in comparison with that of the control. M-KGM and H-KGM significantly decreased the SD when compared with that produced with L-KGM addition. SD had negative correlation with dough plasticity and strength (Peng et al., 2017). The results suggested that M-KGM and H-KGM enhanced the stability and strength of the dough. Farinograph quality number (FQN) reflects dough strength and kneading resistance. KGM significantly increased the FQN of dough compared with that of the control. At the same viscosity, there was an increasing trend in FQN with increasing substitution level of KGM. When the substitution levels of L-KGM, M-KGM, and H-KGM were increased from 0.5% to 1.5%, the FQN of dough increased by 3.67, 4.33, and 13.33 mm, respectively. The FQN of dough with M-KGM was higher than the other two. As mentioned above, KGM, as a dietary fiber, with multiple hydroxyl groups, has a high-water retention ability, and induces a migration of water from gluten and dough during flour mixing. In this study, the WA, DDT, FQN of dough increased with increasing level and viscosity of added KGM.

3.2. Extensograph characteristics of dough

Extensograph characteristics were used to elucidate the effect of KGM addition on the viscoelastic properties of the bread dough. The extensograph curves of dough prepared with the different KGMs are presented in Figs. S11-S20, and the extensograph characteristics are shown in Fig. 1. As the extensibility (Ex) increases, the dough tensile strength increases, the dough becomes progressively easier to be stretched, and more resistant to breakage (Luo et al., 2018). It is observed from Fig. 1B that KGM with different viscosities significantly

Table 1
Farinograph analysis of wheat flours with different levels of KGM.

KGM	Substitution level (%)	WA (%)	DDT (min)	ST (min)	SD (FU)	FQN (mm)
	0	61.9 ± 0.1^{g}	1.44 ± 0.05^{i}	9.38 ± 0.02^{d}	34.3 ± 1.2^{d}	39.7 ± 1.5^{g}
L-KGM	0.5	64.4 ± 0.6^{f}	2.27 ± 0.04^{g}	5.17 ± 0.04^{g}	63.3 ± 1.5^{c}	58.0 ± 1.0^{f}
	1.0	68.6 ± 0.7^{d}	2.34 ± 0.03^{g}	4.52 ± 0.06^{h}	75.3 ± 1.5^{b}	59.7 ± 1.5^{f}
	1.5	73.3 ± 2.1^{b}	2.46 ± 0.02^{f}	3.20 ± 0.01^{i}	89.0 ± 1.0^{a}	61.7 ± 2.5^{f}
M-KGM	0.5	64.8 ± 0.1^{f}	3.27 ± 0.04^{e}	10.34 ± 0.03^{a}	23.0 ± 1.0^{f}	120.0 ± 1.0^{c}
	1.0	68.3 ± 0.1^{d}	4.47 ± 0.03^{d}	10.20 ± 0.04^{b}	20.0 ± 1.0^{g}	122.3 ± 0.6^{ab}
	1.5	74.8 ± 0.2^{a}	6.34 ± 0.02^{a}	9.07 ± 0.04^{f}	18.3 ± 0.6^{g}	124.3 ± 1.5^{a}
H-KGM	0.5	66.5 ± 0.2^{e}	2.07 ± 0.06^{h}	9.55 ± 0.03^{c}	27.7 ± 0.6^{e}	107.0 ± 1.0^{e}
	1.0	69.8 ± 0.1^{c}	5.58 ± 0.03^{c}	9.23 ± 0.03^{e}	24.3 ± 2.1^{ef}	116.3 ± 1.2^{d}
	1.5	74.7 ± 0.2^{ab}	6.29 ± 0.03^{b}	9.14 ± 0.03^{f}	20.7 ± 1.5^{fg}	120.3 ± 1.5^{bc}

L-KGM, low-viscosity konjac glucomannan; M-KGM, medium-viscosity konjac glucomannan; H-KGM, high-viscosity konjac glucomannan. WA, water absorption; DDT, dough development time; ST, stability time; SD, softening degree; FQN, farinograph quality number. Each value is represented as mean ± standard deviation (n = 3). Values followed by different superscripts in the same column indicate significant differences ($P < 0.05$).

