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Effect of natural gums on pasting, rheological, structural and hydrolysis properties of kudzu starch

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ABSTRACT

Hydrocolloids have been widely used to adjust properties of natural starches, but related research on kudzu starch is still rare. In this study, we investigated the effects of gum arabic (AG), sodium alginate (SA), locust bean gum (LG), and guar gum (GG) on kudzu starch from the perspective of its particle size, pasting, texture, rheology, dehydration rate, thermal properties, microstructure, and sensitivity to amyloglucosidase. Results showed that GG significantly increased the particle size of starch. Addition of AG led to lower peak-, final- and holding-viscosity. SA increased the retention viscosity of kudzu starch, while LG and GG increased its peak viscosity. Addition of hydrocolloids increased the hardness, chewiness, and cohesiveness of starch-hydrocolloid complexes, and reduced the dehydration rate of complex gels. Dynamic rheological data showed that the energy storage modulus (G′) was significantly higher than the loss modulus (G″). The magnitude of modulus increased with frequency, and elastic properties were better than viscous properties. Thermal analysis showed that hydrocolloids increased the starting temperature (To), and the final temperature (Tc). With addition of each of these four hydrocolloids, a more regular and porous thick-wall dense structure was formed, which effectively lowered kudzu starch's sensitivity to amyloglucosidase. It indicated that the binding of hydrocolloid to starch may slow down glucose release into blood during digestion. These results will help understand effects of natural hydrocolloid on kudzu starch, as well as expanding its application in food industry.

1. Introduction

Kudzu is a natural herb widely distributed in China and other East Asian countries (Zhao et al., 2021). It has been used in traditional Chinese medicine for centuries (Liu et al., 2011), which positively regulates the central nervous and cardiovascular systems. Kudzu also alleviates the symptoms of diabetes (Song et al., 2021) or of alcohol addiction (Zhang et al., 2013). Isoflavone or puerarin isolated from kudzu, which exhibits strong antioxidant activities, is a good raw material for either medicine or food (Chen et al., 2012). Kudzu starch is usually extracted from the tuber of kudzu root via water grinding (Soni and Agarwal, 1983).

Starch has been applied in food or beverage industries as thickener or sweetener, as well as in paper or textile industries (Slattery et al., 2000). However, natural grain starches are usually not appropriate for food development (Shahzad et al., 2019b). Similar to other grain starch, kudzu starch has poor resistance to dehydration, a tendency to retrograde after pasting and a fast digestion rate (Chen et al., 2017). In order to overcome this innate defect of kudzu starch during food processing, researchers had tried various methods, such as addition of salt or polysaccharide (Guo and Du, 2014; Jóźwiak et al., 2018; Li et al., 2019).

Hydrocolloids are biopolymers with high molecular weight, which are usually water-soluble due to the presence of polar functional groups. They generate viscous dispersions upon dissolution into water (Sciarini

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et al., 2009). Gum arabic (AG), sodium alginate (SA), locust bean gum (LG) and guar gum (GG) are four types of natural and widely available hydrocolloids, which have been applied to regulate thickening, gel stability, taste or texture (Ferrero, 2017; McClements, 2017).

Combinations of starch and hydrocolloid had been reported to improve the properties of starch-based food (Chen et al., 2015). In order to achieve a specific goal (e.g., change of viscosity, gel strength, or paste elasticity) (Kim and BeMiller, 2012), it is critical to select an appropriate hydrocolloid (type, concentration) to mix with starch. By employing the synergistic effects of hydrocolloids, it is possible to modify the physical or chemical properties of starch to meet consumers' needs (Shahzad et al., 2019b). Due to the increasing demand of kudzu starch worldwide (Zhao et al., 2021), this study focused on the effect of different natural hydrocolloids on the pasting, gelation, rheological properties and digestive characteristics of kudzu starch. We aimed to obtain first-hand experimental data on how hydrocolloid affects the pasting property of kudzu starch. Results would provide better understanding for further application of hydrocolloid in kudzu starch-based food products and provide useful information for healthy food development.

2. Materials and methods

2.1. Materials

Chemicals, regents and kits were purchased from companies listed as below: glucose monohydrate (20170614, AR) from Sinopath Chemical Reagent Company; DNS (PH1844) chromogenic agent w from Fejing Biotechnology Co., LTD.; starch glucosidase (A107823, 100000u/mL) from Aladdin Biochemical Technology Co., LTD.; gum arabic (MW: 22-30 $\times$ 10^5) and guar gum (TG004302, MW: 0.5-8x10^5) from Huasheng Food & Chemical Co.; locust bean gum (SK72210, MW: 3 $\times$ 10^5) from Azealis International Trading Co.; sodium alginate (YP210607, MW: 5 $\times$ 10^5) from Qingdao Mingyue Seaweed Group Co.; the total starch content kit (A148-1-1) from Jiancheng Bioengineering Co. Purity of chemicals and reagents were equal to analytical grade, unless stated otherwise.

2.2. Preparation of kudzu starch and starch gum blends

Kudzu starch was separated as stated in literature (Shahzad et al., 2019a). Crushed kudzu roots were then mixed with ultrapure (UP) water with a volume ratio of 1:1, stirred for 3 min, and strained through cambric twice. The starch precipitated at room temperature (R.T.), and the supernatant and dark colored layer were discarded. The precipitated starch was re-suspended with UP water. The mixture was allowed to sediment again overnight, and the supernatant was discarded to obtain clean starch. The separated starch was air-dried and ground into fine powder, which was then passed through a 0.45 mm mesh and stored in an air-tight container. The total starch content was estimated with a starch content kit (A148-1-1), which was 90.50%.

Starch-hydrocolloid mixtures were prepared according to literature (Shahzad et al., 2019b). Kudzu starch was mixed with one of these four hydrocolloids (AG, SA, LG, GG) with a ratio of 1.0% or 2.0% (w/w). The mixture was blended with UP water to achieve a total solid ratio of 8.0% (w/w). The mixture was stirred with a magnetic stirrer at R.T. for 1 h, followed by continuous stirring in a 95–98 °C water bath for 20 min. The resulted gel was ready for measurements of Rheological and Syneresis properties.

2.3. Granule size distribution

Aqueous solution of the starch-hydrocolloid mixture (12%, w/w) was prepared and mixed well. The distribution of particle sizes of the separated un-pasted starch was analyzed with a laser scattering-based particle size analyzer (Mastersizer, 2000; Malvern, UK).

