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Effects of Starch Addition on KGM Sol's Pasting, Rheological Properties, and Gel Texture

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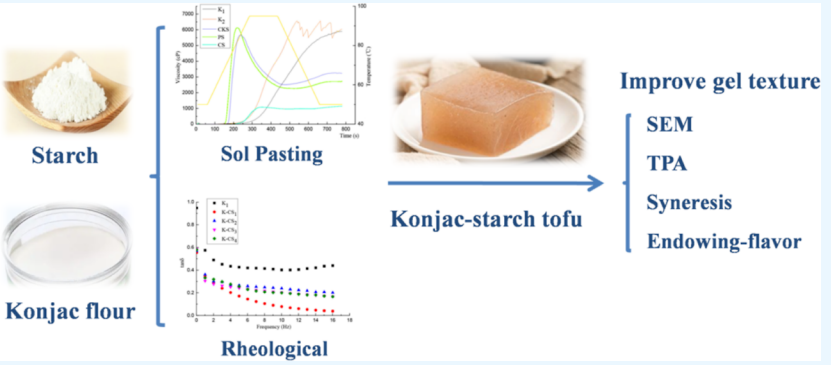

ABSTRACT: Konjac tofu is an irreversible gel formed by removing the acetyl group from konjac glucomannan (KGM) through alkaline heating. This type of food is low in calories, filling, and healthy, making it popular in the market. However, pure konjac tofu has a hard texture and lacks flavor when heated. To improve its taste and appearance, the effects of three varieties of native starch, including corn starch (CS), *Canna edulis* Ker starch (CKS), and potato starch (PS), on the formation of pasting and rheological properties of the KGM sol were investigated. Konjac tofu samples that incorporated different types and quantities of starch were prepared and analyzed in terms of structure, texture, dehydration, and flavor, with pure konjac tofu serving as a reference. The findings revealed that KGM mixed with a concentration of 4.2% CS, or 0.85% CKS, or 0.85% PS of the total mass produced a gel with the highest viscosity and a steady structure. Texture profile analysis indexes of these combinations were superior to pure KGM, and the konjac-starch tofu had a lamellar network structure. Thus, konjac tofu with the addition of starch has a higher quality texture, lower dehydration, and improved flavor compared to pure KGM gel.

1. INTRODUCTION

Konjac glucomannan (KGM) is a naturally occurring nonionic polymer[1] that is water-soluble and primarily composed of glucomannan. Its structure consists of glucose and mannose units linked by β-1,4-bonds, with a low degree of acetyl group at the C-6 position of the side chain.[2] When KGM is heated under alkaline conditions, the acetyl group is removed, resulting in the formation of konjac gel, commonly known as konjac tofu. This thermally irreversible gel possesses excellent intestinal probiotic properties[3] and can be used in the creation of bionic food.[4] However, the elimination of the acyl group from the konjac tofu can lead to a decrease in its water holding capacity, making it prone to dehydration and shrinkage.[5] Moreover, konjac tofu composed solely of KGM is typically soft and lacks elasticity at room temperature but becomes harder and less desirable in taste when heated, which can negatively affect its market appeal. To improve the overall quality of konjac tofu, starch is commonly incorporated. Starch is one of the most abundant and significant hydrocolloids found in nature, widely utilized in the food industry as a thickener, stabilizer, gelling agent, and water-retaining agent.[6]

While much research has focused on KGM due to its potential health benefits, such as weight reduction,[7] blood sugar level regulation,[8] improvement of intestinal microecology,[9] relief of constipation,[9] and potential application in combating drunkenness and alcoholism,[10] studies on konjac tofu have primarily centered on optimizing the production process. This includes investigating coagulation conditions, hardness, water retention, and the mechanism by which alkali promotes KGM gel formation.[11] The influence of KGM on the gelatinization, rheological properties, and freeze-thaw stability

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of various starches has also been extensively explored in the existing literature.[12−15] In an effort to enhance the firmness and water release rate of konjac tofu, Sun et al. introduced hydroxypropyl starch to konjac flour.[16] Meanwhile, Chen utilized chitosan and sodium alginate as wall materials to encapsulate various food flavoring additives. These additives were then mixed with KGM to produce flavored konjac bionic food in an alkaline environment.[17] However, there is a lack of studies on how different types of starch addition impact the rheological and gel properties of konjac tofu.

The present study aims to investigate the effects of different types and quantities of starch on the pasting and rheological characteristics of KGM. It also examined the influence of starch addition on the texture, syneresis, and flavor of konjac tofu, as well as the interaction between KGM and starch by comparing it with pure konjac tofu. The findings of this research contribute to a better theoretical understanding of the role of starch in konjac gel products and provide insights for enhancing the taste quality and marketability of konjac tofu.

2. MATERIALS AND METHODS

2.1. Materials. Konjac flour was purchased from Sichuan Sentaiyuan Biotechnology Co., Ltd. (Sichuan, China). The corn starch (CS) was purchased from Hebei Yufeng Industrial Group Co., Ltd. (Hebei, China). The canna starch extracted from *Canna edulis* Ker. (CKS) was purchased from Guizhou Xingyi Yujiang Canna Starch Factory (Guizhou, China). The potato starch (PS) was purchased from Beijing Haoliyu Industry and Trade Co., Ltd. (Beijing, China). Amylose and amylopectin were purchased from Beijing Solabo Science and Technology Co., Ltd. (Beijing, China). The hotpot soup base was purchased from Chongqing Dezhuang Agricultural Products Development Co., Ltd. (Chongqing, China). All reagents, whether chromatographic or analytical grade, were purchased from Chongqing Chuan Dong Chemical Co., Ltd. (Chongqing, China).

2.2. Proximate Analysis of Konjac Flour and Starch. The moisture content in konjac flour and starch was determined following the direct drying method outlined in GB5009.3-2016 "Determination of Moisture in Foods".[18] The content of KGM, viscosity, pH value, and SO_2 content in konjac flour were measured according to the standard method of "Konjac flour" (NY/T494-2010)[19] and GB5009.34-2016 "Determination of SO_2 in Foods".[20] The determination of amylose and amylopectin content was slightly modified based on the dual-wavelength method by Liu et al.[21] Samples, including amylose and amylopectin, CS, CKS, and PS, were refluxed and extracted with methanol for 4∼6 h at a rate of 5∼6 drops per second to remove grease. After degreasing, the samples were placed in an uncovered Petri dish and allowed to sit for 2 days to remove residual methanol and reach moisture equilibrium. For analysis, 0.050 g of the degreased sample was weighed and mixed with anhydrous ethanol. The sample was then dissolved by adding 10 mL of 1 M NaOH solution and heating it in a hot water bath. The resulting solution was diluted to 50 mL with distilled water and left to stand for 20 min. A control sample was prepared using the same procedure but without any starch. For each starch sample solution, 5 mL was taken and 20∼30 mL of distilled water was added. The pH value was then adjusted to approximately 3.5 with 0.1 M HCl. To each solution, 0.5 mL of iodine reagent was added, and the resulting volume was adjusted to 50 mL with distilled water. The absorbance of amylose was measured at a wavelength of 620 nm (A_1) and a reference wavelength of 448 nm (A_2), while the absorbance of amylopectin was measured at a measurement wavelength of 534 nm (A_1) and a reference wavelength of 757 nm (A_2). The absorbance difference between amylose and amylopectin was calculated using the equation $\Delta E = A_1 - A_2$ for both components. The starch content was determined using the standard curves for amylose and amylopectin, which had R^2 values of 0.9969 and 0.9992, respectively.

