Food Chemistry: X 27 (2025) 102361

Contents lists available at ScienceDirect

Food Chemistry: X

journal homepage: www.sciencedirect.com/journal/food-chemistry-x

Performance comparison between different hydrocolloids to improve properties of dough and noodles made from maize-based composite dough

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ARTICLE INFO

Keywords:
Hydrocolloids
Maize-based composite
Physicochemical properties

ABSTRACT

The effect of hydrocolloids xanthan gum (XG), sodium alginate (SA) and sodium carboxymethyl cellulose (CMC—Na) on the properties and noodle quality of maize-based composite dough has been studied. The composite flour showed more comprehensive nutritional characteristics than maize flour. Rheological studies have shown that the three hydrocolloids dramatically increased the elasticity and viscosity of composite dough. All hydrocolloids significantly ($p < 0.05$) change the texture properties of noodles in composite dough, and XG had the most obvious effect. The addition of hydrocolloids improves the cooking properties of noodles in composite dough. The improvement of XG on the resistance to extension and extensibility is also obvious. Generally, adding hydrocolloids to maize-based composite dough appears to be a highly effective way to improve the quality of dough, and the application prospect of hydrocolloids, especially XG, is very promising.

1. Introduction

Gluten-related diseases are common globally, and their prevalence is continuously growing. Gluten intake can cause a number of gluten-related illnesses, including coeliac disease, dermatitis herpetiformis (skin symptoms of coeliac disease), gluten ataxia, and non-celiac gluten sensitivity (Vici et al., 2016). The effective measure to treat gluten-related diseases was following a gluten-free diet (Al-Toma et al., 2019). Therefore, it is necessary to develop more gluten-free products from gluten-free cereals, pseudo-cereals, and other naturally gluten-free foods.

Maize is an excellent gluten-free food source. It is a globally produced cereal crop that is high in carbs, dietary fiber, vitamins, minerals, and other micronutrients (H. Sun et al., 2019). In addition, the utilization of maize in human food is currently less than that in animal or poultry feed. One of the principal reasons for this is that maize has low protein content and lacks essential amino acids such as lysine and tryptophan, which do not meet daily nutritional needs of humans (Shobha et al., 2015). The problem of uneven nutrition in maize flour can be solved through the combination of raw materials, making it more suitable as a gluten-free food for the human body. Studies have shown that the nutritional defects of maize flour can be improved by blending with gluten free flours rich in protein such as finger millet, buckwheat, quinoa, and rice flour, which have a higher gluten content than maize flour (Burešová et al., 2017; De Arcangelis et al., 2020; Kumar et al., 2023; Sosa et al., 2019). Mancebo, C.M.et.al. mixed maize flour, rice flour and wheat starch to optimize the quality of gluten-free bread and produced a nutritionally balanced gluten-free product that is better suited to human needs (Mancebo et al., 2015).

Gluten must be removed for producing gluten-free goods. This reduces the dough’s viscoelasticity, ductility, and air retention, resulting in poor product quality. Currently, a number of methods are being used to improve the nutritional deficiencies of gluten-free foods. Physical modifications, such as heat treatment, pressure, etc. improve the function of maize protein by increasing the molecular flexibility or elasticity of the maize protein network. In addition, various alternative ingredients and/or additives are being tested to mimic the stickiness and elasticity of gluten-containing dough (Li & Nie, 2016). Among them, hydrocolloids are an additive that plays the role of gluten protein, with thickening, emulsification, water retention, gelling and bonding properties, which can improve the structure and quality of gluten-free foods (Brites et al., 2010; Dahal et al., 2021; Jayakody et al., 2023; Sadat et al., 2023; Zhang, Xu, et al., 2022). Macromolecular hydrophilic colloids are able to significantly influence and control the rheological and organizational properties of their content systems at relatively low and low concentrations through appropriate interactions with a large number of water molecules, while at the same time these compounds can also increase viscosity by absorbing water, thereby increasing the stability of

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https://doi.org/10.1016/j.fochx.2025.102361
Received 12 December 2024; Received in revised form 1 March 2025; Accepted 8 March 2025
Available online 13 March 2025

certain food systems (Belorio & Gómez, 2022). And the improvement effect of different hydrocolloids on dough and products is also different. Most studies have shown that hydrophilic colloids have special effects on G' and G", which may be related to their structure. For example, the pseudoplastic behavior of XG allows it to increase dough stability, water absorption, and gas maintenance (Li & Nie, 2016). Romero also observed an increase in apparent viscosity and elasticity of millet gluten-free dough with the addition of XG and SA (Motta Romero et al., 2017). In addition, hydrophilic colloid can affect dough quality, moisture, temperature, and fermentation time. For instance, in the study by Jang et al., the addition of XG and SA to buckwheat noodles decreased cooking loss and turbidity (Jang et al., 2015). Nicolae also reported that the addition of CMC-Na increased the water absorption, development time, and stability time of gluten-free rice dough and enhanced the specific volume and sensorial properties of bread (Nicolae et al., 2016). The above studies demonstrate the impact of different hydrocolloids on the viscoelastic dough formation capabilities of plain dough. However, there are few studies on the effects of hydrocolloids on the properties of composite corn flour and its products, and further studies are needed to fully understand the effects of various hydrocolloids types on the structure and function of corn-based composite dough, and to explore the synergistic improvement of compounding and hydrocolloid on gluten-free foods.

Based on the nutritional defects of maize flour, this study uses nutritional compounding to make up for them and obtain nutritionally balanced composite flour. Moreover, the effects of three hydrocolloids on the quality of pure maize flour and the best formula maize-based compound flour were also studied. This study was expected to provide theoretical basis for improving the processing adaptability of composite maize flour, and provide ideas for the application and development of gluten-free food.

2. Materials and methods

2.1. Materials

Maize, buckwheat, quinoa and yellow millet grains were sourced from Qinfeng Technology Co., LTD (Shaanxi, China), Wanjia Modern Agriculture, Animal Husbandry Development Service Co. LTD (Gansu, China), Qinghai Qingfengtang trading Co.and, LTD (Qinghai, China), and the local market of Shaanxi, China, respectively. All the above grains were subsequently milled into flour using a mill from Porton Ruihua Scientific Instruments Co., LTD, (Beijing, China). Soy protein isolate was obtained from Shaanxi Yunsheng Biotechnology Co., LTD (Shaanxi, China). Xanthan gum, sodium alginate, and sodium carboxymethyl cellulose were sourced from Shaanxi Yuansheng Biotechnology Co., LTD with food grade specifications. All other reagents used in this study were analytical grade.

2.2. Nutritional components and nutritional evaluation of flours

The moisture, ash, crude protein, and crude fat of flours were measured according to AACC 2002 44–19, AACC 2002 08–12, AACC 2002 46–11, and AACC 2002 30–10, respectively. The dietary fiber was determined by the Total Dietary Fiber Assay Kit (K-TDFR-200 A, Megazyme Co. Ltd., Wicklow, Ireland).

The index of nutrition quality (INQ) was calculated to evaluate the nutritional value of flours. The calculation formula is as follows:

$$INQ = \frac{Protein\ content\ in\ food/Protein\ recommended\ intake}{Heat\ energy\ supplied\ in\ food/Heat\ energy\ recommended\ intake} \quad (1)$$

Determination of amino acid content: determination with amino acid analyzer (L-3000, Jiangsu Huachen Instrument Technology Co., LTD). The amino acid automatic analyzer was injected with the mixed amino acid standard working liquid. According to the JJG1064–2011 amino acid analyzer verification regulations and instrument instructions, the instrument operating procedures and parameters and the buffer solution reagent ratio for elution were appropriately adjusted to confirm the instrument operating conditions. Determination of tryptophan content: dihydroxyacetate colorimetry was used for determination.