2.4. Pasting property test

Pasting properties were measured with a Rapid Viscosity Analyzer (RVA, Sydney, Australia). Both the starch-hydrocolloid mixture (3 g) and UP water (25 g) were added to an RVA aluminum can. The sample were held at 50 °C for 1 min, heated with an elevation rate of 11.96 °C/min until 95 °C was reached in 4.76 min, and held at 95 °C for 2.53 min. It was then cooled down to 50 °C with a rate of 11.84 °C/min, which was reached in 4.80 min, and held at 50 °C for 1.4 min. Data processing was executed with a Thermocline software (Newport Scientific, Australia).

2.5. Texture profile analysis of starch gel

Kudzu starch gels collected from RVA experiments were stored in aluminum jars (65 mm height, 36 mm diameter) at R.T. for 24 h. Texture of gels were analyzed with a Textural Profile Analysis (TPA) secondary compression mode model of TAXT plus equipped with P1/S probes. Experimental parameters were set as below: 1.0 mm/s for the predicted speed, test speed and post-test speed, 75% for the strain, automatic for the trigger type, 0.1 g for the trigger force. Hardness, cohesiveness and chewiness were measured afterwards.

2.6. Rheological properties of the mixture of hydrocolloid and starch

Rheological properties of gels in Section 2.2 were measured to obtain rotating rheometer (HAAKE RheoStress 6000). First, a sample was held at R.T. for 20 min, and a paste was cooled to 25 °C. After the sample was loaded, the excess gel was discarded. Then the sample was sealed with mineral oil to prevent water evaporation, and equilibrated on a platform for 5 min to allow residual stress relaxation. The linear viscoelastic zone of gel was measured through a stress sweep procedure in an oscillatory mode. Experimental parameters were set as below: 35 mm circular plate probe, 1 mm parallel plate spacing, 25 °C, frequency sweep range of 0.1–10 Hz. Effects of hydrocolloids on dynamic rheological properties of starch were assessed via a frequency-sweep procedure, in order to clarify energy storage modulus (G') and loss modulus (G'').

2.7. Syneresis properties

A modified method according to literature (Liu et al., 2019a) was applied to evaluate freeze-thaw properties of gels obtained in Section 2.2. All samples were frozen in a freezer at −19 °C for 22 h and then thawed at 28 °C for 2 h. These thawed gel samples were centrifuged at 2800×g for 10 min. The supernatant was then decanted and the residue was weighed.

2.8. Micro differential scanning

A micro differential scanning calorimeter (Micro DSC-III, SETARAM) equipped with a refrigerated cooling system was applied for the gelation process. The starch mixture samples were weighed onto aluminum DSC pans and UP water was added with a micropipette to form a suspension with the final concentration of 25% starch-hydrocolloid (w/w) mixture. The sample pans were sealed, allowed to stand overnight at 4 °C, and then heated in the Micro DSC-III from 30 °C to 90 °C with an elevation rate of 1 °C•min^{-1}. Micro DSC-III was calibrated against an empty pot of distilled water. Based on the collected data from raw graphs, the onset temperature (To), conclusion temperature (Tc) and enthalpy (ΔH) of starch pasting were calculated with software equipped on Micro DSC-III. Results were reported as the average of three measurements.

2.9. Scanning electron microscopy (SEM)

Scanning electron microscopy (JSM-6390LV, Japan) was used for high-resolution imaging. The paste obtained after the above RVA test was stored in an aluminum can, frozen in a −80 °C refrigerator for 24 h,

and finally freeze-dried in a vacuum freeze-dryer for 48 h. The dried samples were subsequently cut into thin slices and fixed on a sample stage via ion sputtering for metal spraying. Sample images were taken at a magnification of 15 kV accelerating voltage.

2.10. Digestion of granular and gelatinized starches to starch glucosidase

According to literature (Guo et al., 2016), a starch-hydrocolloid mixture (100 mg) was evenly dispersed in a container with 10 mL UP water inside, and then heated in a boiling-water bath for 20 min to make starch fully pasted. Afterwards, the pasted starch solution was cooled to R.T. and mixed thoroughly with acetate buffer (5 mL, pH = 5.4). Then amyloglucosidase (5 mL, 10 U/mL) was added and incubated in a shaking water bath at 37 °C for 140 min. Subsequently, starch hydrolysate was immediately placed in boiling water for 10 min to inactivate amyloglucosidase activity. The supernatant was centrifuged, and glucose in the supernatant was quantified via reaction with 3,5-Dinitrosalicylic acid (DNS), which was measured at 530 nm.

2.11. Statistical analysis

Unless otherwise stated, all of the above experiments were performed in triplicates. Data were analyzed via one-way analysis of variance (ANOVA). Experimental data was processed with Origin2018 for graphing. Data analysis was performed with SPSS software 18.0. Values were expressed as mean ± SD for parametric distributions. A p values of $\leq$0.05 was considered statistically significant.

3. Result

3.1. Distribution of the particle size of granule

As shown in Fig. 1 and Table S1, original graphs and parameters of the distribution of particle sizes were presented for the Control (kudzu starch only), and kudzu starch-gel complexes (KS + AG, KS + SA, KS + LG and KS + GG complexes). D [4,3] is the mean of volume and represents the average particle diameter of volume, while D [3,2] is the mean of surface area moment and represents the average particle size of surface area. D50 is the median diameter and is commonly used to express the average particle size (Zhou et al., 2020). As shown in Table S1, addition of hydrocolloids tended to enlarge the starch particle size.

D [3,2] increased to 3.55 μm, D [4,3] increased to 15.83 μm, and D50 increased to 8.61 μm in the presence of 1% GG. D [3,2] increased to a maximum of 4.3872 μm, D [4,3] increased to 22.96 μm, and D50 increased to 8.97 μm in the presence of 2% GG. The largest difference between D [4,3] and D [3,2] was observed for 2% GG, indicating that 2% GG led to a wider distribution of particle sizes of kudzu starch (Zhou et al., 2020).

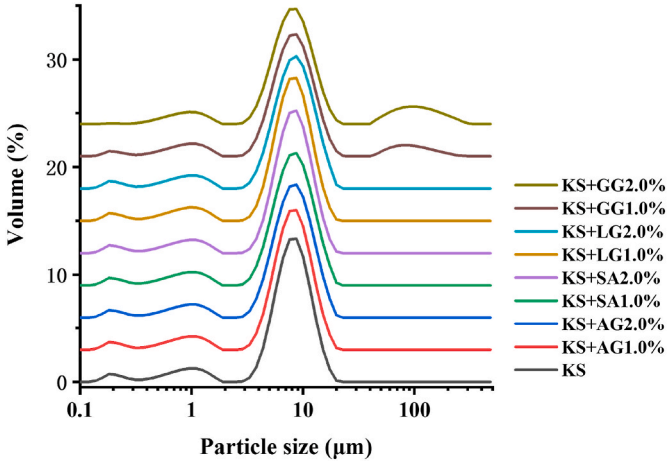

Fig. 1. Distribution of the particle sizes of kudzu starch-gel complexes.