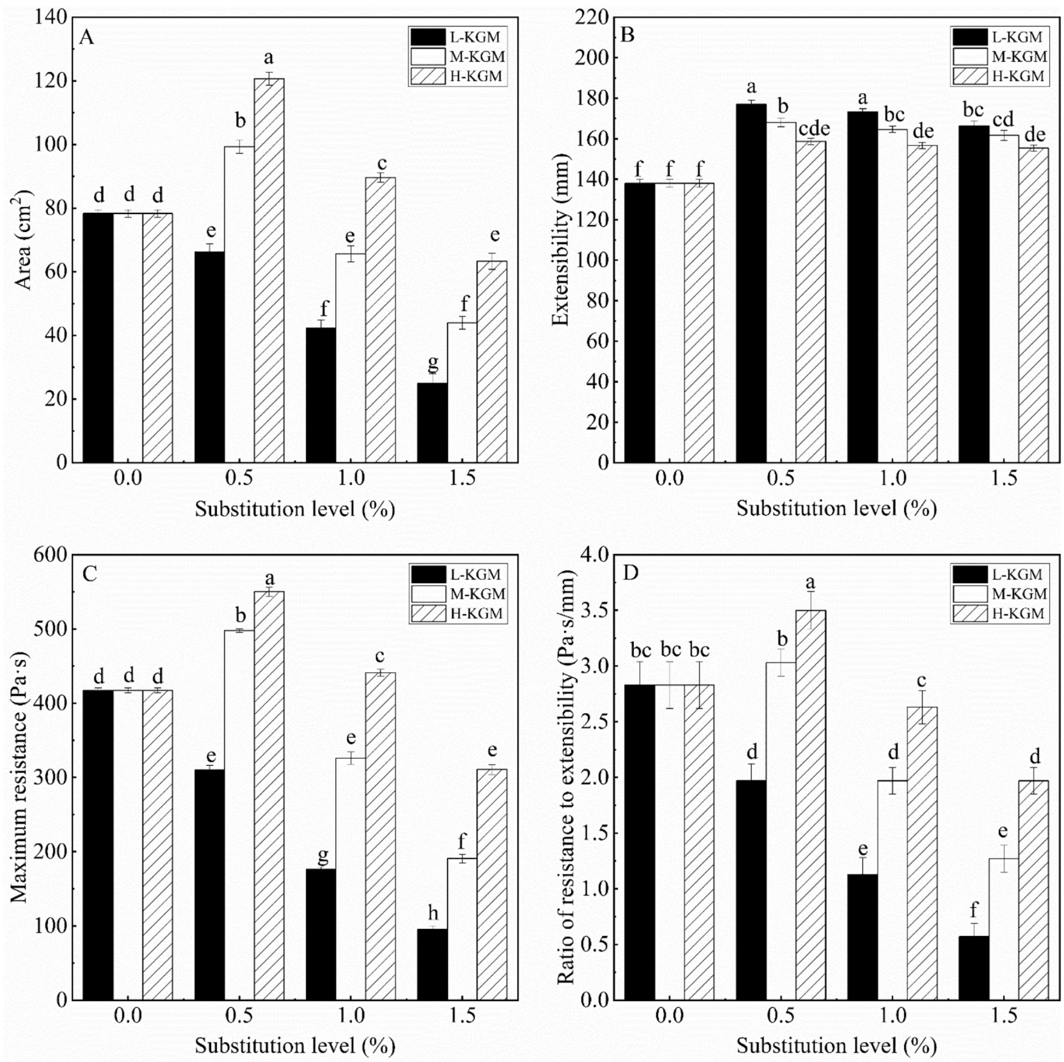

Fig. 1. Extensograph properties of dough with different added amounts of KGM with a resting time of 135 min: (A) area (energy), (B) extensibility, (C) maximum resistance, and (D) ratio of resistance to extensibility. L-KGM, low-viscosity konjac glucomannan; M-KGM, medium-viscosity konjac glucomannan; H-KGM, high-viscosity konjac glucomannan. Error bars represent mean standard deviations of triplicate determinations. Different lowercase letters on the error bars indicate significant differences among samples ($P < 0.05$).

increased the Ex value of dough compared with that of the control. The reason for this phenomenon may be that KGM has strong gelling capacities which can restrain the weakening effect of hydration on the dough structure, thus increasing the Ex of the dough. When the substitution level of KGM was 0.5%, the addition of L-KGM, M-KGM, and H-KGM increased the Ex value of dough by 28.26%, 21.74%, and 14.98%, respectively. L-KGM showed the most significant effect on the Ex value of dough. The small height and side diameter of L-KGM can affect the formation of gluten protein (Mironeasa et al., 2019). Therefore, L-KGM has a greater impact on dough Ex. The Ex of dough decreased with increasing addition of KGM. When the substitution levels of L-KGM, M-KGM, and H-KGM increased from 0.5% to 1.5%, the Ex of dough decreased by 10.67, 6.33, and 3.34 mm, respectively. The reason may be that a higher KGM substitution level led to an increase in water absorption, which in turn led to an increase in gluten dilution strength and a gradual decrease in dough strength and Ex.

The area (energy) under the curve expresses the total energy required to break down the dough (Yu et al., 2019). A larger area indicates dough with higher elasticity. Adding the three types of KGM significantly reduced the area (energy) under the curve of dough, except for 0.5% M-KGM and H-KGM compared with that of the control (Fig. 1A). When the substitution level of KGM was 1.5%, the addition of L-KGM, M-KGM, and H-KGM led to the area (energy) of dough reduced by 213.32%, 78.02%, and 23.67%, respectively. This indicated that a low substitution level (<0.5%) of KGM had a positive impact, whereas a higher substitution level (>0.5%) had a negative impact on the formation of the gluten network. This is consistent with a previous study in which the addition of dietary fiber decreased the area (energy) of dough (Tang et al., 2019). Similar trends were observed in the case of maximum resistance (Rm) and ratio of maximum resistance to extensibility (Rm/Ex). The Rm and Rm/Ex values decreased after the addition of KGM compared with those of the control (Fig. 1C, 1D). When the KGM viscosity was the same, the values of Rm and Rm/Ex displayed a decreasing trend with an increasing substitution level of KGM. When the substitution level of L-KGM, M-KGM, and H-KGM increased from 0.5% to 1.5%, the Rm of dough decreased to 214.67, 307.00, and 239.33 Pa·s, and the Rm/Ex value of dough decreased to 1.4, 1.76, and 1.8 Pa·s/mm, respectively. The Rm and Rm/Ex of the dough were significantly correlated with the added amount of KGM ($P < 0.05$), similar to the results reported by Sim, Noor Aziah and Cheng (2011). In general, these three types of KGM have the same tendency to affect the extensographic properties of the dough. Dough with KGM at 0.5% substitution level had the higher Rm, Rm/Ex, and area (energy) values. This suggested that KGM at 0.5% addition level weakened the overall extensographic properties of dough. On the contrary, KGM at 1.0% and 1.5% substitution levels enhanced the extensographic properties of the dough.