2.3. Effect of Exogenous Starch Addition on the Pasting Properties of KGM. Our preliminary experimental study used the total texture profile analysis (TPA) index and water holding capacity of commercially available konjac tofu as benchmarks. Through a two-factor random combination test, we optimized the formula for producing pure konjac tofu. To further improve the quality of konjac tofu, we conducted an experimental study on formula optimization for konjac tofu with CS (K-CS), CKS (K-CKS), and PS (K-PS), correlating the TPA indexes of our self-made pure konjac tofu with those of the commercially available konjac tofu. The research findings revealed that the ideal composition for homemade pure konjac tofu consists of 2.0% KGM and an amount of $Ca(OH)_2$ equivalent to 3% of the KGM quantity. Additionally, the optimal blend of konjac-starch tofu was achieved by incorporating CS, CKS, or PS, as indicated in Table 1. Based on preliminary assessments, it was determined that the ideal composition of CS, CKS, and PS was reached when their amounts were 4, 1.5, and 1.5 times that of KGM, respectively. This led to the creation of konjac-starch tofu that displayed water holding capacity and TPA index equivalent to those of pure konjac tofu. As a result, various concentration gradients were implemented to investigate the gelation and rheological characteristics of the sol, confirming and enhancing the konjac-starch ratio. Simultaneously, control samples consisting of three distinct types of pure starch with a concentration of 7% were established, as outlined in Table 2.

Table 1. Optimized Formula for Konjac Tofu (Calculated as a Percentage of Total Mass, %)[a]

	KGM	CS	CKS	PS	$Ca(OH)_2$
pure konjac tofu (KGM)	2				0.06
konjac tofu with CS (K-CS)	1.4	4.2			0.04
konjac tofu with CKS (K-CKS)	1.7		0.85		0.05
konjac tofu with PS (K-PS)	1.7			0.85	0.05

[a]"-" means not added.

A rapid viscosity analyzer (TechMaster RVA, Perten Instrument Co. Ltd., Sweden) was used to determine the pasting properties. Each sample, as listed in Table 2, was suspended in distilled water and allowed to equilibrate at 50 °C for 1 min. Subsequently, the suspension was heated to 95 °C at a rate of 12.5 °C/min and held at that temperature for 2.5 min. The sample was then cooled to 50 °C at a rate of 12 °C/min and maintained at that temperature for 2 min. During the initial 10 s, the paddle was set to rotate at 960 rpm and for the remaining test period, it was set to rotate at 160 rpm. All measurements were performed in triplicate.

2.4. Effect of Exogenous Starch Addition on the Rheological Characteristics of KGM. *2.4.1. Samples Preparation.* According to Table 2, a specific quantity of KGM and starch was measured and placed into a 250 mL beaker. Distilled water was then added to the mixture to reach a total mass of 100 g. The resulting paste was heated in a

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Table 2. Amount of KGM and Starch Used in the Test Group (Calculated as a Percentage of Total Mass, %)[a]

sample	KGM	CS	sample	KGM	CKS	sample	KGM	PS
K_1	1.4	0	K_2	1.7	0	K_3	2.0	0
$K\text{-}CS_1$	1.4	1.4	$K\text{-}CKS_1$	1.7	0.85	$K\text{-}PS_1$	1.7	0.85
$K\text{-}CS_2$	1.4	2.8	$K\text{-}CKS_2$	1.7	1.7	$K\text{-}PS_2$	1.7	1.7
$K\text{-}CS_3$	1.4	4.2	$K\text{-}CKS_3$	1.7	2.55	$K\text{-}PS_3$	1.7	2.55
$K\text{-}CS_4$	1.4	5.6	CKS	0	7	PS	0	7
CS	0	7						

[a]"-" means not added.

boiling water bath for 20 min with continuous stirring. Additional distilled water was added to compensate for any water lost during the heating process. Subsequently, the paste was cooled to a temperature of 25 °C to facilitate steady rheological determination. For the preparation of dynamic viscoelasticity scanning, 3% $Ca(OH)_2$ of the amount of KGM was added to the cooled solution, thoroughly stirred, and left to stand for 30 min.

2.4.2. Rheological Properties of Samples. The rheological assessments were conducted following the methodology of Gong et al. with slight modifications, using a rotational rheometer [HR-1, texture analyzer (TA) Instruments, USA].[22] A standard parallel plate (PP-25, 25 mm diameter, and 1 mm gap) was employed for the measurement. To prevent moisture loss, silicone oil was applied to the sample edge. Steady shear measurements (represented by flow curves) were performed within the range of shear rates 0.1−200 s^{-1}. The correlation between shear stress and shear rate was determined by fitting a Power-Law model (eq 1).

$$\tau = K\gamma^n \tag{1}$$

where τ is the shear stress (Pa), γ is the shear rate (1/s), K is the consistency coefficient (Pa·s^n), and n is the flow behavior index.

The dynamic viscoelastic rheological properties were evaluated at a temperature of 25 °C and a scanning strain value of 5%. Using a rheometer, the storage modulus (G'), loss modulus (G''), and loss angle tangent (tan δ) were measured over a range of oscillation frequencies from 0.1 to 100 rad/s.

2.5. Preparation of the Konjac Tofu. The preparation of konjac tofu was conducted following the method outlined by Lei with minor modifications.[23] A specific amount of KGM and starch, as indicated in Table 1, was weighed into a 250 mL beaker, and distilled water was added to reach a total mass of 100 g. The ingredients were dispersed in water, stirred, and allowed to swell in a 70 °C water bath for 1 h. A certain amount of 10% $Ca(OH)_2$ turbid solution was added, stirred evenly, left to stand for 30 min, and then steamed for 30 min to obtain konjac tofu.

2.6. Scanning Electron Microscopy Analysis of Konjac Tofu. The small pieces of freeze-dried tofu were attached to a stage using a conductive adhesive and subsequently subjected to scanning electron microscopy (SEM) analysis (SU8020; Hitachi Co. Ltd., Japan) to examine their internal microstructure. Prior to imaging, a conductive coating was applied using a surface treatment machine.[24] The imaging was performed at an accelerating voltage of 3.0 kV and at magnifications of 50× and 1000×, respectively.