Enlargement of starch particle size may be due to attachment of hydrocolloid to the surface of starch granules and the microencapsulation ability of hydrocolloids to encapsulate starch granules. Moreover, the expanded particle size might reduce the contact probability between enzyme and starch, thus causing reduced sensitivity towards amyloglucosidase as reported later.

3.2. Measurements of pasting properties

The pasting parameters of natural kudzu starch and hydrophilic gum mixtures were shown in Fig. 2 and Table S2. Pasting temperature (PT) is the temperature at which viscosity starts increasing in the process of heating. Compared to the Control group, SA, LG or GG complexes significantly boosted the pasting temperature, and AG improved the pasting time. These results indicated that addition of hydrocolloids may slow down heat absorption of starch, which therefore improves the stability of starch products and prolongs the shelf life of starch food.

Peak viscosity (PV) is usually related to starch swelling or its capability binding free water molecules (Lin et al., 2021). PV and hold viscosity (HV) of kudzu starch increased significantly upon addition of LG or GG, which might be attributed to formation of hydrogen bond between starch and hydrocolloids.

PV with 1.0% SA decreased by 74 mPa s compared to the Control, while PV with 2.0% SA increased by 348 mPa s. This phenomenon was similar to what was reported about SA on maize starch (Li et al., 2019). It might be explained by the theory that when straight-chain starch is leached into a continuous phase, hydrocolloid at high concentrations synergizes with swollen starch or leached straight-chain starch, resulting in an increased viscosity. Addition of AG caused a decrease in PV and HV compared to the Control. Takahiro Funami et al. (2008) studied the effect of soybean polysaccharides and AG on the pasting of wheat starch, who reported that addition of AG significantly reduced PV and HV and breakdown viscosity (BV) of starch paste after pasting. This may be attributed to the ability of hydrocolloids to cover the surface of starch granules, thus limiting water absorption of starch and enhancing the association among granules and inter-granules, which leads to reduced swelling of starch granules and limited increase of PV (Chen et al., 2015). In addition, the effect of 2.0% AG was more distinctive than 1.0% AG. This may help the development of beverage-based food.

Final viscosity (FV) is the ability of dextrinized starch to form a viscous paste upon cooling to 50 °C (Nawab et al., 2016). As shown in Table S2, addition of SA or LG significantly increased FV of kudzu starch, and greater FV was obtained with higher concentrations of SA or LG. FV reduction was more significant with 2.0% AG than with 1.0% AG, probably due to blockage of cross-linking between starch molecules in the presence of more AG molecules.

Breakdown viscosity (BV) is also an important index to evaluate starch pasting, which is the difference between peak- and trough-viscosity, reflecting the degree of destruction of starch granules and the stability of starch paste upon heating (Yang et al., 2021). Addition of LG or GG significantly increased BV of kudzu starch, which may be due to the fact that the shear force of the dissolved granules was much greater than that in the starch-water suspension (Von Borries-Medrano et al., 2019). This result is similar to what was reported about the effect of guar gum on pea starch (Kim and BeMiller, 2012).

3.3. Texture measurement

Texture is an attribute to assess consumers' acceptability. Textural parameters of kudzu starch alone and starch-hydrocolloid complexes were summarizes in Table 1. Starch granules absorbed water, got swollen, and broke down during heating, along with decreased hardness (Xiao et al., 2021). As reported in literature (Keetels et al., 1996; Leloup et al., 1992), the structure of straight-chain starch was a double-helix

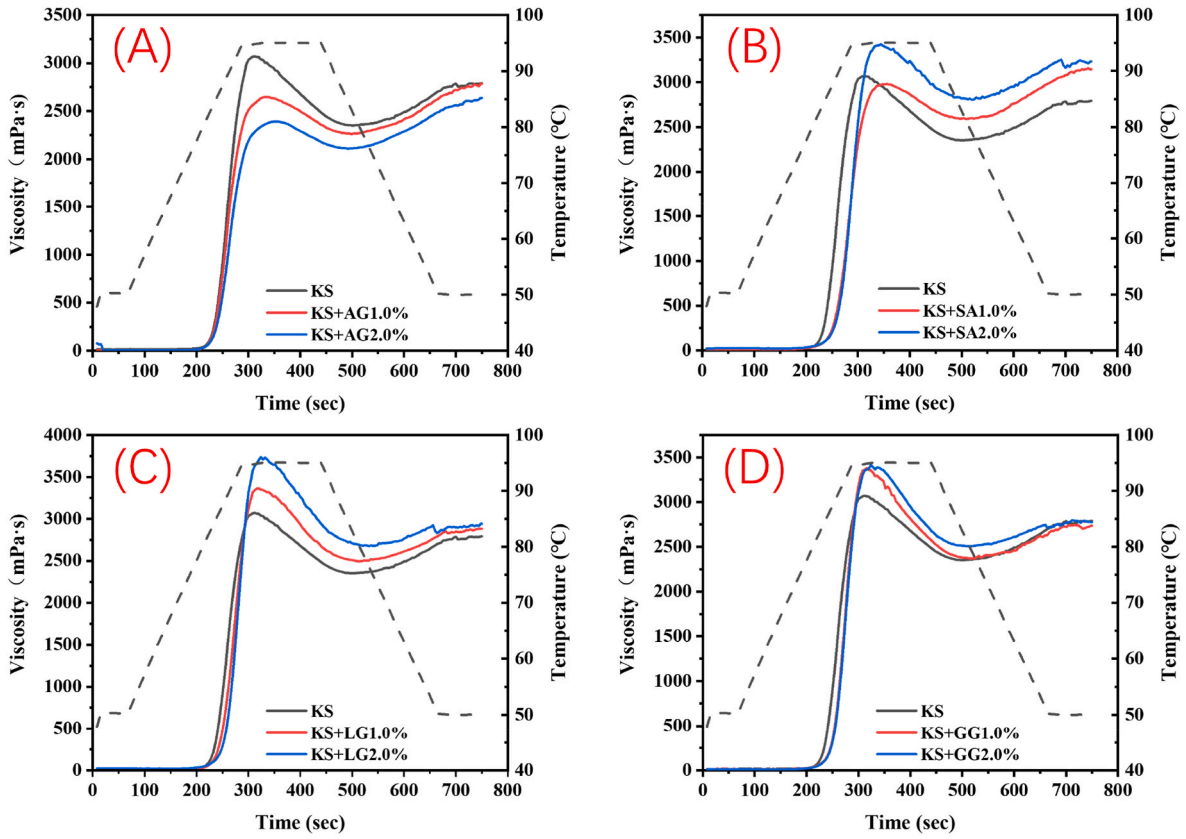

Fig. 2. Pasting curves of kudzu starch with different hydrocolloids at varied concentrations: A (Gum arabic); B (Sodium alginate); C (Locust bean gum); D (Guar gum).