3.3. Pasting properties of wheat flour blends

Pasting characteristics are indispensable for assessing the quality of foodstuffs and have been used to modify the texture and improve the stability of starch-based foods (Guo et al., 2020). The pasting curves of dough prepared with different KGMs are presented in Figs. S21-S30, and the pasting parameters are shown in Fig. 2.

The pasting temperature (PT) of wheat flour with KGM was improved compared with that of the control (Fig. 2A). Here, the PT of wheat flour increased by 5.58%, 4.76%, and 10.20% as a result of the addition of 1.5% L-KGM, M-KGM, and H-KGM, respectively. H-KGM had the most significant effect on the PT of dough. H-KGM has better wrapping behavior to improve the thermal stability of wheat flour compared with that of L-KGM. The PT of wheat flour increased with increasing KGM substitution level. When the substitution levels of L-KGM, M-KGM, and H-KGM were increased from 0.5% to 1.5%, the PT of wheat flour increased by 2.3, 3.1, and 4.4 °C, respectively (Fig. 2A). Similar results were also found by Blanco Canalis, León and Ribotta (2019), who reported a significant increase in pasting temperature with the maximum level of incorporation for multiple fibers. However, Guo et al. (2020) reported that KGM decreased the PT value of frozen starch. This contrast may be due to the difference of the system. There are many ingredients such as protein and starch in the dough, which have multiple effects on the PT value.

Peak viscosity (PV) reflects water-binding or granule swelling and is the most important aspect of the product quality (Guo et al., 2020). Through viscosity (TV) reflects the stability of flour during cooking (resistance to breakdown due to shear). The PV, TV, and final viscosity (FV) of the wheat flour decreased with increasing KGM (Fig. 2B-2D). When the substitution levels of L-KGM, M-KGM, and H-KGM were increased from 0.5% to 1.5%, the PV of wheat flour decreased by 22.78%, 19.10%, and 25.60%, respectively. Peressini, Tat and Sensidoni (2019) also suggested that due to the presence of dietary fiber, the viscosity of the continuous phase and the shear force on expansive particles increased, resulting in particle breakage and decreased viscosity. One reason is that the dietary fiber competes with starch to absorb water during the starch gelatinization phase, which impedes the gelatinization of the starch (Farbo, Fadda, Marceddu, Conte, Del Caro & Piga, 2020). Another reason is that KGM leads to a decrease in granule swelling power (Guo et al., 2020). Here, the TV decreased with an increase in KGM substitution level. KGM with varying viscosities had different