2.7. TPA of Konjac Tofu at Different Temperatures. The TPA was conducted following the method developed by Wang et al. with minor modifications.[25] The konjac tofu was shaped into cylinders (h 15 mm × d 23 mm) and exposed to varying temperatures of 25, 35, 45, 55, 65, 75, 85, and 95 °C for 30 min. Hardness measurements were taken at each temperature point. Additionally, the hardness, adhesiveness, springness, and chewiness of the konjac tofu were measured at 25 °C using a TA (Plus, Stable Micro System Co. Ltd., UK). A two-cycle compression test was performed using a cylinder probe (36 mm diameter). Each sample was compressed to a depth of 10 mm with a compression force of 5 g and a compression rate of 1 mm/s. Five measurements were taken for each sample, and the mean value was taken as the result.

2.8. Syneresis Analysis of Konjac Tofu. Syneresis analysis was conducted according to the method developed by Hu et al. with minor modifications.[26] The initial mass of the konjac tofu was labeled as m_1, and it was subjected to centrifugation at a speed of 8000 rpm for 30 min. Then, the surface of the konjac tofu was gently wiped with filter paper, and its mass was noted as m_2. The extent of syneresis (Q_S) was determined using the following formula (eq 2)

$$Q_s = \frac{m_1 - m_2}{m_1} \times 100\% \tag{2}$$

where Q_S stands for the extent of syneresis of the sample, m_1 stands for the initial mass (g), and m_2 stands for the mass after centrifugation (g).

2.9. Endowing-Flavor Characteristics of Konjac Tofu. The endowing-flavor characteristics of konjac tofu were evaluated based on its ability to absorb, adhere to, and blend with flavor substances in seasoning. The absorption of salt and oil from seasoning by konjac tofu was used as a representative indicator to evaluate the endowing flavor characteristics.[17,27] To conduct the experiment, 80 g of hotpot soup base was added to 250 mL of boiling distilled water, followed by the addition of KGM, K-CS, K-CKS, and K-PS with uniform cubes. After cooking for 30 min, the konjac tofu samples were drained on filter paper for 5 min. The salt content and oil absorption of the cooked konjac tofu were determined using the acid hydrolysis methods outlined in GB 5009.44-2016 "Determination of Chloride in Food"[28] and GB 5009.6-2016 "Determination of Fat in Food",[29] respectively.

2.10. Statistical Analysis. All measurements were performed in a minimum of triplicate and expressed as "average ± standard deviation". Statistical analysis was conducted using SPSS 20.0 software. Figures were generated using OriginLab 2017 software and Excel 2010.

3. RESULTS AND DISCUSSION

3.1. Basic Indicators of Konjac Flour and Starch. According to Table 3, all of the indicators satisfy the specified requirements. Starch is made up of two components, namely, amylose and amylopectin, and their proportions vary depending on the source of the starch. Waxy starch typically contains less than 15% amylose, while ordinary starch ranges from 20 to

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Table 3. Basic Indicators of Konjac Flour

indicators	values	standard of konjac flour
water content (%)	11.23 ± 0.25	≤12.00, NY/T 494-2010, KGM
KGM content (%) (on a dry basis)	75.19 ± 0.54	≥70.00, NY/T 494-2010, KGM
viscosity (mPa·s) (on a dry basis)	29700 ± 1838	≥13000, NY/T 494-2010, KGM
SO_2 (g/kg) (on a dry basis)	0.25 ± 0.003	≤0.9, GB 2760-2014, sulfur-fumigated konjac flour
pH	6.08 ± 0.01	5.00~7.00, NY/T 494-2010, KGM

35% amylose, and high amylose starch typically contains more than 40% amylose.[30] As indicated in Table 4, the CS, CKS, and PS utilized in this study are classified as ordinary starch, with CKS having the highest amylose content.

Table 4. Basic Indicators of Starch[a]

tndicators (%)	CS	CKS	PS
water content	12.18 ± 0.24^c	18.76 ± 0.18^a	17.25 ± 0.11^b
amylopectin content (on a dry basis)	73.53 ± 0.23^a	67.80 ± 0.24^c	70.61 ± 0.22^b
amylose content (on a dry basis)	25.36 ± 0.14^c	31.49 ± 0.21^a	28.12 ± 0.13^b
total starch content (on a dry basis)	98.89 ± 0.37^a	99.29 ± 0.44^a	98.73 ± 0.35^a

[a]Note: Different lowercase letters in the same line indicate significant difference ($p < 0.05$).

3.2. Effects of Starch Type and Amount on KGM Gelatinization. Upon heating starch granules in the presence of water, the granules undergo swelling due to water absorption, resulting in a structural change from ordered semi-crystalline granules to an amorphous state. This process is known as gelatinization, leading to the release of amylose into the water and an increase in the viscosity of the starch paste until it reaches its peak viscosity.[31] The pasting curves of the sols of KGM, starch, and mixtures of KGM and starch are shown in Figure 1a–d, and the corresponding pasting parameters are listed in Table 5.

The K_1 curve (Figure 1a) exhibited a steady upward trend with no discernible peak or valley in viscosity. The initial viscosity rise rate was considerably lower than that of the pure starch group. However, a significant increase in viscosity was observed at a temperature of 95 °C. During the cooling process, the rate of increase in viscosity gradually slows down and at 50 °C, the rate of increase decreased significantly. The viscosity curve of K_2 exhibited similarities to K_1, but with an overall higher viscosity. However, during the cooling process, when the temperature reached 75 °C, the viscosity of K_2 experienced fluctuations before ultimately stabilizing at a level similar to K_1, indicating that KGM has a slow water absorption rate, and the expansion rate of KGM is influenced by temperatures. As shown in Table 5, the pasting temperature of PS was lower than that of CKS and significantly lower than that of CS. The peak viscosity and breakdown value of PS were slightly higher than those of CKS and considerably higher than those of CS. The setback of CKS was slightly higher than that of PS and significantly higher than that of CS. These differences can be attributed to the shape, size, and crystal structure of starch, as well as the proportion of amylose and amylopectin.[32]