Table 1
Texture parameters and dehydration properties of kudzu starch-gel complexes.

	Gum (%)	Control	Gum arabic	Sodium alginate	Locust bean gum	Guar gum
Hardness(g)	1.0	94.90 ± 5.37d	176.91 ± 3.30b	148.91 ± 11.99c	214.86 ± 4.95a	186.30 ± 7.79b
	2.0	94.90 ± 5.37d	149.29 ± 6.06b	149.05 ± 1.97b	336.51 ± 11.36a	115.11 ± 5.01c
Chewiness	1.0	97.40 ± 4.85d	165.92 ± 5.70BCE	151.18 ± 7.16c	207.49 ± 4.40a	173.22 ± 6.80b
	2.0	97.40 ± 4.85c	141.02 ± 6.65b	145.90 ± 1.68b	304.31 ± 17.01a	114.25 ± 5.14c
Cohesiveness	1.0	0.99 ± 0.0a	0.96 ± 0.02a	0.98 ± 0.01a	0.98 ± 0.0a	0.96 ± 0.03a
	2.0	0.99 ± 0.0a	0.97 ± 0.0a	0.98 ± 0.01a	0.93 ± 0.02b	0.97 ± 0.01a
Syneresis(%)	1.0	3.57 ± 0.74a	1.64 ± 0.57b	1.15 ± 0.57b	0.84 ± 0.39b	0.64 ± 0.07b
	2.0	3.57 ± 0.74a	1.74 ± 0.48b	1.31 ± 0.51b	0.79 ± 0.31b	0.95 ± 0.35b

Values were presented as Means ± SD of triplicates.
Values with superscript letters a, b, c, and d were significantly different across rows ($P < 0.05$).

after pasting, hardness of which was modified via regeneration.

In this study, addition of any of these four hydrocolloids (1.0% or 2.0%; AG, SA, LG, or GG) increased the hardness and chewiness of kudzu starch-gel complexes (Table 1). It may be due to the rearrangement of gel structure and formation of a stable starch-gel network via the interaction of starch with hydrocolloid matrix (Rong et al., 2022). Hardness of kudzu starch-LG complexes was significantly stronger than other gel matrixes, indicating that LG is a better candidate for hardness improvement. LG may help the formation of more hydrogen bonds between starch and colloidal macromolecules, resulting in greater gel hardness (Gałkowska et al., 2014). Furthermore, it seemed no difference of cohesiveness upon addition of 1% or 2% gum, except slightly decreased cohesiveness with 2.0% LG (Table 1), showing that the effect of these four hydrocolloids on relative crystallinity of kudzu starch may be overlooked.

Overall, the textural properties of kudzu starch were significantly affected by AG, SA, LG or GG. Gels improved the hardness and chewiness, suggesting more dense structure was formed upon addition of any of these gels.

3.4. Dynamic rheological measurements

Solid- and liquid-like properties of kudzu starch-gel complexes were presented with the energy storage modulus (G′) and loss modulus (G″) in Fig. 3, respectively. In all samples, G′ was significantly higher than G″ throughout the 0.1–10 Hz interval. Additionally, no crossover was observed between moduli, indicated that their elastic properties were superior to their viscous properties. Shahzad et al. reported a strong correlation between angular frequency and elasticity, i.e. higher angular frequency along with higher elasticity (G' > G″), in one system composed of starch and hydrocolloid (Shahzad et al., 2019a). For these samples in our study, the dependence of each composite system on frequency was relatively stable, with both G′ and G″ increased with frequency that exhibited solid-like behavior and indicated the formation of weak gels (Sun and Yoo, 2015).

The effect of gum on viscoelasticity was very diverse, similar to what was reported in literature (Shahzad et al., n.d.). Addition of AG