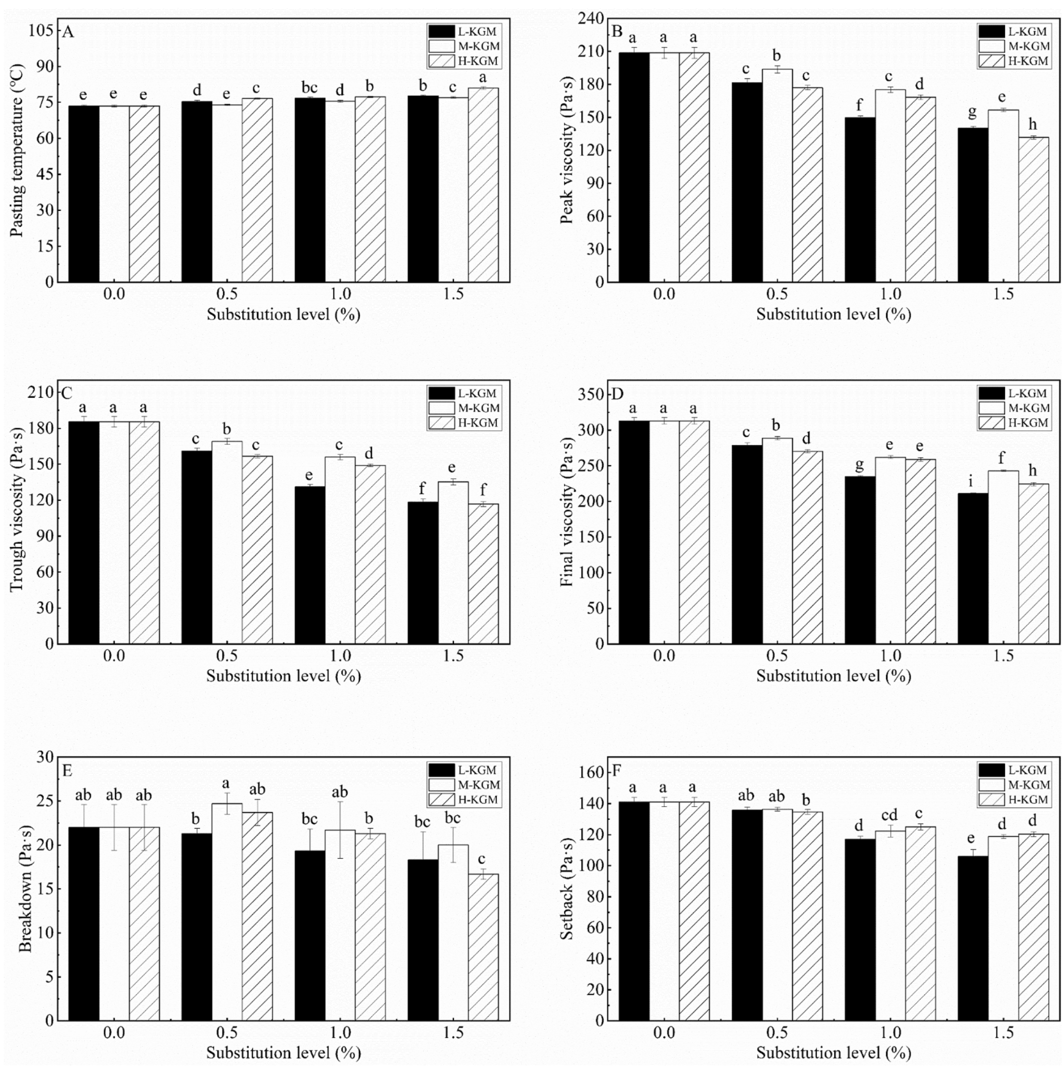

Fig. 2. Pasting properties of wheat flour with different added amounts of KGM: (A) pasting temperature, (B) peak viscosity, (C) trough viscosity, (D) final viscosity, (E) breakdown, and (F) setback. L-KGM, low-viscosity konjac glucomannan; M-KGM, medium-viscosity konjac glucomannan; H-KGM, high-viscosity konjac glucomannan. Error bars represent mean standard deviations of triplicate determinations. Different lowercase letters on the error bars indicate significant differences among samples ($P < 0.05$).

effects on the PV, TV, and FV of wheat flour. The PV of wheat flour first increased and then decreased with the increase in KGM viscosity. When the substitution level of KGM was 1.5%, the addition of L-KGM, M-KGM, and H-KGM decreased the PV of wheat flour by 32.92%, 24.92%, and 36.90%, respectively (Fig. 2B). H-KGM had the most significant effect on the PV of dough. This could be related to the interactions between hydrocolloids and solubilized starch (Li et al., 2019b). Starch granules and hydrocolloids had a synergistic thickening effect, which increased the viscosity of the starch paste (Farbo et al., 2020). On the other hand, KGM is a dietary fiber with a low degree of branching, which favors thermodynamically compatible interactions with amylose (Guo et al., 2020). KGM can interact with leached amylose and low molecular weight amylopectin in starch granules. This resulted in an increase in the viscosity of the system (Guo et al., 2020).

The breakdown (BD) mainly reflects the degree of decomposition of starch granules during pasting. The BD also reflects the stability of starch granules during heating, with a higher value indicating less granule integrity (Guo et al., 2020). When wheat flour was substituted with 0.5% M-KGM and H-KGM, the BD increased by 12.27% and 7.73%, compared with that of the control (Fig. 2E). In contrast, wheat flour with higher M-KGM and H-KGM substitution levels (>0.5%) exhibited lower BD. The BD of wheat flour first increased and then decreased with the increase of KGM viscosity. A decrease in the BD of wheat flours indicated increasing heat and shear stress stability of the flours during cooking (Adegunwa, Kayode, Kayode, Akeem, Adebowale & Bakare, 2020).

The setback (SB) characterizes the degree of molecular recrystallization after starch pasting (Guo et al., 2020). The addition of KGM decreased the SB of the wheat flour (Fig. 2F). When the substitution levels of L-KGM, M-KGM, and H-KGM increased from 0.5% to 1.5%, the SB of wheat flour decreased by 21.89%, 12.91%, and 10.69%, respectively. A similar phenomenon was found by Farbo et al. (2020), who indicated that the adding 0.5% methylcellulose and 0.5% psyllium gum decreased the SB of dough. A decreased SB indicates that amylose is severely broken and dough is difficult to age. When the substitution level of KGM was 1.5%, the addition of L-KGM, M-KGM, and H-KGM decreased the SB of wheat flour by 24.82%, 15.82%, and 14.68%, respectively. The dough containing H-KGM had a higher SB, indicating a higher retrogradation affinity, and more syneresis taking place (Ahmed & Thomas, 2018).

3.4. Rheological properties of dough

The dynamic modulus can be used to study the interactions between the dispersed and continuous phases in some polymer solutions (Blanco Canalis et al., 2019). G′ and G″ are presented in Fig. 3. As shown in Fig. 3A and 3B, the values of G′ and G″ increased with frequency in all samples in the range of 0.1–20 Hz. The G″ value was lower than the G′ value, indicating the viscoelastic characteristics and solid-like behavior of the dough (Li et al., 2019b; Farbo et al., 2020; Li et al., 2019c). This was likely due to the electrostatic interactions between KGM and gluten (Farbo et al., 2020). The G′ and G″ values of wheat dough with KGM were lower than the values of the control. These meant that KGM had a significantly negative effect on the dynamic moduli of wheat flour dough. This is consistent with the results reported by Zhao et al. (2017). One reason for this is that addition of KGM can weaken the gluten matrix (Mironeasa et al., 2019). Alternatively, a large amount of KGM can disturb the structure and intensity of the continuous gluten network during the formation of dough (Mironeasa et al., 2019). In addition, hydrogen bonds are readily formed between KGM and water molecules, which reduces gluten content, thereby weakening the gluten network structure (Tang et al., 2019).