2.3. Maize-based composite flour optimization

The orthogonal test to optimize the formulation of maize-based composite flour was performed by the Design Expert software. Soy protein isolate (3, 4 and 5 %), buckwheat flour (17, 19 and 21 %), quinoa flour (9, 12 and 15 %), and millet flour (15, 20 and 25 %) were used as independent variables. Box-Behnken experimental design was employed to evaluate the effects of independent variables on the formulation of maize-based composite flour. Based on the INQ, the optimal formulation of maize-based composite flour was 47 % maize flour, 5 % soy protein isolate, 19 % buckwheat flour, 9 % quinoa flour, 20 % millet flour.

2.4. Preparation of maize-based composite dough

The maize-based composite flour (100 g) was mixed with different proportions of food hydrocolloids in a dough mixer. The different hydrocolloids ratios were the optimal addition ratios obtained from previous experiments (H. Zhang et al., 2023). The addition ratios of food hydrocolloids on the flour basis (*w*/w) of maize-based composite flour were as follows: 0.2 %, 0.6 %, and 1.0 % for XG, 0.3 %, 0.9 %, and 1.5 % for SA, and 1.0 %, 2.0 %, and 3.0 % for CMC—Na, respectively. The ingredients were mixed with 60 % distilled water in a dough mixer for 15 min. The prepared dough was covered in plastic wrap and rested for 10 min at room temperature.

2.5. Pasting properties of maize-based composite flour

The Rapid Visco Analyzer (RVA-4500, Perten Instruments, Sweden) was employed to assess the pasting properties of maize-based composite flour. Slurry was prepared by adding 3 g of the composite flour to 25 g of distilled water. The heating and cooling protocol outlined by Shen was followed for the analysis (Shen et al., 2022).

2.6. Rheological properties of dough

The Discovery HR-1 rheometer (TA Instruments, USA) was used to determine the frequency sweep and creep recovery tests of maize-based composite dough. The dough was compressed to 1.6 mm using an aluminium parallel plate with 40 mm diameter. The linear viscoelastic region was obtained by dynamic strain sweep under the strain range of 0.02 % - 20 % at 1 Hz and 25 °C.

2.6.1. Frequency sweep tests

The frequency sweep tests of the dough were measured from 0.1 to 10 Hz at 25 °C. The strain was 0.1 %. The elastic modulus (G') and loss modulus (G'') were recorded.

2.6.2. Creep recovery tests

The creep recovery tests were performed at 1 Hz and 25 °C. In the creep stage, a constant shear stress of 250 Pa was applied to the dough for 100 s at 25 °C. In the recovery phase, the dough was allowed to rest for 280 s to recover the elasticity of the deformation.

2.7. Texture properties of dough

The method of texture properties of dough was referred to L. Kaur method and improved on this basis (X. Sun et al., 2023). The texture analyzer (TA-XT Plus, Stable Microsystems Ltd., Godalming, UK) equipped with a P/36R probe was applied to determine the textural properties of maize-based composite dough. The dough was cut with a mold into cylinder with a diameter of 30 mm and a height of 30 mm. The trigger force was 5 g. The compression ratio was 50 %. The speed during the pre-test, test, and post-test were maintained at 1 mm/s.

2.8. Microstructure of dough

The dough microstructure was observed following the method of Guo (Guo et al., 2022). A tiny dough piece was mounted in 3 % glutaraldehyde for 12 h (4 °C) and rinsed with 0.1 mol/L phosphate buffer for four times. Then, the dough was eluted in 30 %, 50 %, 70 %, 90 % and 100 % ethanol for 15 min at each gradation, and isoamyl acetate was used to remove the ethanol. The dough samples were dried using a supercritical carbon dioxide drying system (SC-CO_2 drying System) (SFC-500, Thar Technologies Ltd., Pittsburgh, USA). And the parameters used were: Pressure: 13 MPa; Temperature: 45 °C; Time: 6 h; CO_2 flow rate: 4 L/min. The samples of dried dough on the mount were then sputtered with gold for 50 s. And the parameters of the ion sputtering coating machine (Q150R ES, Quorum Technologies Ltd., Salisbury, UK) were as follows: Vacuum $<5 \times 10^{-2}$ mbar; Sputtering current: 10–15 mA; Coating thickness: 5–10 nm; Sample speed: 10–20 rpm. The gold-sputtered samples were coated with a thin layer of gold and observed using a scanning electron microscope (SEM) (JCM-7000, JEOL, Akishima, Japan) at an accelerating voltage of 5 kV, and the photo magnification was 200× and 800× respectively.

2.9. Preparation of maize-based composite noodles

The dough prepared in section 2.5 was pressed to obtain noodles with a diameter of 3.5 mm through the noodle machine (DTM—10B, Fuxing Machinery Co., Ltd., Longkou, China).

2.10. Evaluation of noodles quality

2.10.1. Cooking properties

The water absorption rate and cooking loss were measured using the procedure described by Zhang (Q. Zhang et al., 2021). Fifty-five 15 cm long noodles were cooked in boiling water for the optimal cooking time. The cooked noodles were picked out and rinsed with cold water for 30 s. Broken rate is expressed as the percentage of broken noodles during cooking.

$$\text{Broken rate (\%)} = \frac{\text{The number of broken noodles}}{\text{The number of raw noodles (55)}} \times 100 \quad (2)$$

2.10.2. Texture and tensile properties

The texture analyzer (TA-XT Plus, Stable Microsystems Ltd., Godalming, UK) was used to measure the texture and tensile properties of noodles according to the method of Zhang (Zhang, Chen, et al., 2022). The noodles were cooked in boiling water for the optimal cooking time and rinsed with cold water for 30 s. 5 cooked noodles were placed closely on the base and a P/6 probe was used for texture properties test. The other test conditions were the same as Section 2.6. The A/KIE probe was used for tensile properties test. The distance was set to 50 mm. The test speed was 10 mm/s and the trigger force was 5 g.

2.11. Statistical analysis

All experiments were repeated three times. All data were statistically analyzed using SPSS 20 (Chicago, IL, USA). Duncan's multiple tests were conducted for analysis at a $p < 0.05$ significance level. The data were expressed as mean ± standard deviation.

3. Results and discussion

3.1. Nutritional evaluation of flours

The results of the basic nutritional components of the composite flour and maize flour are shown in Table 1. Compared with maize flour, the crude protein content, total energy and INQ value of composite flour were increased, the protein quality was qualified, and the fat content, dietary fiber content and total starch content were decreased, indicating that the nutrition was more balanced. In recent years, there has been

Table 1
Basic nutrients and amino acid components of maize and composite flour.[a, b]