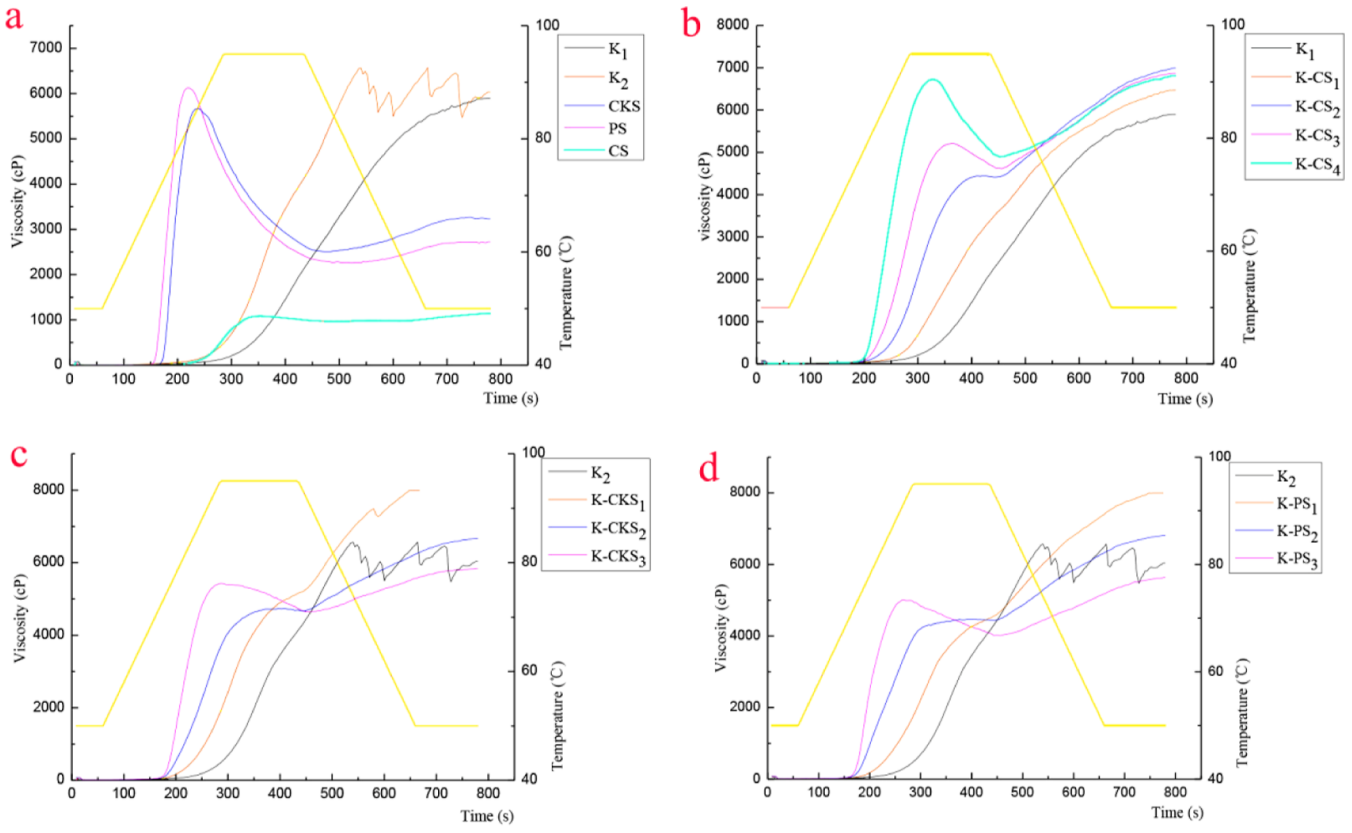

Figure 1. Pasting curves of pure starch and pure KGM sols (a), KGM and K-CS sols (b), KGM and K-CKS sols (c), and KGM and K-PS sols (d).

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Table 5. Effect of Starch on the Pasting Properties of KGM Sol[a]

	peak viscosity/cP	breakdown/cP	final viscosity/cP	setback/cP	peak time/min	pasting temperature/°C
K_1			5924 ± 35^{e}			
K_2			6120 ± 121^{e}			
CKS	5669 ± 85^{c}	3160 ± 27^{b}	3233 ± 64^{g}	724 ± 6^{f}	3.93 ± 0.04^{g}	70.95 ± 0^{ef}
PS	6127 ± 54^{b}	3866 ± 11^{a}	2724 ± 61^{h}	463 ± 18^{g}	3.67 ± 0^{h}	68.60 ± 0^{g}
CS	1120 ± 49^{g}	122 ± 7^{f}	1184 ± 59^{i}	186 ± 16^{h}	5.83 ± 0.05^{c}	85.12 ± 1.73^{a}
K-CKS_1			8000 ± 0^{a}			
K-CKS_2	4688 ± 76^{ef}	74 ± 4^{f}	6556 ± 159^{d}	1943 ± 79^{c}	6.83 ± 0.05^{ab}	72.65 ± 0^{d}
K-CKS_3	5278 ± 215^{d}	786 ± 4de	5642 ± 279^{f}	1151 ± 68^{e}	4.87 ± 0.09^{e}	71.72 ± 0.04^{de}
K-PS_1			8000 ± 0^{a}			
K-PS_2	4423 ± 71^{f}	33 ± 7^{f}	6686 ± 173^{cd}	2296 ± 110^{b}	6.67 ± 0.19^{b}	71 ± 0e^{f}
K-PS_3	4907 ± 148^{e}	980 ± 27^{d}	5498 ± 190^{f}	1570 ± 69^{d}	4.43 ± 0.05^{f}	70.2 ± 0.07^{f}
K-CS_1			6470 ± 0^{e}			
K-CS_2	4490 ± 69^{f}	30 ± 6^{f}	7096 ± 146^{b}	2636 ± 84^{a}	6.94 ± 0.09^{a}	79.92 ± 0.04^{b}
K-CS_3	5308 ± 135^{cd}	639 ± 62^{e}	6948 ± 111^{bc}	2279 ± 38^{b}	6.00 ± 0.09^{c}	77.5 ± 0^{c}
K-CS_4	7005 ± 402^{a}	2026 ± 281^{c}	6894 ± 120^{bcd}	1916 ± 0.7^{c}	5.40 ± 0.09^{d}	76.28 ± 0.60^{c}

[a]All data represent the means of triplicates. Means within a column with different letters are significantly different ($p < 0.05$). "/" indicates no data.

Incorporating CS resulted in higher viscosity throughout the entire RVA process compared to K_1 (Figure 1b). When the quantity of CS added equaled 1.4% (K-CS_1), there is a lack of peak and valley values. As the amount of CS added increased to 2.8% (K-CS_2), 4.2% (K-CS_3), and 5.6% (K-CS_4), the peak time occurred earlier, the peak temperature decreased, and the peak viscosity and breakdown values became larger. Nevertheless, the final viscosity was not significantly different ($p > 0.05$).

As depicted in Figure 1c, the viscosity of K-CKS_1 consistently exceeded that of K_2, and the rapid viscosity increase occurred earlier. At a temperature of 85 °C, the viscosity increased significantly, but at approximately 390 s, there was a brief period of plateau in the viscosity increase, which may be caused by the breakdown of starch. When 1.7% (K-CKS_2) and 2.55% (K-CKS_3) of CKS were added, the pasting curves exhibited distinct peaks and valleys. The more CKS that is added, the earlier the peak viscosity appeared, and the higher the peak viscosity and breakdown value, while the lower the valley viscosity. This phenomenon may be attributed to the absorption of water by CKS and its gelatinization in the early stages, which reduces the availability of water molecules to KGM and hinders its swelling.