Tan δ is the ratio of G″ to G′, which reflects the protein quality (Zhao et al., 2020). The values of tan δ were between 0.1 and 1 (Fig. 3C), indicating that the dough was solid-like (Li et al., 2019b). The tan δ of

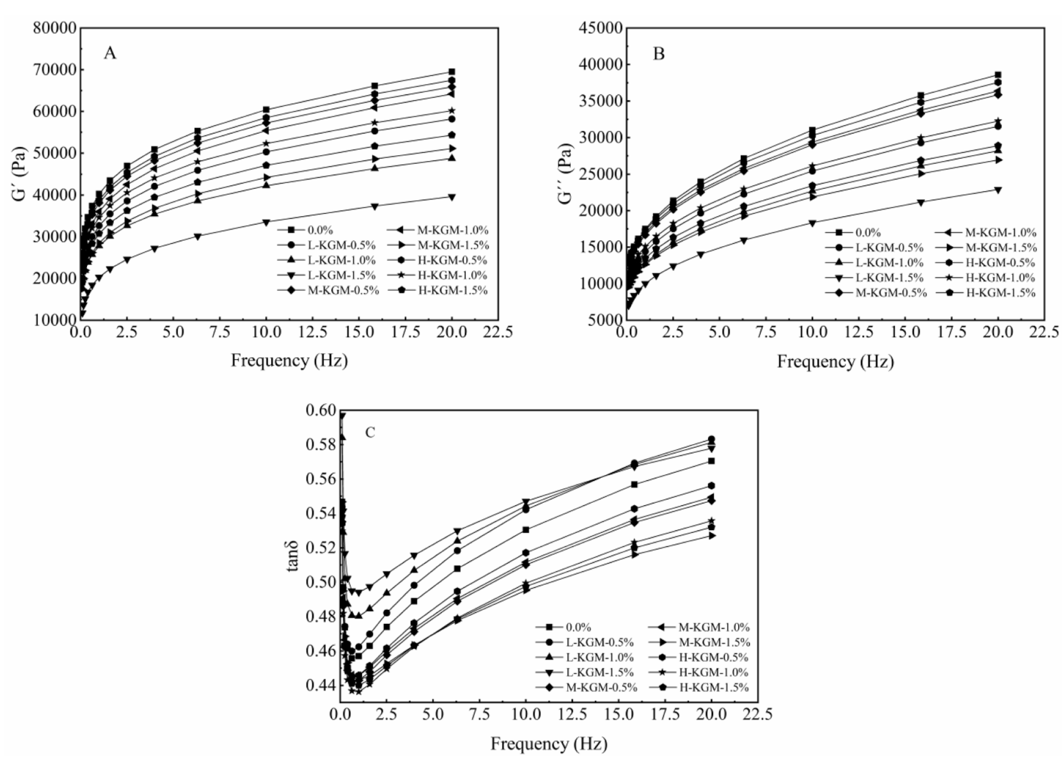

Fig. 3. Effects of KGM on the rheological properties of dough: (A) G′, elastic moduli, (B) G″, viscous moduli, and (C) tan δ, loss tangent. L-KGM-0.5%, dough with 0.5% low-viscosity konjac glucomannan; L-KGM-1.0%, dough with 1.0% low-viscosity konjac glucomannan; L-KGM-1.5%, dough with 1.5% low-viscosity konjac glucomannan; M-KGM-0.5%, dough with 0.5% medium-viscosity konjac glucomannan; M-KGM-1.0%, dough with 1.0% medium-viscosity konjac glucomannan; M-KGM-1.5%, dough with 1.5% medium-viscosity konjac glucomannan; H-KGM-0.5%, dough with 0.5% high-viscosity konjac glucomannan; H-KGM-1.0%, dough with 1.0% high-viscosity konjac glucomannan; H-KGM-1.5%, dough with 1.5% high-viscosity konjac glucomannan.

the dough containing H-KGM flour increased while the tan δ of the dough containing L-KGM and M-KGM flour decreased compared with that of the control. Dough prepared with highly viscous KGM behaved more like a solid throughout the tested frequency range, and the addition of highly viscous KGM shifted the dough network to a more elastic and rigid structure (Li et al., 2019b). Wang et al. (2017) reported that KGM existed as an independent polymer chain in the system. During the heating process, KGM further expanded to make the dough more elastic (Wang et al., 2017). There were more polymerization reactions in H-KGM, so KGM with a higher viscosity makes the dough more elastic. These findings indicated that the viscosity of KGM increased, the stability of the dough structure was enhanced while the viscosity and