Nutritional components		Maize flour	Composite flour
Basic nutrients	Moisture (%)	10.955 ± 0.097a	11.055 ± 0.005b
	Ash (%)	1.224 ± 0.030a	1.468 ± 0.013b
	Crude protein (%)	7.910 ± 0.090a	13.664 ± 0.285b
	Crude fat (%)	3.670 ± 0.062b	3.066 ± 0.015a
	Total dietary fiber (%)	7.833 ± 0.283b	6.010 ± 0.031a
	Carbohydrate(%)	68.338 ± 2.203b	65.758 ± 1.351a
	Total energy(KJ)	1493.780 ± 1.506a	1511.696 ± 0.875b
	INQ	0.765 ± 0.021a	1.307 ± 0.033b
Amino acid composition	Aspartic acid(g/100gprotein)	6.301 ± 0.048a	8.137 ± 0.056b
	Histidine(g/100gprotein)	2.251 ± 0.063b	2.148 ± 0.051a
	Arginine(g/100gprotein)	4.951 ± 0.087a	6.444 ± 0.062b
	Serine(g/100gprotein)	4.163 ± 0.335a	4.361 ± 0.475b
	Glutamic acid(g/100gprotein)	16.766 ± 0.166a	17.381 ± 0.354b
	Proline(g/100gprotein)	14.966 ± 0.112b	11.782 ± 0.438a
	Glycine(g/100gprotein)	3.263 ± 0.096a	3.580 ± 0.131b
	Alanine(g/100gprotein)	6.864 ± 0.423b	5.728 ± 0.389a
	Cystine(g/100gprotein)*	0.900 ± 0.030b	0.846 ± 0.057a
	Valine(g/100gprotein)*	3.938 ± 0.073a	4.296 ± 0.069b
	Methionine(g/100gprotein)*	1.013 ± 0.027a	1.107 ± 0.020b
	Isoleucine(g/100gprotein)*	3.038 ± 0.058a	3.580 ± 0.064b
	Leucine(g/100gprotein)*	11.140 ± 0.433b	9.244 ± 0.398a
	Tyrosine(g/100gprotein)*	3.263 ± 0.077b	2.864 ± 0.061a
	Phenylalanine(g/100gprotein)*	4.951 ± 0.020a	5.143 ± 0.029b
	Lysine(g/100gprotein)*	2.926 ± 0.015a	4.101 ± 0.032b
	Threonine(g/100gprotein)*	3.376 ± 0.084a	3.580 ± 0.053b
	EAA	34.545 ± 0.158a	34.761 ± 0.112b
	EAA/TAA(%)	36.722 ± 0.092a	36.853 ± 0.083b
	EAA/NEAA(%)	58.034 ± 1.034a	58.361 ± 0.967b

[a] * is essential amino acid (EAA), the rest is non-essential amino acid (NEAA); TAA is the total amino acid.
[b] The a in a row indicates that the group of indicators is small, and b indicates that the group of indicators is high.

some research into adding alternative (gluten-free) sources of ingredients to gluten-free recipes, such as cassava, cassava, maize, potatoes, beans and rice, to compensate for the nutritional deficiencies of gluten-free foods (Kim et al., 2015; Onyango et al., 2011).

At the same time, the determination results of amino acid content of the composite flour and maize flour are also shown in Table 1. A total of 17 amino acids were detected in maize flour and composite flour, and amino acids were relatively complete. Compared with maize flour, the proportion of amino acids with high content of proline and leucine decreased in composite flour, while the content of essential amino acids such as methionine, valine, isoleucine, phenylalanine and lysine increased in composite flour. Notably, the proportion of lysine in the composite flour increased significantly. At the same time, the results of tryptophan determination by dihydroxyacetate coloration showed that the tryptophan content of maize flour was 113.902 mg/100 g, and the pink amino acid content of complex powder was 190.732 mg/100 g, and the increase of the tryptophan content of the composite flour proved that that the tryptophan content of composite flour was well compensated. On the other hand, the ratio of essential amino acids to total amino acids was between 36 and 37, which was slightly lower than the standard value of 40 proposed by the FAO/WHO model. The EAA/TAA and EAA/NEAA of the composite flour were higher than those of maize flour. The essential amino acids of maize flour and composite flour were further evaluated, and the results were shown in Table 2. Compared with maize flour, the essential amino acids of the composite flour were closer to the FAO/WHO recommended model, in which the AAS values of isoleucine, lysine and valine increased significantly, and the AAS values of methionine + cystine and threonine increased less. A comprehensive comparison of the essential amino acid AAS value of the composite flour showed that the AAS value of most essential amino acids was above 0.8, indicating excellent amino acid composition quality. It can be concluded that the protein quality of the composite flour is better, and the amino acid types of the composite flour are more complete and the amino acid distribution is more reasonable than that of maize flour.

Table 2
Comparative analysis of amino acid evaluation of corn flour and compound flour.[a, b]

Essential amino-acid	FAO/WHO recommendation model	Maize flour		Composite flour	
		EAA	AAS	EAA	AAS
Isoleucine	4.0	3.038 ± 0.058a	0.760 ± 0.072a	3.580 ± 0.064b	0.895 ± 0.033b
Leucine	7.0	11.140 ± 0.433b	1.591 ± 0.314b	9.244 ± 0.398a	1.321 ± 0.276a
Lysine	5.5	2.926 ± 0.015a	0.532 ± 0.276a	4.101 ± 0.032b	0.746 ± 0.052b
Methionine + Cystine	3.5	1.913 ± 0.042a	0.547 ± 0.019a	1.953 ± 0.027b	0.558 ± 0.016b
Phenylalanine + Tyrosine	6.0	8.214 ± 0.071b	1.369 ± 0.068b	8.007 ± 0.086a	1.334 ± 0.075a
Threonine	4.0	3.376 ± 0.084a	0.844 ± 0.041a	3.580 ± 0.053b	0.895 ± 0.048b
Valine	5.0	3.938 ± 0.073a	0.788 ± 0.025a	4.296 ± 0.069b	0.859 ± 0.037b

[a] AAS = (Essential amino acid content) / (Essential amino acid content in FAO / WHO recommended model).
[b] The a in a row indicates that the group of indicators is small, and b indicates that the group of indicators is high.

3.2. Pasting properties of maize-based composite flour

Pasting properties reflect alterations in flour viscosity resulting from water absorption, swelling, disruption of crystalline structure, amylose leaching, and rearrangement (Thirumdas et al., 2016). The data presented in Table 3 indicates that the inclusion of XG results in a notable increase in peak viscosity. Similarly, trough viscosity (TV) also shows an increasing trend, while breakdown (BD) and pasting temperature (PT) show a decreasing trend. Peak viscosity (PV) shows the capacity of starch to bind water and the size of amylase activity, indicating the point of maximum expansion point of flour particles, which is related to the quality of the final product. This indicates that XG could significantly improve the starch adhesion of the composite flour in the cooking process, and also enable the composite flour to absorb water and gelatinize at a lower temperature, which is similar to the results of Kaur (Kaur et al., 2015). This may be due to the fact that amylose in the crystal zone of starch particles is easy to interact with XG, which makes it easier to water bond and increase the viscosity. In addition, the addition of SA also increases the PV. Different from XG, the addition of SA increases the trend of BD, the change of PT is not obvious, and the trend of setback (SB) decreases. These results indicated that SA could significantly reduce the revaluation of the composite flour and inhibit the aging in addition to increasing the viscosity of the composite flour paste. At the same time, the addition of CMC-Na made the PV also show the same increasing trend, except for SB which showed a decreasing trend and PT which did not change significantly, other indexes increased accordingly. This may being because CMC-Na is an ionic hydrocolloid, which can change the osmotic pressure inside and outside the cell wall, accelerate the combination of water and starch particles, improve the degree of starch gelatinization, and inhibit the aging of starch (Bi et al., 2022).

3.3. Rheological properties of dough

3.3.1. Frequency sweep tests of dough

The energy storage modulus (G') of the frequency scan reflects the elastic properties of the dough, and the viscosity of the dough is reflected by the loss modulus (G″) (Chen et al., 2018). The variation of storage modulus (G') and loss modulus (G″) of the composite dough fortified with hydrocolloids are presented in Fig. 1. The G' value was higher than

Table 3
Effect of food hydrocolloids on pasting properties of composite flour [a, b].