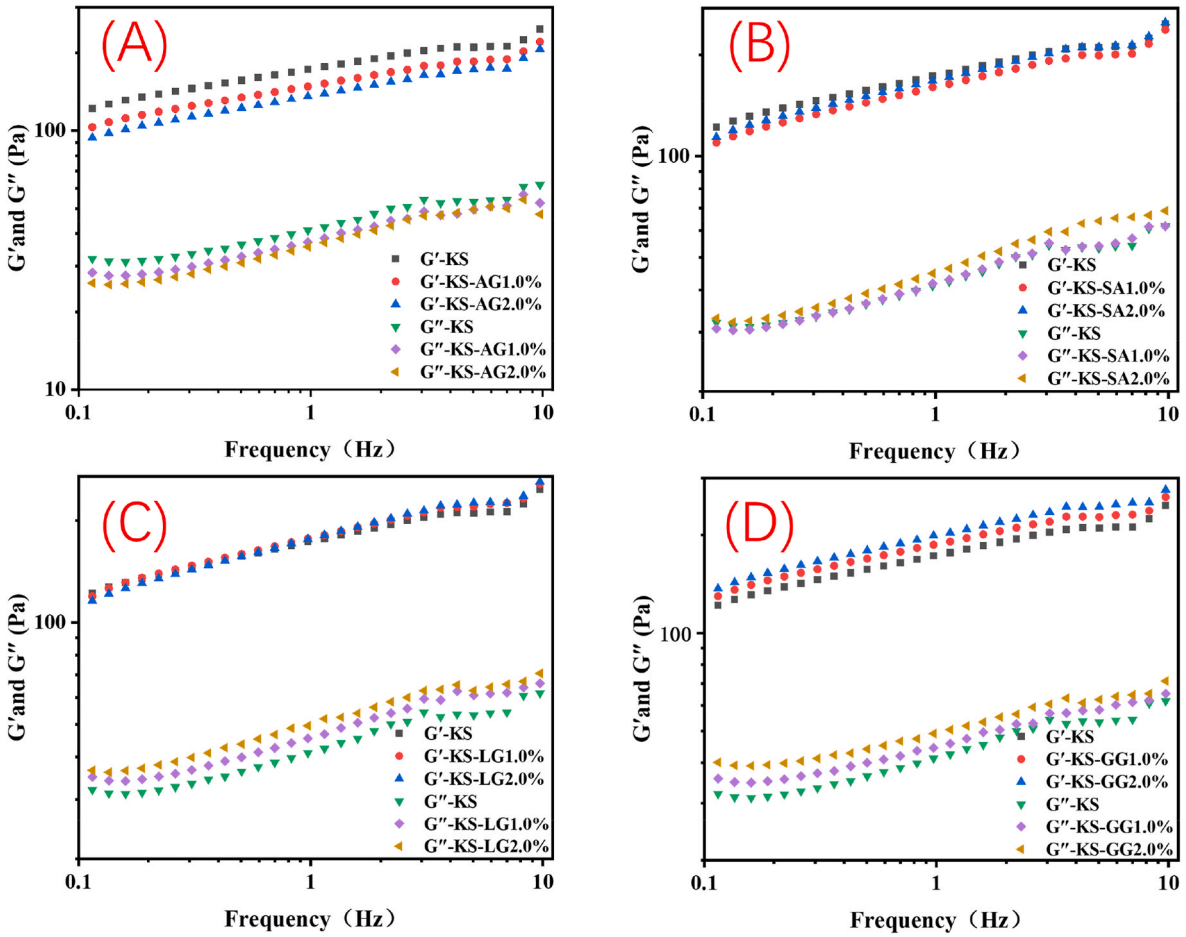

Fig. 3. Storage modulus (G′) and loss modulus (G″) curves of kudzu starch-gel complexes with hydrocolloid at different concentrations: A (Gum arabic); B (Sodium alginate); C (Locust bean gum); D (Guar gum).

significantly decreased G′ and G″, which declined as the concentration of AG increased and was similar to what was observed in chickpea starch-AG (Shahzad et al., 2019b), vanilla starch-AG (Shrivastava et al., 2018) and corn starch-SA (Ji et al., 2017). Lower modulus might be related to higher temperature that causes macromolecular depolymerization.

The presence of GG (1% or 2%) improved the storage and loss moduli of kudzu-GG complexes compared to the Control. SA or 1.0% LG had little effect on the storage modulus (G′), but LG, GG or 2.0% SA increased the loss modulus (G″) of complexes. Modulus levels got even lower along with increased concentrations of in LG and GG.

These results were similar to what was found by Zheng et al. in the system where xanthan gum interacted with kudzu starch, increased the modulus of the kudzu starch-gel system and led to a predominantly elastic behavior (Zheng et al., 2020). In this study, the reason why kudzu starch-GG complexes exhibited strong (high G′) elasticity may be due to the interaction between kudzu and GG molecules (Rong et al., 2022).

3.5. Syneresis properties

During food transportation, stable moisture is critical to maintain the original quality of food. Percentage of dehydration and shrinkage of gels can be used to assess the capability of cold-paste starch to withstand adverse physical changes during freeze-thaw cycles (Charoenrein et al., 2011). Dehydration and shrinkage were mainly caused by regeneration of straight-chain starch, which led to water loss from gel (Saartrat et al., 2005). Dehydration rates of these complexes were shown in Table 1, measured after 22 h of storage at −19 °C.

The dehydration rate of kudzu starch alone after regeneration was at 3.57%, significantly higher than that of complexes: gum arabic (1.64% for 1% AG, 1.74% for 2% AG), sodium alginate (1.15% for 1% SA, 1.31% for 2% SA), locust bean gum (0.84% for 1% LG, 0.78% for 2% LG), and guar gum (0.64% for 1% GG, 0.95% for 2% GG) ($p \leq 0.05$). Slower dehydration and shrinkage indicated that the modified starch-gel complexes had lower regeneration rates, as well as more retained moisture content (Liu et al., 2019a). Dehydration of kudzu starch in this study was significantly lower in the presence of hydrocolloids, which is consistent with one previous study by mixing acacia bean gum and guar gum with water chestnut starch (Lee and Chang, 2015). In another study by Silva Costa and co-workers (Silva Costa et al., 2020), addition of guar gum or xanthan gum resulted in decreased dehydration of bamboo taro starch. However, the opposite effect was also observed when hydrocolloids such as gum Arabic were added to lozenge starch (Lutfi et al., 2017), i.e. faster dehydration rate, which might be due to lower starch content and weaker starch network in the presence of hydrocolloids.

3.6. Gelatinization thermal properties

Transition temperature parameters (To, Tc, and ΔH) represented gelatinization thermal properties of kudzu starch-gel complexes, which were shown in Table 2. In this study, addition of any of these four hydrocolloids altered melting parameters, especially To and Tc. Pasting and swelling of starch were delayed, and pasting temperature after addition of gels was increased, with a higher value of To, Tc and Tc-To. Moreover, the effect of LG was more pronounced. Similar results were reported in other starch systems (Zhang et al., 2018). This phenomenon

Table 2
Effect of hydrocolloids on DSC spectra of kudzu starch-gel complexes.

	Gum (%)	Control	Gum arabic	Sodium alginate	Locust bean gum	Guar gum
T_0(°C)	1.0	54.96 ± 0.04d	55.51 ± 0.03c	55.84 ± 0.01b	56.18 ± 0.06a	55.88 ± 0.02b
	2.0	54.96 ± 0.04d	55.23 ± 0.03c	55.74 ± 0.01b	56.28 ± 0.01a	56.02 ± 0.01a
Tc(°C)	1.0	83.45 ± 0.04c	85.04 ± 0.04b	85.78 ± 0.08b	88.64 ± 0.01a	85.35 ± 0.28b
	2.0	83.45 ± 0.04e	85.1 ± 0.07c	85.67 ± 0.12b	87.45 ± 0.05a	84.15 ± 0.07d
ΔH (J/g)	1.0	2.73 ± 0.01a	2.6 ± 0.01a	2.59 ± 0.01a	2.13 ± 0.02b	2.66 ± 0.01a
	2.0	2.73 ± 0.01a	2.5 ± 0.02b	2.72 ± 0.01a	2.30 ± 0.02c	2.62 ± 0.01 ab

Values were presented as Means ± SD of triplicates.
Values with superscript letters a, b, c, and d were significantly different across rows ($P < 0.05$).

might be due to competition between hydrocolloid and starch for water molecules, therefore delaying the transfer of water to starch (Varela et al., 2016).