The pasting curves of K-PS were found to be similar to those of K-CKS, as depicted in Figure 1d. When equal amounts of PS or CKS were added, the peak time of K-PS occurred earlier, the pasting temperature was lower, and the breakdown value was higher, which is consistent with the pasting properties of pure starch. However, the peak viscosity of the sample that was added with CKS was higher than that of PS with the same dosage, as indicated in Table 5. This could be attributed to the fact that PS has a stronger affinity for water compared to CKS, resulting in a greater impact on the swelling of KGM.[33] Figure 1a illustrates that the water absorption and gelatinization ability of CS were significantly lower than those of CKS and PS. Therefore, in the mixture of KGM and CS, the ability of CS to compete for water was weak and had a negligible impact on the swelling process of KGM.

The results indicate that the breakdown and retrogradation values of the samples do not reflect the breakdown and retrogradation of starch, as KGM does not possess the same properties. This is due to the interaction between KGM and starch particles, as well as their competition for water, which can affect their swelling degree and the three-dimensional network formed during the leaching and retrogradation of amylose in starch particles.[34] It has been observed that higher starch concentrations, regardless of their type, result in increased breakdown values, which can be attributed to the more pronounced properties of starch and the heightened shear force exerted on the swelling particles in the shear field, leading to the disintegration of particle integrity and thus reducing paste viscosity.[35]

3.3. Effects of Starch Type and Amount on the Rheological Characteristics of KGM Gel. The flow curves of KGM and KGM-starch samples were analyzed in Figure 2a−c. It was observed that the apparent viscosity of the samples decreased as the shear rate increased, indicating that both KGM sols with or without starch exhibited the typical characteristics of shear-thinning non-Newtonian fluids. These findings are consistent with those reported by Ma et al.[36] The apparent viscosity of K-CS increased with the increase in CS concentration, but the viscosity of K-CS_1 (with CS of 1.4%) was lower than that of pure KGM (K_1). The viscosity of the samples with the addition of CKS or PS decreased. When the addition of CKS or PS was 0.85%, the apparent viscosity was similar to that of pure KGM (K_2).

The Power-Law model was utilized to fit the data points, and the relevant parameters are presented in Figure 2d. The fitting coefficient of determination R^2 increased, and the fitting accuracy improved as the amount of starch added increased. However, when the addition of CS was 5.6% (K-CS_4), the fitting accuracy was notably low at 0.566. All samples exhibited pseudoplastic non-Newtonian fluid with $n < 1$. When the concentration of CS was 1.4% (K-CS_1), the K value decreased, and the viscosity was significantly lower than that of K_1. But as the concentration of CS increased, the K value and viscosity also increased, while the K value and viscosity decreased as the concentration of CKS or PS increased. The smallest n, the highest viscosity, and largest K were observed when the concentration of CS was 4.2%, CKS was 0.85%, and PS was 0.85%, which is favorable for processing. This finding is consistent with the optimization formula of konjac-starch tofu presented in Table 1.

The graphical representations of the frequency-dependent behavior of G', G'', and tan δ are presented in Figure 3a−f. The findings suggest that KGM, with or without starch, exhibits a

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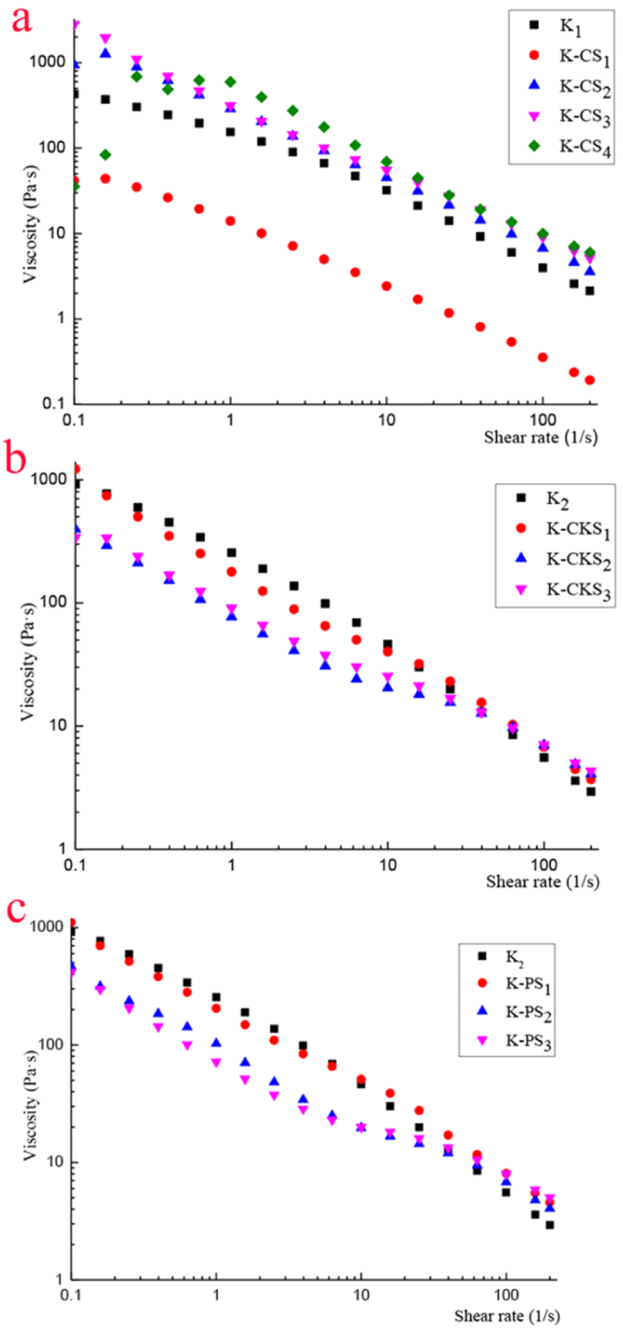

d

	K (Pa·s^n)	n	R^2
K_1	131.36±3.57^g	0.282±0.021^d	0.888
K_2	226.50±2.41^c	0.237±0.017^f	0.902
K-CS_1	12.34±0.53^k	0.253±0.025^{ef}	0.913
K-CS_2	266.84±1.39^b	0.210±0.038^{fg}	0.917
K-CS_3	353.87±4.03^a	0.194±0.014^g	0.945
K-CS_4	174.41±1.88^f	0.482±0.037^h	0.566
K-CKS_1	193.04±2.47^e	0.279±0.015^{de}	0.972
K-CKS_2	86.06±1.12^j	0.430±0.041^b	0.979
K-CKS_3	96.47±1.72^i	0.425±0.036^{bc}	0.991
K-PS_1	213.01±1.33^d	0.307±0.031^d	0.979
K-PS_2	98.48±1.03^h	0.393±0.027^c	0.981
K-PS_3	83.93±1.26^j	0.455±0.038^a	0.987