Samples	PV (cP)	TV (cP)	BD (cP)	FV (cP)	SB (cP)	PT (°C)
Composite flour	1195 ± 21c	1014 ± 11c	181 ± 9b	2346 ± 42c	1332 ± 30b	79.15 ± 0.00a
0.2 % XG	1193 ± 8c	1043 ± 8c	150 ± 1c	2410 ± 20b	1367 ± 28ab	77.48 ± 0.04b
0.6 % XG	1195 ± 9c	1074 ± 3bc	121 ± 7 cd	2507 ± 42a	1433 ± 39a	77.43 ± 0.04b
1.0 % XG	1213 ± 0c	1114 ± 3b	99 ± 3d	2528 ± 8a	1414 ± 5a	77.03 ± 0.53b
0.3 % SA	1197 ± 6c	1050 ± 10c	147 ± 16c	2242 ± 11d	1192 ± 1c	78.68 ± 0.67a
0.9 % SA	1324 ± 25b	1152 ± 21b	172 ± 4b	2301 ± 22 cd	1149 ± 1c	79.05 ± 0.00a
1.5 % SA	1453 ± 8a	1243 ± 21a	210 ± 13a	2369 ± 13c	1126 ± 35c	78.73 ± 0.60a
1.0 % CMC-Na	1197 ± 18c	1078 ± 40bc	139 ± 22c	2267 ± 106d	1189 ± 66c	78.70 ± 0.57a
2.0 % CMC-Na	1291 ± 2b	1150 ± 0b	141 ± 2c	2288 ± 6d	1138 ± 6c	78.70 ± 0.57a
3.0 % CMC-Na	1378 ± 17a	1231 ± 6a	147 ± 23c	2334 ± 39c	1103 ± 45c	79.48 ± 0.60a

[a] PV, Peak viscosity; TV, Trough viscosity; BD, Breakdown; FV, Final viscosity; SB, Setback; PT, Pasting temperature.
[b] Values with different letters in the same column are significantly different at $p < 0.05$.

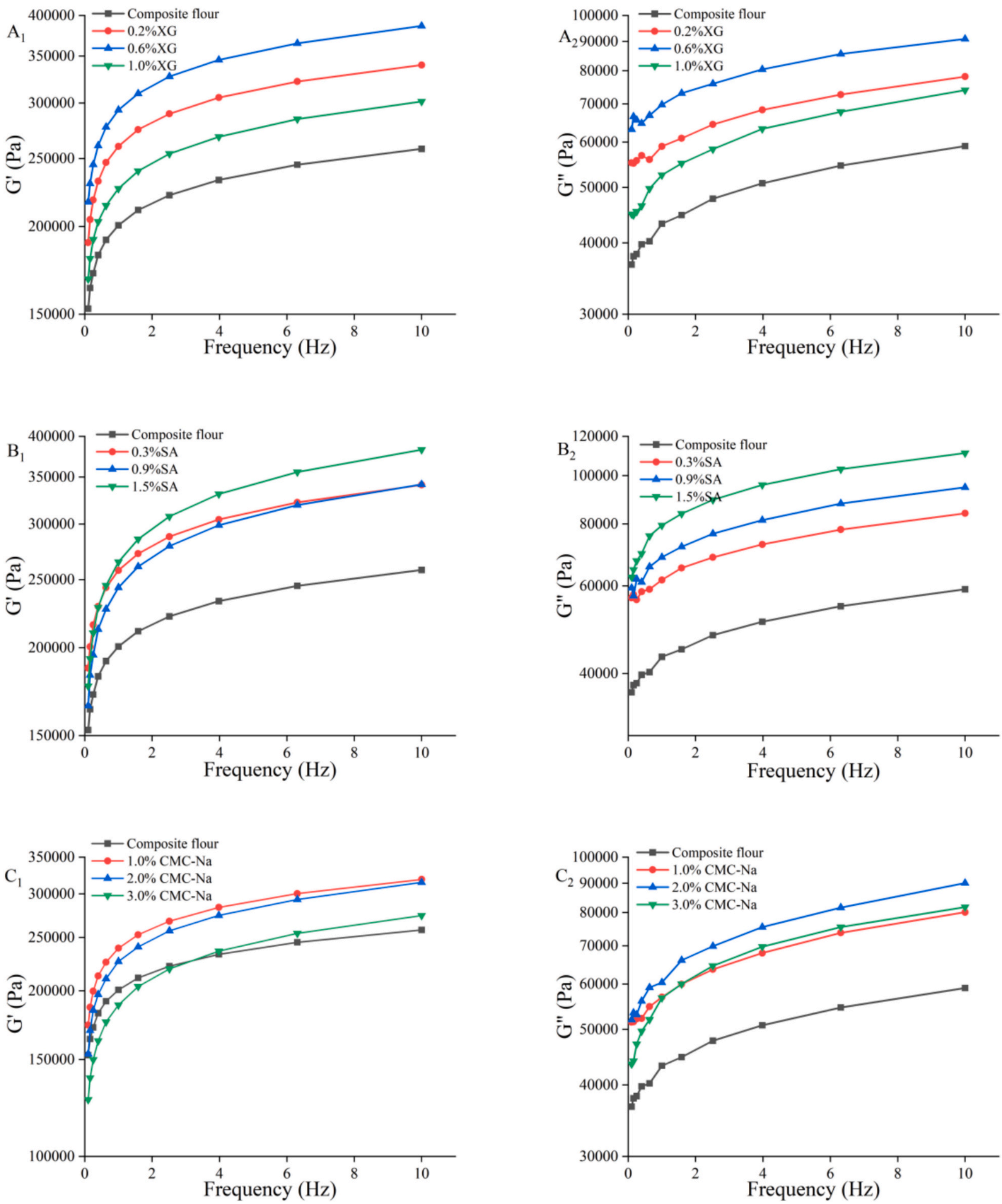

Fig. 1. (1) Storage modulus (G') and (2) loss modulus (G″) of maize-based composite dough with different hydrocolloids (A, B and C represent the rheological properties results of dough with XG, SA and CMC—Na, respectively).

G″ for all composite doughs in the tested frequency range (0.1–10 Hz), suggesting the composite dough presented a more elastic behavior. Compared with the maize dough, the G' and G″ of composite dough were significantly increased by the addition of XG, SA, and CMC—Na, which means that XG, SA, and CMC-Na dramatically increased the elasticity and viscosity of composite dough and improved the quality of composite dough. XG and CMC-Na are anionic hydrocolloids that can establish electrostatic interactions with positively charged protein molecules, resulting in enhanced elastic and viscous characteristics (H. Zhang et al., 2023). Besides, the XG solution presented a pseudoplastic, which can increase dough stability and water absorption (Li & Nie, 2016). The higher elasticity shown by XG was attributed to its property to form a weak gel at low shear rates. The increment in G' and G″ of dough by the presence of SA might be related to the strong hydration capacity and gel-forming properties of SA (Xu et al., 2022). Compared with the three food gels, xanthan gum had little effect on the loss factor of the mixed flour dough, while sodium alginate and CMC-Na significantly increased the loss factor, indicating that the latter was more inclined to increase the viscosity of the dough. This may be because SA can establish electrostatic interactions with proteins, enhancing the gluten network structure to a certain extent (Lazaridou et al., 2007; Song & Zheng, 2007).