Strong hydration capacity of hydrocolloids usually implies poor water mobility and weak water absorption by starch (BeMiller, 2011). RVA measures the increase of viscosity with torque changes after starch gelation, while DSC measures the energy required to melt the starch crystals. Therefore, the onset temperature of starch-gel mixtures measured by DSC is usually relatively lower than the pasting temperature measured by RVA (Shahzad et al., 2019b). The most noticeable decreases of pasting enthalpy (ΔH) were from kudzu starch-LG complexes, with 2.13 J/g for 1% LG and 2.30 J/g for 2% LG (Table 2), respectively. Formation of hydrogen bond between hydrocolloid and leached straight-chain starch might explain decreased enthalpy, which limited internal interactions between branched and straight-chain starch (Tang et al., 2013).

On the other hand, decreased ΔH might imply more complicated pasting or incompletely pasted starch in the presence of hydrocolloid, which was presented as "partially pasted" by Yang and co-workers (Yang et al., 2021). In one study about rice, potato and pea starch, transition temperatures (To, Tc, and ΔH) were significantly descended after addition of konjac mannan. It supported the hypothesis that changes of crystal structure altered thermal stability of starch. However, increased ΔH was found in another study about the incorporation of polysaccharide into wheat starch (Funami et al., 2008). This opposite effect may be attributed to the reduction of chain mobility between starch and polysaccharide, which subsequently required greater thermal energy for starch pasting.

3.7. Microstructure characterization

SEM images were presented with a 1000-time amplification in Fig. 4A1, which included polyhedral, rhombic, spherical and hemispherical particles with smooth surface and without cracks, in line with what was reported in literature (Zhao et al., 2021). Microstructures of kudzu starch and kudzu starch-gel complexes were delivered with a 300-time magnification (Fig. 4 A2-E2). Kudzu starch after pasting was more homogeneous with pores lacking regular shapes (Fig. 4A2). All these starch-gel complexes exhibited porous structures with high percentage of stomata and furrowed surface (Fig. 4B1-E2), which were more organized with a network of pores and skeletons.

Larger pores and thicker walls represented more entanglement among starch fragments (Liu et al., 2019b). Compared to other three hydrocolloids, addition of SA resulted in even larger pores (Fig. 4C1-C2). Addition of LG showed more continuous, tight and fine cracks and pores (Fig. 4D1-D2). Addition of 2.0% GG formed more flabby structure and larger pores (Fig. 4E1-E2), which was consistent with reported structural changes of pea starch after mixed with different hydrocolloids (Rong et al., 2022). Rong et al. also reported that water was re-distributed during storage, and pores facilitated water-locking and reduced water-leaching. In another study, addition of SA or xanthan gum resulted in formation of regular skeleton structure or ice-crystal enlargement after the pasting of corn starch (Zhang et al., 2018). These results showed that addition of hydrocolloid effectively changed the structure of starch.

3.8. Susceptibility of granular- and gelatinized-root starch to glucosidase

Sensitivity of pasted kudzu starch to amyloglucosidase was measured in the absence or presence of gel (Fig. 5, Table S3). Kinetics of starch hydrolysis by amyloglucosidase was presented as biphasic. Glucose content of the Y axis represented how fast starch was hydrolyzed. The general trend was that the hydrolysis rate increased sharply during the first 40 min and then slowed down and got stabilized after 80 min (Fig. 5A–D).

Kudzu starch alone was more susceptible to enzymatic digestion and exhibits a greater increasing rate of glucose production, compared to the starch-gel mixtures at each detected time point. At 20 min, addition of LG, GG or SA significantly reduced the rate of starch hydrolysis, with the lowest glucose content in the presence of 2.0% GG. At 120 min, each of these four hydrocolloids significantly reduced hydrolysis of kudzu starch, with the lowest glucose content detected in the presence of 1.0% LG.

Similar results were reported by Zhou et al. (2020) and Guo et al. (2016), showing kudzu starch was more readily hydrolyzed after pasting than un-pasted starch granules. Zheng and co-workers reported that xanthan gum at higher concentrations effectively hindered the release of glucose during hydrolysis, indicating the potential of xanthan gum to control blood glucose levels (Zheng et al., 2020). In another *in vitro* digestion study of potato starch (Gularte and Rosell, 2011), the decrease of potato-induced (fast degradable starch, RSD) sugar content was positively correlated with the viscosity of guar gum and starch paste. Similarly, SA and GG effectively reduced the GI value (glycemic index) of wheat or whole wheat flour (Jang et al., 2015), and addition of 0.5% AG slowed the digestibility of new rice starch (Jung et al., 2017).

Why hydrocolloid slowed down digestion of dextrinized starch? It may be explained by the hydrophilic nature of hydrocolloid that limits the utilization of water as a substrate for enzymatic reactions, as well as the microencapsulation ability of hydrocolloid to form a barrier between enzyme and starch granules (Jang et al., 2015).

4. Conclusion

In this study, effects of natural gels (AG, SA, LG, GG) on the physical and hydrolysis properties of kudzu starch were systematically investigated for the first time. The particle size of kudzu starch was enlarged with addition of these hydrocolloids, indicating attachment or wrapping of hydrocolloid with starch. In fact, bigger sizes of these starch-hydrocolloid mixtures were consistent with later-on characterized properties.

AG reduced the viscosity of kudzu starch, which may be useful for development of protective coating for confectionery, beverages or food products of kudzu. SA, LG and GG increased kudzu starch-gel viscosity and PT, as well as delaying starch water absorption and disintegration. Kudzu starch-gel mixture exhibited a weak gel-like structure. Strain resistance, elasticity and hardness of kudzu starch were improved by adding GG. AG, SA, LG and GG improved the thermal stability of kudzu starch, and slowed down the heat absorption of starch. LG adjusted pasted kudzu starch with more prominent viscoelasticity, hardness, chewiness, and thermal stability than other gels, indicating that LG may be a more effective player of the modification of kudzu starch. All four hydrocolloids reduced dehydration rates of kudzu starch and improved the water-holding capacity, which was in accordance with their