Figure 2. Static shear curves of KGM and K-CS (a), KGM and K-CKS (b), and KGM and K-PS (c). Flow properties of KGM and its mixtures with various concentrations of starch (d).

rheological profile that is characteristic of a feeble gel structure. As the concentration of CS increased, there was a corresponding increase in G' (Figure 3a), while tan δ experienced a substantial decrease (Figure 3b). When the concentration of CS was ≥2.8%, the value of G' surpassed that of pure KGM, indicating that the addition of CS led to the formation of a more solid-like gel network within the KGM. This could be attributed to the phase separation that occurred due to the incompatibility of KGM and CS in the continuous phase. This separation resulted in an increase in the concentration of starch and KGM by holding onto water molecules, ultimately leading to the development of a more robust gel structure.[36] Figure 3c−f illustrates that the effect of adding CKS and PS to KGM was opposite to that of CS. As the concentration of CKS and PS increased, the G' decreased. However, when their concentrations were at 0.85%, a higher G' was observed compared to the pure KGM group. Varela et al. discovered that adding KGM to PS did not have a significant effect on the mixture's viscosity and G′, but it resulted in a higher tan δ.[37] G″ exhibited a similar trend as G' with regard to the concentration of starch, and G'' had a weak dependency on frequency, indicating a robust gel structure with minimal differentiation between the sample groups.

The effect of CS on the rheological properties of the mixture was contrary to that of CKS and PS, which may be attributed to the high content of KGM in K-CKS and K-PS, and the strong water binding capacity of CKS and PS. As the concentration of starch increased, the resistance to the

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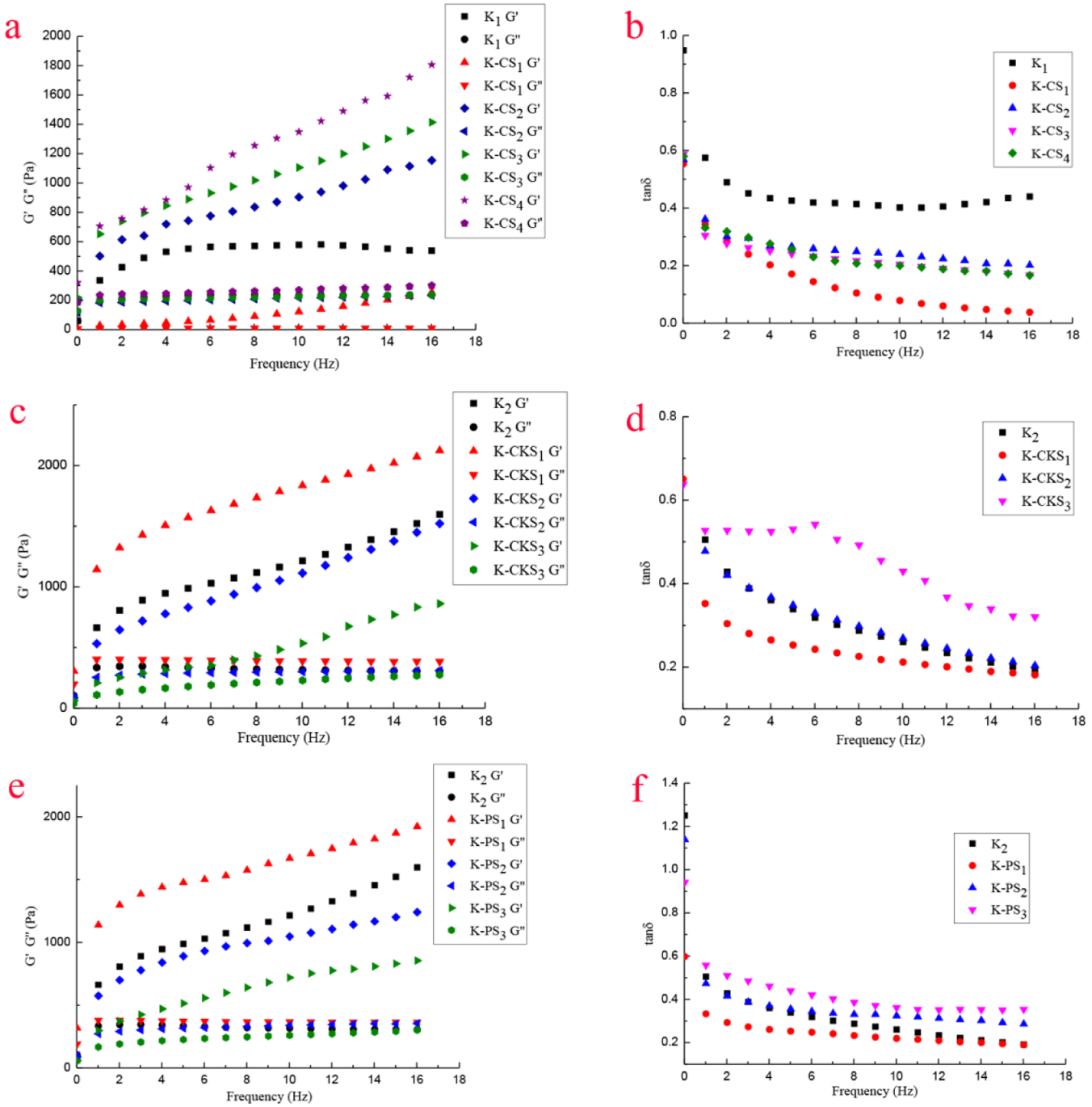

Figure 3. G', G'' (a), and tan δ (b) as functions of frequency for KGM and K-CS gels; G', G'' (c), and tan δ (d) as functions of frequency for KGM and K-CKS gels; and G', G'' (e), and tan δ (f) as functions of frequency for KGM and K-PS gels.

absorption of water molecules by KGM also increased, leading to a reduction in the swelling degree of KGM and a subsequent decrease in the rheological properties of the mixture. In the K-CS gel, the KGM content was found to be low, while the water molecules were sufficient. Moreover, the ability of CS to compete for water was weak. Due to the presence of adequate water, KGM was able to fully swell and combine with CS. As the concentration of CS increased, the rheological properties of the mixture were enhanced.