3.3.2. Creep recovery tests of dough

The recovery of dough creep is generally completed in two steps. First, the stress is kept constant (250 Pa) and the change law of strain with time is observed. This stage is called the creep stage. Then remove the stress and observe the law of strain change with time, this stage is called the recovery stage. The creep-recovery curves of the composite dough fortified with hydrocolloids are reported in Fig. 2. When different proportions of hydrocolloids were added, all the doughs showed a typical creep recovery curve. The addition of XG, SA, and CMC-Na to composite dough resulted in an observed increase in the maximum creep strain, indicating a decrease in the dough's resistance to deformation. The creep-recovery curves exhibited an increase in magnitude with the addition of gums, except for xanthan which displayed a contrasting trend over time. The results showed that these hydrocolloids could reduce the hardness and increase the elasticity and recovery ability of dough. Similar results were also obtained by Onyango (Onyango et al., 2009). This is consistent with the results obtained from frequency scanning. This may be because of the adhesive action of hydrocolloids itself, which binds small starch particles and large molecules such as protein together to form a structure similar to the gluten network, thus reducing the space gap of the dough and improving the density and strength of the dough.

3.4. Texture properties of dough

The important mechanical properties which affect dough size and texture are dough strength and extensibility (Gandikota & MacRitchie, 2005). The effects of three kinds of hydrocolloids on the texture characteristics of compound flour dough are shown in Table 4. With the addition of XG, the hardness, elasticity, cohesion, viscosity and chewability were significantly increased ($p < 0.05$). The addition of XG increased the water absorption of the dough, resulting in an increase in the hardness of the dough, and the special secondary and tertiary structure of XG made it have good viscoelasticity, making the dough more viscous and not easy to loosen (Jang et al., 2015; Peressini et al., 2011). At the same time, hardness, gumminess and chewiness increased significantly with the addition of SA ($p < 0.05$). However, other indicators did not show the phenomenon of first increase and then decrease. These results indicate that adding an appropriate amount of SA can improve the texture properties of dough, mainly hardness, gumminess and chewiness, because a large number of acetic acid ions contained in SA will be transformed, resulting in changes in its hydrophilic and functional properties. But the texture properties of dough had no obvious change or even deteriorated after adding more than a certain amount. This may be because sodium alginate belongs to ionic hydrocolloid, and excessive addition will destroy the protein and starch structure inside the system, making the dough structure loose and the texture quality decreased (Bi et al., 2022). In addition, cohesiveness, gumminess, chewiness and chewiness increased significantly with the addition of CMC-Na ($p < 0.05$), and hardness showed a downward trend. This is mainly because CMC-Na contains a large number of hydrophilic groups, which are easily combined with water to form hydrophilic colloidal groups in the process of blending, and have a strong water retention ability, so that water is not volatile, thereby improving the organizational structure of dough and reducing its hardness (Liu et al., 2024).

3.5. Microstructure of dough

The effect of adding hydrocolloids on the microstructure of

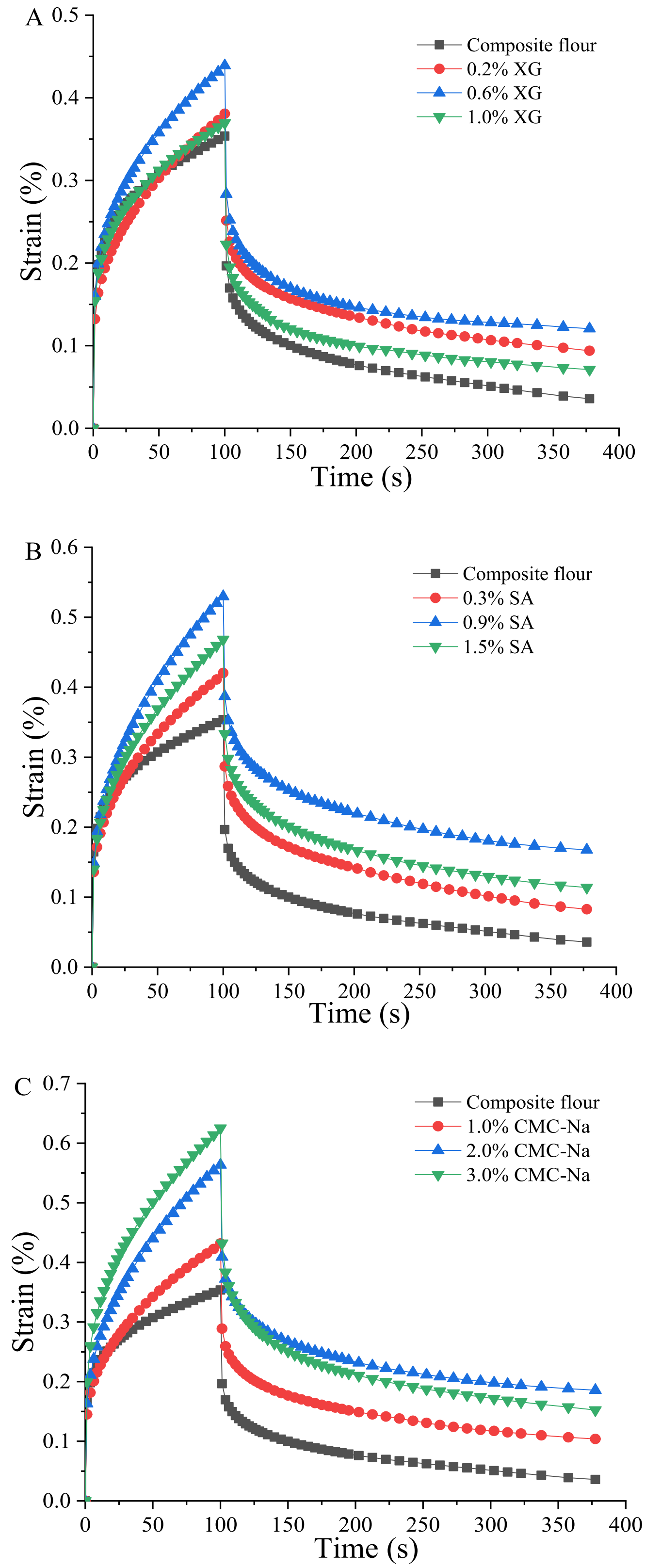

Fig. 2. The creep-recovery curves of the composite dough fortified with hydrocolloids (A, B and C represent the peristalsis recovery results of dough with XG, SA and CMC—Na, respectively).

Table 4
Effect of food hydrocolloids on texture properties of composite flour dough [a].

Samples	Hardness (g)	Springiness	Cohesiveness	Gumminess	Chewiness	Resilience
Composite flour	2621 ± 37d	0.148 ± 0.004de	0.132 ± 0.003e	352 ± 18 cd	49.692 ± 5.148c	0.042 ± 0.001c
0.2 % XG	2955 ± 37c	0.204 ± 0.001b	0.147 ± 0.001c	431 ± 6c	75.531 ± 5.546b	0.045 ± 0.000c
0.6 % XG	3541 ± 0b	0.256 ± 0.001a	0.185 ± 0.004a	552 ± 36b	91.544 ± 6.618b	0.051 ± 0.001b
1.0 % XG	3995 ± 50a	0.176 ± 0.001c	0.170 ± 0.005b	690 ± 1a	125.659 ± 5.648a	0.057 ± 0.001a
0.3 % SA	2765 ± 51 cd	0.142 ± 0.003e	0.141 ± 0.001d	392 ± 3c	55.263 ± 2.257c	0.043 ± 0.000c
0.9 % SA	2928 ± 22c	0.155 ± 0.003d	0.142 ± 0.002d	414 ± 5c	64.204 ± 0.542c	0.041 ± 0.000c
1.5 % SA	3234 ± 48b	0.135 ± 0.003f	0.133 ± 0.000e	417 ± 15c	66.132 ± 0.930c	0.041 ± 0.001c
1.0 % CMC-Na	2113 ± 2e	0.146 ± 0.006de	0.148 ± 0.003c	312 ± 7d	40.931 ± 6.046 cd	0.038 ± 0.000d
2.0 % CMC-Na	2040 ± 44e	0.147 ± 0.003de	0.149 ± 0.003c	305 ± 0d	44.773 ± 0.752 cd	0.040 ± 0.001 cd
3.0 % CMC-Na	1877 ± 52f	0.141 ± 0.001e	0.154 ± 0.005c	265 ± 15e	36.033 ± 0.358d	0.037 ± 0.000d