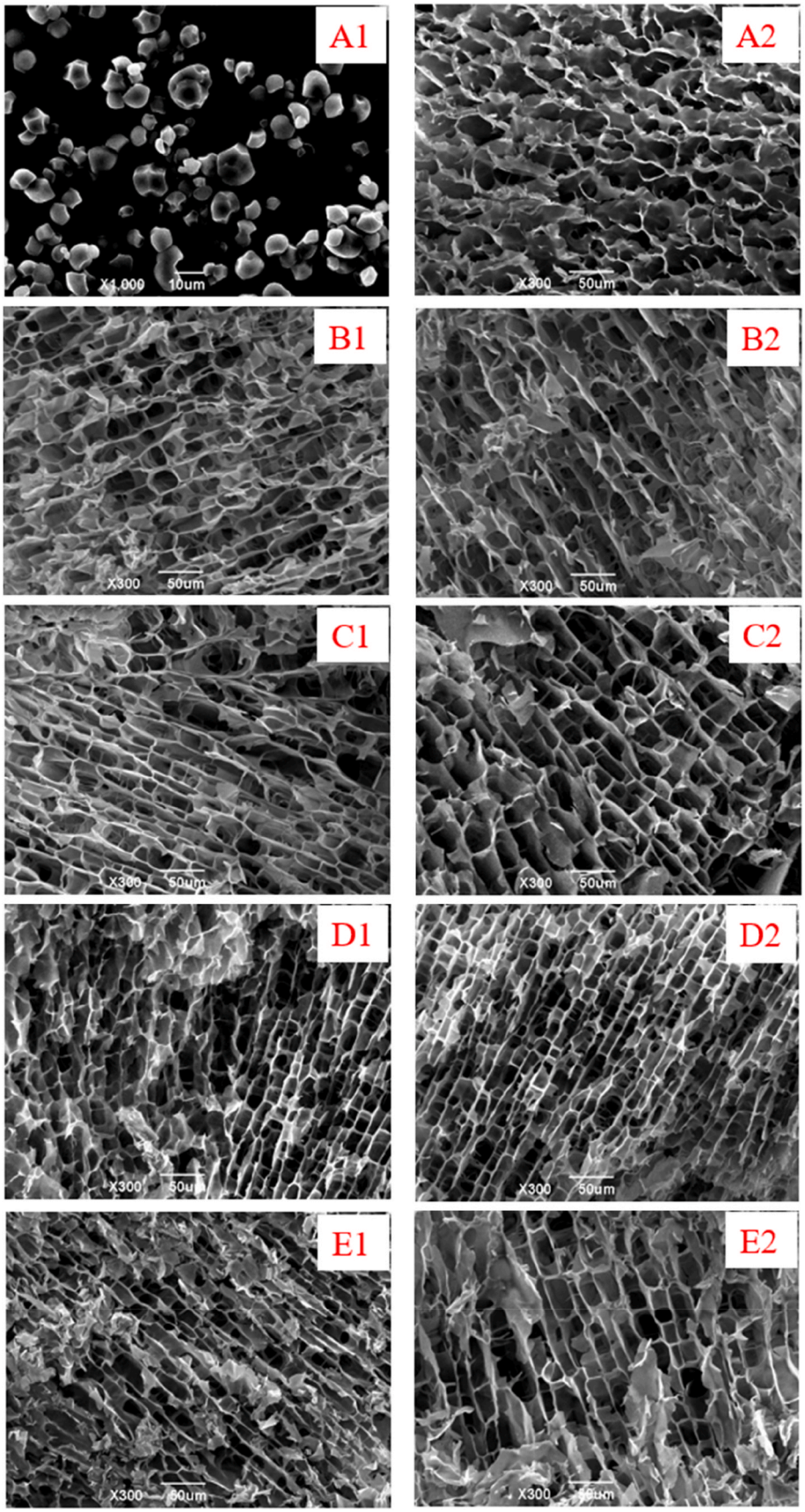

Fig. 4. SEM images of kudzu starch-gel complexes: A1: kudzu granules; A2: kudzu starch alone; B1: 1%AG; B2: 2%AG; C1: 1%SA; C2: 2%SA; D1: 1%LG; D2: 2%LG; E1: 1%GG; E2: 2%GG.

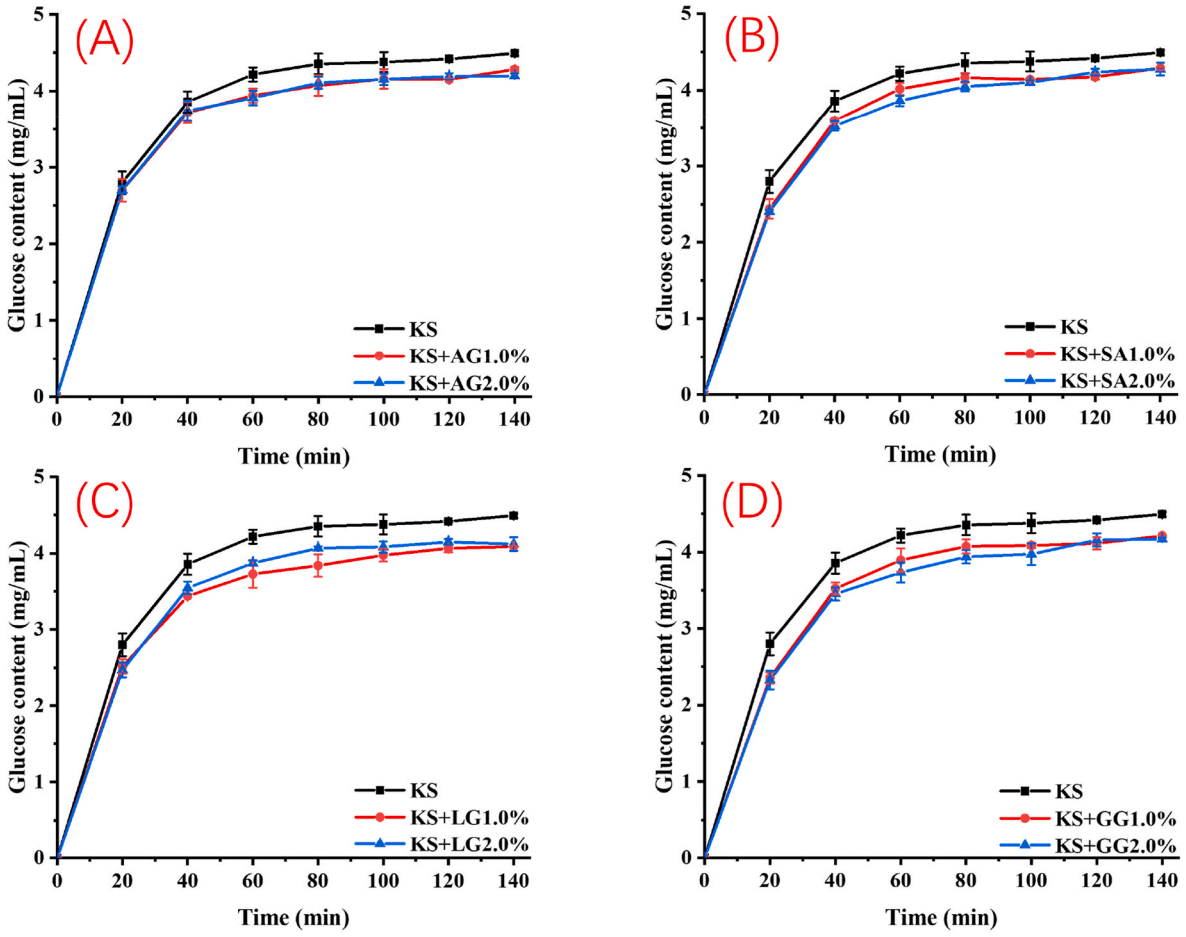

Fig. 5. Hydrolysis of kudzu starch-gel complexs by starch glucosidase: A (Gum arabic); B (Sodium alginate); C (Locust bean gum); D (Guar gum).

capability reducing the sensitivity of kudzu starch to amyloglucosidase and slowed its hydrolysis.