3.4. SEM Image Analysis of Konjac Tofu. SEM images of KGM, K-CS, K-CKS, and K-PS gels in Figure 4 reveal their important structural characteristics. At a magnification of 50×, the structural uniformity of pure KGM gel was found to be inconsistent, leading to the formation of small bubbles during production. In contrast, K-CS, K-CKS, and K-PS gels exhibited a uniform structure. Notably, the K-CS gel was denser than K-CKS and K-PS gels, which can be attributed to its higher starch content. Upon magnification at 1000×, the pure konjac tofu exhibited an irregular honeycomb structure with a chaotic network and thin fragile connections. Conversely, the K-CS, K-CKS, and K-PS gels were all in the sheet form, with a compact texture. This can be attributed to the formation of the network by KGM, which is then filled by starch molecules, thereby rendering the structure more robust and stable. Zhou et al. utilized a confocal laser scanning microscope to observe a similar structure. Upon examination, they found that the starch

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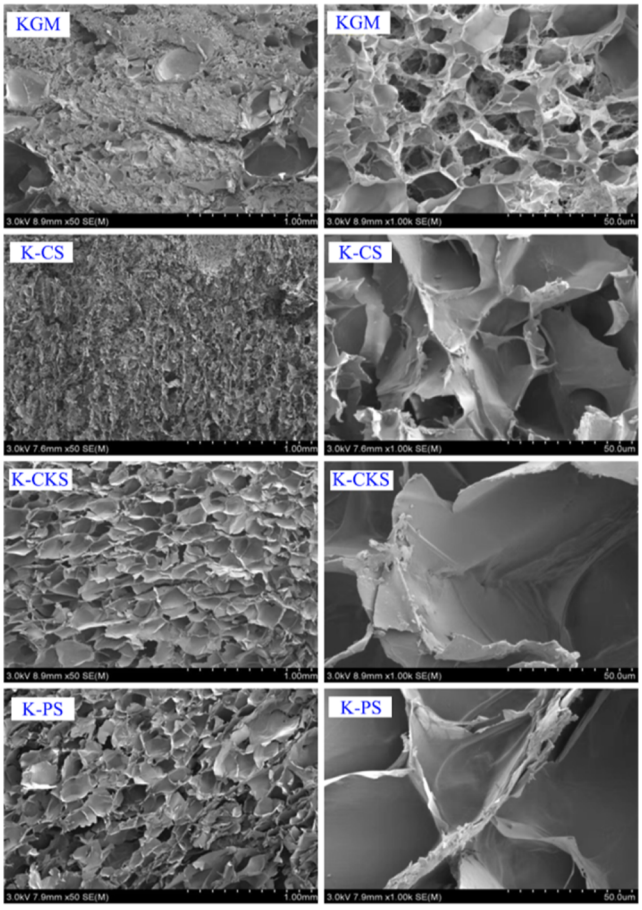

Figure 4. SEM images of KGM gels containing CS (K-CS), CKS (K-CKS), and PS (K-PS) (50× magnification on the left, 100× magnification on the right).

granules formed a continuous and glutinous network around the surface of the swollen granules in Na_2CO_3-KGM-starch composite systems.[38] Furthermore, K-CS exhibited a more compact lamellar network structure, possibly due to the incorporation of a greater amount of starch into the KGM network structure.

3.5. Texture Properties of Konjac Tofu. The effect of different types and amount of starch on the texture of konjac tofu at 25 °C is analyzed and reported in Table 6, based on the data in Table 1. Results indicate that K-CS exhibited superior texture properties compared to pure KGM, with significantly higher levels of hardness, adhesiveness, springness, and chewiness. Furthermore, K-CKS also showed higher adhesiveness and springness than pure KGM, demonstrating that the addition of starch and reduction of KGM can result in a gel with similar or improved texture properties.[39]

Figure 5 demonstrates the impact of different temperatures on the hardness of gels. Pure konjac tofu was consistently

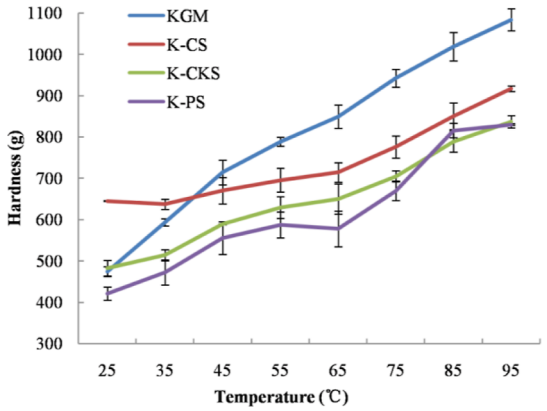

Figure 5. Effect of different temperatures on the hardness of gels.

harder than konjac-starch tofu made with K-CKS and K-PS. At room temperature, K-CS had the highest hardness, however, when heated to 45 °C, the hardness of pure konjac tofu surpassed that of K-CS. This is due to the honeycomb-like structure of pure konjac tofu, which expands and hardens when heated. In contrast, konjac-starch tofu has a more stable and flakier microstructure with a limited expansion space, resulting in minimal changes in hardness (Figure 4). The ideal temperature for consuming konjac tofu is around 45 °C, at which point the hardness of K-CKS and K-PS is significantly lower than that of pure konjac tofu. Adding starch to konjac tofu can increase its hardness at room temperature, prevent changes in hardness with temperature, and improve its overall edibility. Lei et al. also found similar results when they added CS and CKS to KGM, respectively, to create konjac-starch tofu.[23]

3.6. Syneresis Analysis of Konjac Tofu. Figure 6 demonstrates the effects of different types of starches on gel

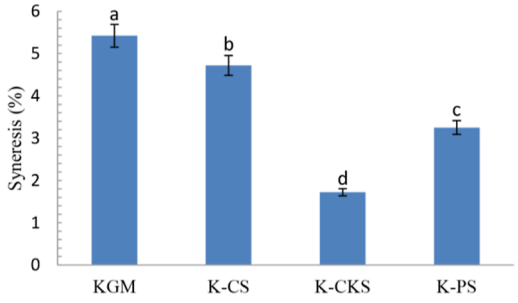

Figure 6. Effects of different starches on syneresis of KGM gels. Note: different lowercase letters in the bar indicate significant differences ($p < 0.05$).

syneresis. K-CS, K-CKS, and K-PS gels exhibit less syneresis compared to KGM gels. This may be attribute to the fact that KGM-starch gels exhibit a more robust water holding capacity

Table 6. Effects of the Different Starch on Hardness, Adhesiveness, Springiness, and Chewiness of Gels at 25 °C[a]

	KGM	K-CS	K-CKS	K-PS
hardness (g)	474.60 ± 4.96^{b}	645.23 ± 25.31^{a}	482.33 ± 8.23^{b}	421.46 ± 11.21^{c}
adhesiveness (g·s)	12.73 ± 1.37^{b}	14.19 ± 1.53^{ab}	15.31 ± 1.06^{a}	12.53 ± 1.33^{b}
springness (%)	88.59 ± 0.39^{c}	91.19 ± 0.36^{a}	89.26 ± 0.26^{b}	88.22 ± 0.22^{c}
chewiness (J)	207.03 ± 19.62^{bc}	373.33 ± 15.88^{a}	225.86 ± 14.39^{b}	193.42 ± 16.73^{c}

[a]All data represent the mean of triplicates. Means within a row with different letters are significantly different ($p < 0.05$).