[a] Values with different letters in the same column are significantly different at $p < 0.05$.

compound flour dough are shown in Fig. 3. Under the field of view of 200 times, the dough structure composed mainly of starch and protein can be observed. Under an 800-fold field of view, it can be observed that the addition of hydrocolloids can make small starch particles closely bind together, making the overall microstructure of the dough smaller and more compact. Similar result was also reported by Hong (Hong et al., 2021).This may be due to the adhesive effect of hydrocolloid itself, which binds small starch particles and large molecules such as protein together to form a structure similar to gluten network, thus reducing the space gap of the dough, which leads to the improvement of dough texture properties and rheological properties, so as to enhance the quality of dough. Dough density and strength increase. It is worth noting that the dough containing 0.6 % xanthan gum has the densest microstructure and the best effect, which may be related to the unique secondary tertiary structure of xanthan gum, and its special chain winding method gives it good stability (Motta Romero et al., 2017).

3.6. Cooking properties of noodles

The cooking quality is an important index to evaluate the quality of noodle products. Effect of food hydrocolloids on cooking properties and broken rate of noodles are shown in Table 5. The addition of three kinds of hydrocolloids all improved the cooking properties of noodles to some extent. The higher the cooking property of the dough, the higher the quality, which may also be due to the increased viscosity of the dough (Gulia et al., 2014). Water absorption rate and broken rate decreased significantly with the addition of XG ($p < 0.05$). The results showed that the addition of XG could significantly improve the cooking quality of the mixed dough. This is mainly because the main chain of XG can form hydrogen bonds, promote the starch particles closely combined, thereby reducing the starch water absorption rate, reduce the water absorption rate of cooking noodles, and low cooking loss is not easy to break and this makes xanthan gum has good viscoelasticity, rheology and stability, and is not easily damaged by the external environment (Motta Romero et al., 2017). This is similar to the change above to get the rheological properties of dough. With the addition of SA, the cooking properties of

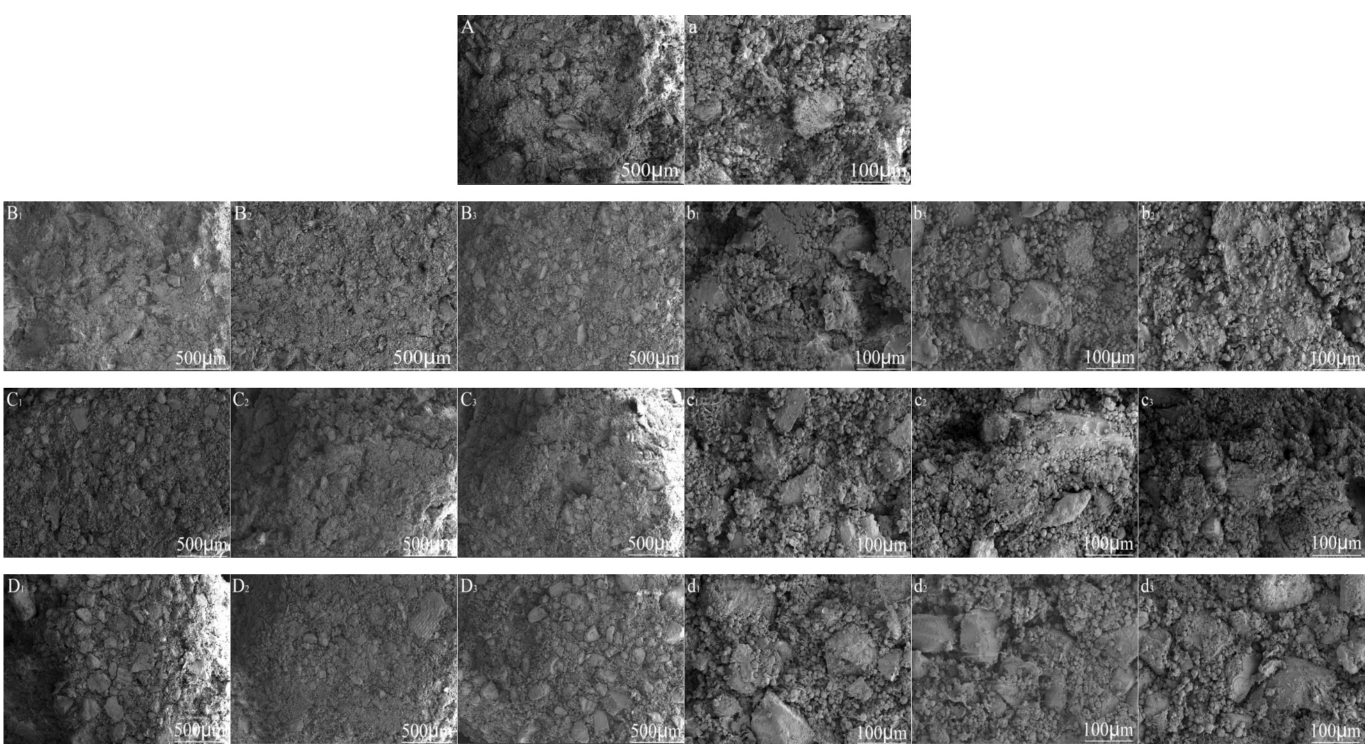

Fig. 3. Effect of food gums addition on microstructure of compound flour dough (A, B, C and D respectively indicate the microstructure of mixed powder, xanthan gum, sodium alginate and CMC-Na dough at 200 times; a, b, c, d represent 800 times the microstructure of the lower group, respectively; different digital labels represent different hydrocolloids concentrations: The concentrations of XG were 0.2 %, 0.6 % and 1.0 %, the concentrations of SA were 0.3 %, 0.9 % and 1.5 %, and the concentrations of CMC-Na were 1.0 %, 2.0 % and 3.0 %, respectively).

Table 5
Effect of food hydrocolloids on cooking properties, texture properties and tensile properties of noodles [a].