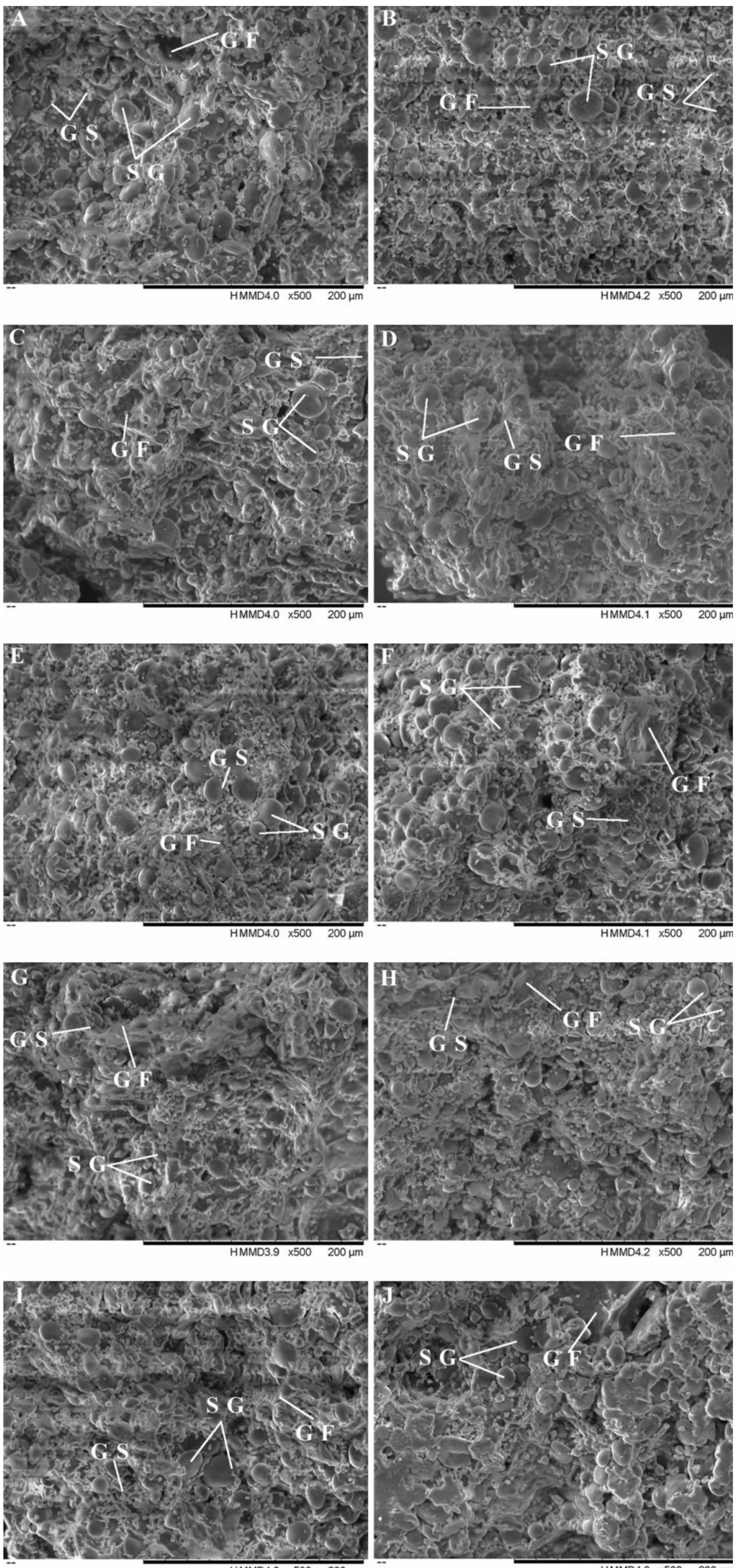

Fig. 4. Representative SEM micrographs of dough. (A) control, dough without konjac glucomannan; (B) L-KGM-0.5%, dough with 0.5% low-viscosity konjac glucomannan; (C) L-KGM-1.0%, dough with 1.0% low-viscosity konjac glucomannan; (D) L-KGM-1.5%, dough with 1.5% low-viscosity konjac glucomannan; (E) M-KGM-0.5%, dough with 0.5% medium-viscosity konjac glucomannan; (F) M-KGM-1.0%, dough with 1.0% medium-viscosity konjac glucomannan; (G) M-KGM-1.5%, dough with 1.5% medium-viscosity konjac glucomannan; (H) H-KGM-0.5%, dough with 0.5% high-viscosity konjac glucomannan; (I) H-KGM-1.0%, dough with 1.0% high-viscosity konjac glucomannan; (J) H-KGM-1.5%, dough with 1.5% high-viscosity konjac glucomannan; GF, gluten film; GS, gluten strand; SG, starch granule.

fluidity of the dough was decreased. The substitution levels of L-KGM and M-KGM were negatively correlated with the tan δ of the dough. These findings indicated that the increased substitution levels of L-KGM and M-KGM improved the stability of the dough structure and reduced the viscosity and fluidity. Ning, Cui, Yuan, Zou, Liu and Pan (2020) reported that KGM was also acted as a thickener, which can hinder the excessive aggregation of the large starch chains and stabilize the mixed system. Several authors have reported that the addition of soluble dietary fiber enhanced the stability of dough because these fibers could bind with other macromolecular chains in the dough (Li et al., 2019c; Li, Liu, Wu, Wang & Zhang, 2016).

3.5. Microstructural characteristics of dough

The microstructure of dough prepared by using different levels and viscosities of KGM is presented in Fig. 4. This analysis provides helpful information for understanding the interactions among dietary fiber, gluten proteins, and starch granules. In the photomicrographs of the control group (Fig. 4A), a continuous gluten network was observed, and starch granules (SG) were tightly embedded in a gluten network consisting of gluten strands (GS) and gluten films (GF). The microstructure of the dough was influenced by the level and viscosity of added KGM. With the increase in the KGM level, the integrity and continuity of the GF became weaker, although more GF were observed and more SG was wrapped by the GF (Fig. 4). The presence of 0.5% KGM in the dough resulted in thicker GS compared with those of the control group (Fig. 4B, 4E and 4H). When the KGM substitution level reached 1.0%, the GS was smaller and the GF became more numerous (Fig. 4C, 4F and 4I). When the substitution level of KGM was 1.5%, the GF covered most areas and the number of starch grains decreased accordingly (Fig. 4D, 4G and 4J). This indicated that KGM affected the formation of gluten network and the distribution of starch granules in the dough. Wang et al. (2017) also observed a thickened gluten layer with 5% KGM by SEM, and KGM can change the gluten conformation through non-covalent interactions and physical entanglement. Cui et al (2019b) reported that dough microstructure had a continuous network and starch granules were inserted in the gluten network, and observed that KGM connected with gluten network and discreted starch granules in the complex system of gluten-KGM.