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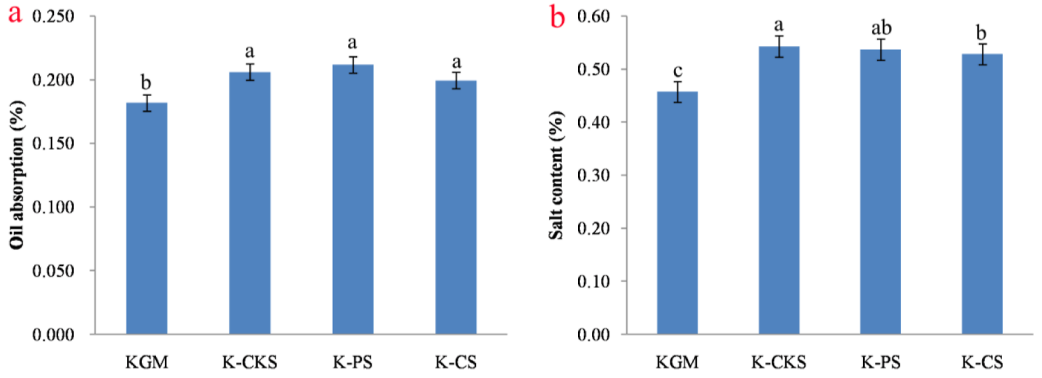
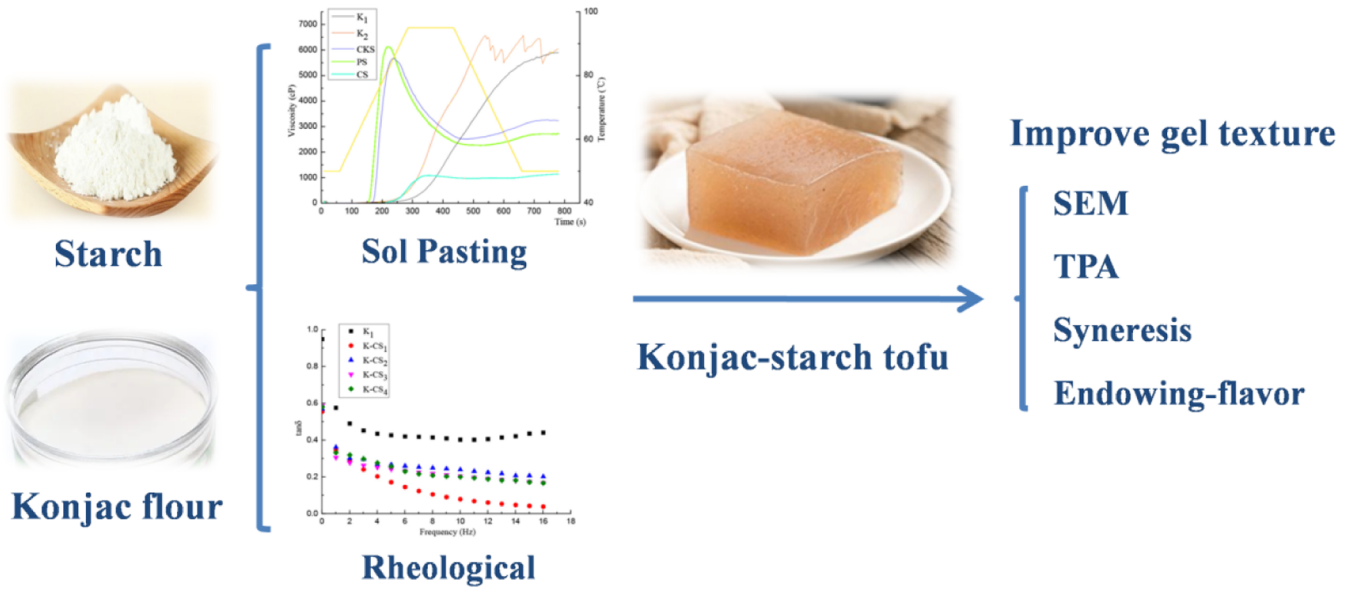


Figure 7. Effect of starch addition on oil absorption (a) and salt content (b) of konjac tofu. Note: different lowercase letters in the bar indicate significant differences ($p < 0.05$).

Scheme 1. Addition of Starch Can Augment the Pasting and Rheological Characteristics of KGM Sol and Also Improve the Gel Texture of Konjac-Starch Tofu



due to their tighter structure. It is observed that K-CKS gels have the lowest syneresis, showing a superior water-holding capacity in comparison to K-CS and K-PS gels. This is primarily attributed to the higher amylase content present in CKS, which is soluble in water and has exceptional water absorption abilities.

3.7. Endowing-Flavor Analysis. KGM is known for its distinct fishy odor, which can be challenging for some individuals to tolerate. The addition of alkali further intensifies this odor. Furthermore, konjac tofu is difficult to flavor during the cooking process, resulting in an unsatisfactory taste that reduces consumer acceptance. Figure 7 shows the effect of starch addition on oil absorption (a) and salt content (b) of konjac tofu. It reveals that adding starch to konjac tofu had a significant effect on both its oil absorption and salt content ($p < 0.05$), resulting in a stronger flavor enhancement compared to pure konjac tofu. On the one hand, the flavor enhancement may occur because amylose can capture various molecules, including iodine, alcohol, lipids, and flavor substances, providing a large central cavity with a simple helical structure to bind ligands.[40] On the other hand, it may be attributed to the fact that although konjac-starch tofu is compact in its flakes, there is a large gap between the flakes, which is conducive to the entry of flavor substances.

4. CONCLUSIONS

This study examined the effects of starch integration on the pasting, rheological properties, and gel structure of KGM sols (Scheme 1). When the CS, CKS, and PS were 1.4, 0.85, and 0.85%, respectively, of the total mass, the gelatinization characteristics of the KGM and starch mixed system were mainly determined by those of KGM, with no peak viscosity or valley viscosity present. However, increasing the amount of starch added caused the gelatinization characteristics of the system to become more similar to those of the added starch. The static rheological characteristics of K-CS sol indicated that the viscosity of the solution increased with an increase in the starch concentration, while the viscosity of K-CKS and K-PS sol decreased. The dynamic viscoelastic properties revealed that the gel stability improved when the concentration of CS exceeded 4.2%, CKS and PS were 0.85%. The TPA analysis demonstrated that the inclusion of starch in the gel preparation process can produce texture properties that were either equivalent to or better than those of pure KGM gel, while also preventing dehydration. Additionally, this could increase

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the gel's hardness at room temperature, reduce its hardness at 45 °C, and improve its palatability.

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Author Contributions

Liling Deng: conceptualization, data processing, analysis, writing, and submission. **Yan Li**: analyzed the SEM, endowing flavor ability. **Geng Zhong**: studied the pasting formation and rheological properties of KGM sol. **Wen Lei:** optimization the technology of konjac tofu, analyzed the TPA and dehydration. **Yongbo Peng:** overall conception and revision of the manuscript. **Zhaojing Zhu**: overall conception and revision of the paper.

Notes

The authors declare no competing financial interest.

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