Samples	Cooking properties			Texture properties						Tensile properties	
	Water absorption rate (%)	Cooking loss (%)	Broken rate (%)	Hardness (g)	Springiness	Cohesiveness	Chewiness	Resilience		Resistance to extension (g)	Extensibility (mm)
Composite flour	80.07 ± 2.18a	4.74 ± 0.07a	99.09 ± 1.29a	266 ± 4d	0.859 ± 0.010c	0.498 ± 0.007d	114 ± 1d	0.208 ± 0.005e		26.39 ± 2.17d	3.01 ± 0.56d
0.2 % XG	82.86 ± 2.44a	4.71 ± 0.07a	70.91 ± 2.57b	278 ± 5c	0.919 ± 0.006b	0.517 ± 0.008c	139 ± 3bc	0.238 ± 0.001d		28.23 ± 1.53d	3.24 ± 0.63d
0.6 % XG	68.35 ± 0.70b	2.51 ± 0.02c	32.73 ± 5.14d	296 ± 3b	0.960 ± 0.025a	0.610 ± 0.003a	174 ± 6a	0.291 ± 0.001b		40.42 ± 0.13b	4.39 ± 0.36bc
1.0 % XG	57.36 ± 0.90d	2.84 ± 0.23c	5.456 ± 0.00f	339 ± 2a	0.953 ± 0.004ab	0.525 ± 0.003c	168 ± 11a	0.257 ± 0.002c		56.14 ± 2.70a	5.57 ± 0.37a
0.3 % SA	72.53 ± 0.38b	2.75 ± 0.35c	65.46 ± 2.57b	286 ± 15bc	0.876 ± 0.027c	0.520 ± 0.009c	125 ± 6c	0.224 ± 0.002de		33.10 ± 1.71c	3.76 ± 0.43c
0.9 % SA	66.65 ± 1.25bc	2.20 ± 0.05c	48.18 ± 1.29c	272 ± 1c	0.912 ± 0.008b	0.536 ± 0.008bc	129 ± 1c	0.258 ± 0.003c		42.52 ± 0.97b	5.01 ± 0.21ab
1.5 % SA	73.76 ± 1.58b	2.40 ± 0.01c	33.64 ± 3.86d	262 ± 1d	0.836 ± 0.015d	0.482 ± 0.006d	114 ± 3d	0.217 ± 0.006de		36.24 ± 0.74bc	4.70 ± 0.39b
1.0 % CMC-Na	64.81 ± 2.63bc	3.33 ± 0.02b	49.09 ± 5.14c	297 ± 2b	0.918 ± 0.007b	0.543 ± 0.002b	128 ± 2c	0.234 ± 0.003d		39.87 ± 0.89b	5.31 ± 0.41ab
2.0 % CMC-Na	61.78 ± 4.51c	3.50 ± 0.14b	30.91 ± 2.57d	265 ± 10d	0.979 ± 0.021a	0.553 ± 0.004b	152 ± 4b	0.318 ± 0.006a		45.06 ± 5.70b	5.72 ± 0.48a
3.0 % CMC-Na	53.61 ± 4.50d	3.29 ± 0.17b	16.36 ± 2.57e	259 ± 6d	0.892 ± 0.009bc	0.556 ± 0.001b	111 ± 5d	0.235 ± 0.003d		30.41 ± 2.52 cd	3.50 ± 0.21 cd

[a] Values with different letters in the same column are significantly different at $p < 0.05$.

the noodles increased first and then decreased. When the addition amount was 0.9 %, the digestible water absorption rate and cooking loss of noodles were the lowest. Continue to add, cooking loss rate slightly increased, and the quality gradually deteriorated. The broken rate of noodles showed a downward trend. The results show that about 1.0 % is the optimal addition ratio of helical noodles for compound flour. Moreover, water absorption rate and broken rate decreased significantly with the addition of CMC-Na ($p < 0.05$). When the addition amount was greater than 1.0 %, it did not change significantly with the increase of the addition amount. However, the cooking loss increased first and then decreased. In contrast, the ability of CMC-Na to improve cooking quality was weak. There are obvious differences in cooking properties and broken rate of dough prepared by adding different hydrocolloids.

3.7. Texture and tensile properties of noodles

The evaluation of pasta quality primarily relies on texture parameters, as consumer perception is significantly influenced by the textural properties of cooked noodles. As can be seen from Table 5, both XG and SA significantly ($p < 0.05$) enhance the hardness of noodles, while the addition of CMC-Na makes the hardness of dough show a downward trend, which may be due to the strong water retention of CMC-Na and the low moisture evaporation of noodles. This is similar to the results presented in Table 4. On the other hand, amounts of hydrocolloid added rather than the hydrocolloid type showed a more critical impact on the cooking loss and turbidity of the noodles.

Resistance to extension and extensibility are important indices for evaluating the toughness and strength of noodles. Owing to their high resistance to extension, noodles have sufficient toughness, are not easy to break, are chewable, and have good quality. The effect of hydrocolloids on the tensile properties of noodles can be observed in Table 5. Compared with the compound flour without hydrocolloids, the addition of XG significantly improved the elongation and extensibility of noodles, whereas the addition of SA and CMC-Na first increased and then decreased the two indexes. The optimal addition proportion of SA was about 0.9 %, and the optimal addition proportion of CMC-Na was 2.0 %. It can be seen that the use of hydrocolloids can improve the quality of noodles, and XG has the most obvious effect on the tensile properties of noodles. Rheological results in a literature by H.R. Tavakoli et al. showed that the unfrozen samples to which arabic gum had been added rendered the highest resistance to extension and this is similar to what we observed (Belorio & Gómez, 2022). This may be related to the bonding effect of the hydrocolloid itself, which binds small starch particles with large molecules such as proteins to form a structure similar to the gluten network, thereby narrowing the spatial gap of the noodles, that is, similar to the microstructure of dough observed in the study. This increases the density and strength of the noodles, which improves the texture and tensile properties of the noodles.

3.8. Principal component analysis (PCA) and potential mechanism

PCA was used to assess the differences among the four samples through structure and physicochemical properties. PC1 and PC2 explained 50.1 % and 21.6 % of the total variance, respectively, accounting for 71.7 % of the total variance (Fig. 4A). The maize-based composite dough without hydrocolloid was in the second quadrant, the XG dough in the first quadrant, and the CMC-Na dough in the third quadrant. The water absorption, resilience and grain viscosity (WAR, CL, R1, TV) of noodles were in the same quadrant in the PCA diagram, and they were in the same quadrant with compound flour without hydrocolloid. The texture properties of the composite dough, the trough viscosity (FV) of flour and the broken rate (BR) of noodles after XG addition are in the same quadrant in the PCA diagram, and the correlation is significant. This may be because these indicators are closely related to the dough microstructure, the addition of XG, so that the starch and protein are closely combined, just can improve the texture properties of the dough. This is similar to the findings of a previous study on the effects of XG on dough (Li & Nie, 2016). It can be seen from the score plot that the partial gelatinization properties (PV, SB) of compound flour are related to the addition of CMC-Na and are located in the same quadrant. This may be because CMC-Na is an ionic hydrocolloid, which can change the osmotic pressure inside and outside the wall, accelerate the combination of water and starch particles, and increase starch PV. In addition, with the addition of CMC—Na, the SB of the composite flour is significantly reduced, and the aging of starch is inhibited. Nicolae reported a similar correlation with the addition of CMC-Na (Nicolae et al., 2016). In addition, the texture properties of dough and noodles are more consistent in the PCA map. The texture properties are closely related to its microstructure, and the close combination of starch and protein is the reason for the corresponding