Here, the addition of L-KGM loosened the microstructure of dough. However, as the viscosity of KGM increased, the dough structure became tighter. The addition of KGM with higher viscosities increased the stability of the dough. The observations are likely to reflect the greater number of binding sites that are present in the KGM of higher viscosity. These sites could bind to gluten proteins. In one study, the gluten network of dough prepared with guar gum was more compact, the proportion of continuous gluten was larger, and the SG was wrapped by gluten network (Li, Yadav & Li, 2019 a). Both guar gum and KGM are linear non-ionic hydrocolloids and can bind to gluten through hydrogen bonds. On the other hand, gluten development is also affected by the competition between hydrocolloids and gluten proteins for water. In one study, the addition of 1% guar gum to dough resulted in the best integrated gluten network (Farbo et al., 2020). Anionic molecules, such as carboxymethyl cellulose or pectin, can interact with gluten proteins through electrostatic forces, which led to a less crosslinked structure (Correa, Ferrer, Añón & Ferrero, 2014). The addition of natural functional materials can improve the textural attributes, processing characteristics and quality of food via non-covalent interactions or covalent bonds between biomolecules in foods (Hu et al., 2019; Tong, Chen, Wang, Zhang, Yu & Ren, 2018). On the other hand, composite materials were fabricated by non-specific interaction via hydrogen bonding, Van der Waals forces and reversible covalent bonds according to direct immobilization approach (Awual, Hasan, Islam, Asiri & Rahman, 2020; Awual, 2019b). Awual (2019c) fabricated the composite material based on the ligand immobilization onto the porous silica with direct coating approach, which offered a cost-effective material. The fabrication of functional materials is an important approach to expand the source of functional materials and produce functional foods.

3.6. Textural properties of steamed bread

The textural characteristics of steamed bread with KGM addition are presented in Table S2. The hardness of steamed bread has an important influence on the taste of steamed bread and is an important factor for people to choose steamed bread. Generally, KGM had various influences on the textural properties of steamed bread. KGM significantly decreased the hardness of steamed bread, compared with control, due to the decreased protein flexibility by KGM (Wang et al., 2017). KGM destroyed the structural integrity of the gluten protein network, and made the steamed bread soft (Hsu et al., 2019). Here, compared with the control, the hardness of steamed bread with addition of 1.5% L-KGM, M-KGM, and H-KGM decreased by 46.16%, 34.83%, and 27.72%, respectively, which indicated that KGM with lower viscosity was more effective for reducing the hardness of steamed bread. This trend is in accordance with results presented earlier on the rheological behaviors of dough with addition of less viscous KGM. This is explained by the influence of KGM with lower viscosity on the weakness of wheat-based dough, which led to the reduction of the hardness of the steamed bread.

Springiness represent the recovery after the first compression. As shown in Table S2, there was a slight decline of the springiness when KGM was added. However, this difference in springiness was negligible. However, He et al. (2020) reported that the addition of 4.5% KGM significantly decreased the springiness of steamed bread. These different results could be explained by the different viscosity of KGM and the type of wheat flour. The cohesiveness and chewiness of steamed bread decreased with increasing substitution level of KGM, indicating that KGM improved the taste of steamed bread (He et al., 2020). Resilience represents the ability of bread to recover from deformation and usually contributes to good bread quality (Zhao, Mu, & Sun, 2019). All three types of KGM affected the resilience of the steamed bread. When the substitution level of KGM was 1.5%, the resilience was all remarkably lower than that of the control ($P < 0.05$). This suggested that KGM weakened the elastic properties of the steamed bread (He et al., 2020). The main reasons for the decrease in the elasticity of steamed bread are likely to be the result of the large amount of hydrogen bonds between KGM and water molecules which reduced the viscoelasticity of dough (Tang et al., 2019). Alternatively, the presence of a large amount of KGM can disturb the structure and intensity of the continuous gluten network during the formation of dough (Mironeasa et al., 2019).

3.7. Specific volume, spread ratio, total dietary fiber and sensory score of steamed bread

Specific volume, spread ratio, and sensory score are important quality attributes of steamed bread (Zhao et al., 2019). The higher the specific volume and spread ratio of steamed bread, the better the appearance of the product and the higher the customer satisfaction (Zhao et al., 2019). As shown in Table 2, the specific volume showed an upward trend with an increase in the amount of M-KGM or H-KGM. The specific volume increased by 6.67% and 11.56%, compared with that of the control, when the substitution level of M-KGM and H-KGM was 1.5%. In contrast, the specific volume showed a downward trend with an increasing amount of L-KGM added. The lowest level of 4.38 mL/g reduced the specific volume by 2.67% compared with that of the control when 1.5% L-KGM was added. This observation is consistent with previous findings of the rheological characteristics of wheat dough with addition of different types of KGM. This increase in specific volume of steamed bread was resulted from the strengthening effect of KGM on gluten network in steamed bread, which led to better gas retention in steamed bread (Guo et al., 2020). On the other hand, KGM inhibited the development of macromolecular entanglements and slowed down starch recrystallization (Xu et al., 2020). Compared with L-KGM, M-KGM and

Table 2
Specific volume, spread ratio, total dietary fiber and sensory score of steamed bread.