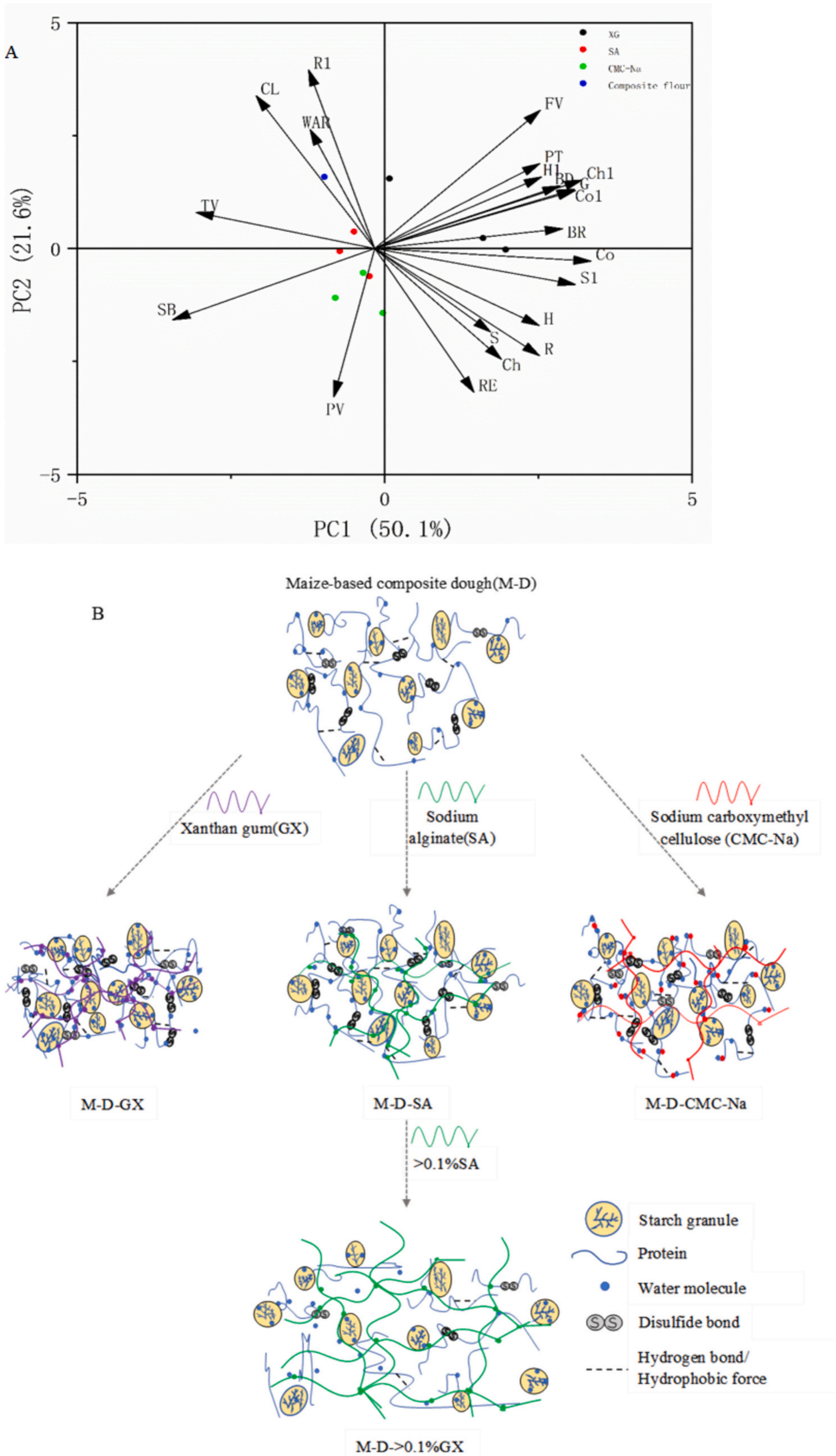

Fig. 4. PCA (A) biplots summarizing the relationships between the samples (maize-based composite dough and the dough with hydrocolloids) (H1, S1, CO1, G, CH1 and R1 respectively represent the hardness, springiness, cohesiveness, gumminess, chewiness and resilience of the groups below. WAR, CL, BR, H, S, CO, CH, R, RE and E respectively represent the water absorption rate, cooking loss, broken rate, hardness, springiness, cohesiveness, chewiness, resilience, resistance to extension and extensibility of the noodles below.) and their physicochemical properties and schematic presentation (B) for the changes in dough structures.

changes in the texture properties index. Sadat also pointed out that hydrophilic glue has a better effect on the properties of maize starch dough (Sadat et al., 2023). This may be because hydrocolloids promote the formation of intermolecular forces and hydrogen bonds, and certain interactions occur between starch, protein and hydrocolloid. It is these interactions that make the microstructure of the sample more compact, thus affecting the properties and quality of the compound flour and related products.

The related mechanisms are shown in Fig. 4B. Hydrocolloids may affect the physicochemical and functional properties of dough to a certain extent. XG is an anionic hydrophilic colloid that contains a large number of hydrophilic groups, such as carbonyl groups, which can absorb a large amount of free water and can interact with amino groups in dough to change each other's structure, thereby improving the water holding capacity of gluten and enhancing the viscoelastic properties of dough (Motta Romero et al., 2017). The unique rigid rod configuration can also compensate for some of the impact of the broken gluten structure on dough rheology. The addition of xanthan gum increases the water absorption of the dough, resulting in an increase in the hardness of the dough, and the adhesive property of xanthan gum itself makes the dough more viscous and difficult to lose (Motta Romero et al., 2017), To improve the quality of compound flour and its related products. The addition of sodium alginate improved dough texture. Because SA is an anionic hydrophilic adhesive similar to XG, a large amount of acetic acid ions contained in SA are transformed, resulting in changes in its hydrophilic and functional properties. The gelatinization characteristics of the composite flour were changed, the microstructure of the dough was more compact, the textural properties were improved, and the textural properties and cooking properties of the noodles were improved. However, when the amount of sodium alginate was greater than 1.0 %, the texture of the dough did not change significantly or even deteriorated. This may be because sodium alginate is an ionic hydrocolloid, and excessive addition destroys the protein and starch structure inside the system, such as making it a random curl, so that the dough structure is loose, and the texture quality is reduced (Bi et al., 2022). CMC-Na contains a large number of hydrophilic groups, which are easily combined with water to form hydrophilic colloidal groups in the kneading process, and has a strong water retention ability; thus, the water is not volatile, thereby improving the organizational structure of the dough and reducing its hardness (Liu et al., 2024). This role is similar to that of other anionic hydrophilic colloids. This explains the variation in the textural properties of maize-based composite dough samples (Tables 4 and 5).

Therefore, hydrocolloids can tightly bind the small starch particles of the composite flour, making the dough microstructure more compact and improving the quality of the dough or noodles. Among these, 0.6 % xanthan gum had the most significant effect.

4. Conclusions

The application of hydrocolloids can significantly improve the properties of maize-based composite dough and noodles. The addition of several gels increased the PV; that is, the shear resistance of the composite flour decreased. Additionally, when XG, SA, and CMC-Na were added to the composite dough, the maximum creep strength increased, indicating that XG, SA, and CMC-Na reduced the deformation resistance of the dough. The addition of hydrocolloids significantly changed the textural properties of noodles in maize-based composite dough, and XG had the most obvious effect. Simultaneously, the addition of hydrocolloids improves the cooking properties of noodles in maize-based composite dough. The effect of XG on resistance to extension and extensibility was also obvious. In conclusion, hydrocolloids have a positive impact on enhancing the quality of maize-based composite dough properties and noodles due to their thickening, water retention, gelling, and adhesive properties. The improvement performance of XG for related products is particularly significant. It can be used in maize-based composite dough and similar products.

CRediT authorship contribution statement

Yuan Jiang: Writing – review & editing, Writing – original draft, Methodology. **Sihan Cheng:** Software, Conceptualization. **Jingru He:** Formal analysis, Conceptualization. **Zejia Zhou:** Visualization, Investigation. **Xiangzhen Ge:** Validation, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no conflict of interest. This work is an original research and the data presented in manuscript has not been published elsewhere.

Acknowledgments

This study was financially supported by the Medical Research Foundation of Guangdong Provincial Health Commission (No. A2024258), Guangdong Provincial Department of Education Project (Young Innovative Talents Category) (No. 2024KQNCX109) and Research group of functional foods development for specific populations (No. 2024ZZ12).

Data availability

Data will be made available on request.

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