KGM	Substitution level (%)	Specific volume (mL/g)	Spread ratio	Total dietary fiber (%)	Sensory score
	0	4.50 ± 0.04^{b}	3.70 ± 0.10^{a}	2.85 ± 0.02^{h}	6.78 ± 1.69^{b}
L-KGM	0.5	4.48 ± 0.20^{b}	3.66 ± 0.06^{a}	3.20 ± 0.03^{g}	6.36 ± 1.34^{b}
	1.0	4.44 ± 0.26^{b}	3.60 ± 0.12^{a}	3.60 ± 0.03^{e}	6.04 ± 1.88^{b}
	1.5	4.38 ± 0.04^{b}	3.60 ± 0.12^{a}	3.90 ± 0.03^{c}	5.90 ± 1.82^{b}
M-KGM	0.5	4.52 ± 0.24^{ab}	3.84 ± 0.06^{a}	3.30 ± 0.03^{f}	7.12 ± 1.73^{b}
	1.0	4.64 ± 0.08^{a}	3.88 ± 0.02^{a}	3.72 ± 0.02^{d}	7.16 ± 1.39^{b}
	1.5	4.80 ± 0.08^{a}	4.02 ± 0.03^{a}	4.10 ± 0.05^{b}	7.36 ± 1.10^{a}
H-KGM	0.5	4.66 ± 0.12^{a}	3.88 ± 0.06^{a}	3.31 ± 0.04^{f}	8.10 ± 0.97^{a}
	1.0	4.80 ± 0.12^{a}	4.26 ± 0.18^{a}	3.80 ± 0.04^{d}	8.62 ± 0.48^{a}
	1.5	5.02 ± 0.20^{a}	4.40 ± 0.12^{a}	4.30 ± 0.03^{a}	8.90 ± 0.55^{a}

L-KGM, low-viscosity konjac glucomannan; M-KGM, medium-viscosity konjac glucomannan; H-KGM, high-viscosity konjac glucomannan. Each value is represented as mean ± standard deviation (n = 3). Values followed by different superscripts in the same column indicate significant differences ($P < 0.05$).

H-KGM significantly increased the specific volume values of dough. Sim et al. (2011) demonstrated that the addition of dietary fiber was reported to result in greater water retention and bread volume, and Li et al. (2019b) stated that KGM improved the fermentation performance of dough and increased porosity stability and gas retention.

The spread ratio is the height-to-diameter ratio of steamed bread. As presented in Table 2, the spread ratio increased slightly, when M-KGM and H-KGM were added. However, those differences were not significant, indicating that the effects of KGM on the steamed bread volume were not substantial. The positive influence of M-KGM and H-KGM was also evident for the surface characteristics and internal structure of the steamed bread (Fig. S31). Steamed bread prepared with the addition of 1.5% M-KGM and H-KGM were plumped with smoother surfaces and more even internal pores compared with the control (Fig. S31). In contrast, steamed bread containing L-KGM showed a texture with single dry rough surface, and large pores (Fig. S31). As for the total dietary fiber content and the sensory score of steamed bread, the addition of H-KGM significantly improved the sensory of steamed bread compared with the control, and at the same time provided people with more dietary fiber.

3.8. *XRD patterns of steamed bread*

Staling of steamed bread is usually caused by the retrogradation of starch, which is usually accompanied by the development of a crystalline matrix (Kang, Reddy, Park, Choi & Lim, 2018). X-ray diffraction was used to measure the crystalline structure of steamed bread during storage. The variation of XRD pattern with time is shown in Fig. S32. During the storage of steamed bread, the addition of KGM had no significant effect on the peak of amylopectin production ($2\theta = 20^{\circ}$), indicating that KGM had no special effect on amylopectin retrogradation, which was similar to the conclusions obtained in previous studies (Curti, Carini, Diantom & Vittadini, 2016) that addition of soluble dietary fiber to bread strengthened bread. With the retrogradation of steamed bread, the recrystallization of amylose increased continuously, while amylopectin remained almost unchanged (Cao et al., 2020a). After 2 days of storage, all steamed bread had two distinct peaks at 17° and 20°, which represented the characteristic recrystallization peaks of amylose and amylopectin. The peak of steamed bread without KGM was more obvious than that with KGM, especially at $2\theta = 17^{\circ}$, indicating that the addition of KGM delayed the staling of steamed bread. This is consistent with the results of the above KGM tests on the pasting characteristics of dough, and also suggested that KGM can effectively reduce the retrogradation of steamed bread, delay the rate of wheat starch recrystallization, and reduce the aging degree of starch. This is because KGM is a linear polysaccharide, which crystalizes during storage, thus inhibiting amylose crystallization.

4. Conclusions

In the present study, the behaviors and rheological characteristics of dough containing three types of KGM were investigated. In particular, the water absorption and the development time of dough increased with increasing KGM content and viscosity. Three types of KGM decreased the PV, TV, and FV of the wheat flour. These effects were more evident in the wheat flour with addition of 1.5% KGM, which resulted in a decreased PV value by 36.90% relative to the control. The addition of KGMs increased the PT of wheat flour, and H-KGM had the most significant effect on wheat flour pasting temperature. The BD of wheat flour first increased and then decreased with the KGM viscosity increasing. More specifically, as the viscosity of KGM increased, the stability of the dough structure increased, while the viscosity and fluidity of the dough decreased. The dough with high-viscosity KGM had denser and more homogeneous microstructures. In general, the extents of the KGM-induced changes in the physical and chemical properties of the dough are related to the substitution level and viscosity of KGM.

Particularly, KGM improved the textural properties and increased the specific volume and spread ratio of steamed bread. In this way, the sensory score of steamed bread reached the highest of 8.9 which was increased by 31.27% compared to the control when 1.5% KGM was added. These results provide useful information for the proper application of three types of KGM in wheat-based foods. Future studies should focus on the gluten-KGM, starch-KGM interactions in the dough.

CRediT authorship contribution statement

Jinying Guo: Conceptualization, Methodology, Software, Writing - review & editing. **Feng Liu:** Conceptualization, Methodology, Software, Data curation, Writing– original draft, Writing - review & editing. **Chuanfa Gan:** Data curation, Writing– original draft. **Yingying Wang:** Visualization, Investigation, Supervision, Software. **Ping Wang:** Visualization, Investigation, Supervision, Software. **Xiaolan Li:** Writing - review & editing. **Jiaxing Hao:** Writing - review & editing.

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 paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodchem.2021.130853.

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