Along with the increasing consumption of kudzu starch by human beings, specific traits of these four hydrocolloids would provide useful information and insights for kudzu product development. Results in this study would also help better understand effects of edible hydrocolloids on starch modification in general, as well as promoting the design of healthy starch food with slower glucose release.

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Authorship contribution statement

Xinming Zhang, Conceptualization, Investigation, Project administration, Writing original draft; Ke Zhang, Software and Methodology; Ning Yang, Characterization, Data curation, Investigation, Visualization; Yaqian Xiao, Data curation, Writing-review, Resources; Yonghong Peng, Writing-review, Resources; Zhigang Han, Data curation, Writing-review; Wei Su, Data curation, Writing-review. Guihong Sun, Responsible for content revision and grammar correction of article; Jun Wang*, Conceptualization, Project administration, Resources, Writing-review & editing.

Declaration of competing interest

No conflict of interest exists in the submission of this manuscript, the research was conducted in the absence of any commercial or financial relationships., and the manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously, and is not under consideration for publication elsewhere, in whole or in part.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crfs.2023.100607.

References

BeMiller, J.N., 2011. Pasting, paste, and gel properties of starch–hydrocolloid combinations. Carbohydr. Polym. 86, 386–423. https://doi.org/10.1016/j.carbpol.2011.05.064.

Charoenrein, S., Tatirat, O., Rengsutthi, K., Thongngam, M., 2011. Effect of konjac glucomannan on syneresis, textural properties and the microstructure of frozen rice starch gels. Carbohydr. Polym. 83, 291–296. https://doi.org/10.1016/j.carbpol.2010.07.056.

Chen, B., Dang, L., Zhang, X., Fang, W., Hou, M., Liu, T., Wang, Z., 2017. Physicochemical properties and micro-structural characteristics in starch from kudzu root as affected by cross-linking. Food Chem. 219, 93–101. https://doi.org/10.1016/j.foodchem.2016.09.128.

Chen, H., Fu, X., Luo, Z., 2015. Effect of gum Arabic on freeze-thaw stability, pasting and rheological properties of tapioca starch and its derivatives. Food Hydrocolloids 51, 355–360. https://doi.org/10.1016/j.foodhyd.2015.05.034.

Chen, T.-R., Shih, S.-C., Ping, H.-P., Wei, Q.-K., 2012. Antioxidant activity and isoflavonoid components in different sections of pueraria lobata root. J. Food Drug Anal. 20, 681–685. https://doi.org/10.6227/jfda.2012200316.

Ferrero, C., 2017. Hydrocolloids in wheat breadmaking: a concise review. Food Hydrocolloids 68, 15–22. https://doi.org/10.1016/j.foodhyd.2016.11.044.

Funami, T., Nakauma, M., Noda, S., Ishihara, S., Asai, I., Inouchi, N., Nishinari, K., 2008. Effects of some anionic polysaccharides on the gelatinization and retrogradation behaviors of wheat starch: soybean-soluble polysaccharide and gum Arabic. Food Hydrocolloids 22, 1528–1540. https://doi.org/10.1016/j.foodhyd.2007.10.008.

Gałkowska, D., Pycia, K., Juszczak, L., Pająk, P., 2014. Influence of cassia gum on rheological and textural properties of native potato and corn starch. Starch - Stärke 66, 1060–1070. https://doi.org/10.1002/star.201400078.

Gularte, M.A., Rosell, C.M., 2011. Physicochemical properties and enzymatic hydrolysis of different starches in the presence of hydrocolloids. Carbohydr. Polym. 85, 237–244. https://doi.org/10.1016/j.carbpol.2011.02.025.

Guo, L., Du, X., 2014. Retrogradation kinetics and glass transition temperatures of *Pueraria lobata* starch, and its mixtures with sugars and salt. Starch - Stärke 66, 887–894. https://doi.org/10.1002/star.201400009.

Guo, L., Hu, J., Zhou, X., Li, X., Du, X., 2016. In vitro digestibility of kudzu starch by using α-amylase and glucoamylase: digestibility of kudzu starch by using enzymes. Starch - Stärke 68, 140–150. https://doi.org/10.1002/star.201500213.

Jang, H.L., Bae, I.Y., Lee, H.G., 2015. In vitro starch digestibility of noodles with various cereal flours and hydrocolloids. LWT - Food Sci. Technol. (Lebensmittel-Wissenschaft -Technol.) 63, 122–128. https://doi.org/10.1016/j.lwt.2015.03.029.

Ji, N., Qiu, C., Xu, Y., Xiong, L., Sun, Q., 2017. Differences in rheological behavior between normal and waxy corn starches modified by dry heating with hydrocolloids: ternary system for increasing solubility and masking bitter tastes. Starch - Stärke 69, 1600332. https://doi.org/10.1002/star.201600332.

Jóźwiak, B., Orczykowska, M., Dziubiński, M., 2018. Rheological properties of kuzu starch pastes with galactomannans. J. Food Sci. Technol. 55, 1575–1581. https://doi.org/10.1007/s13197-018-3047-8.

Jung, D.S., Bae, I.Y., Oh, I.K., Han, S.-I., Lee, S.-J., Lee, H.G., 2017. Classification of hydrocolloids based on in vitro starch digestibility and rheological properties of Segoami gel. Int. J. Biol. Macromol. 104, 442–448. https://doi.org/10.1016/j.ijbiomac.2017.06.063.

Keetels, C.J.A.M., Oostergetel, G.T., Van Vliet, T., 1996. Recrystallization of amylopectin in concentrated starch gels. Carbohydr. Polym. 30, 61–64. https://doi.org/10.1016/S0144-8617(96)00057-4.

Kim, H.-S., BeMiller, J.N., 2012. Effects of hydrocolloids on the pasting and paste properties of commercial pea starch. Carbohydr. Polym. 88, 1164–1171. https://doi.org/10.1016/j.carbpol.2012.01.060.

Lee, Y., Chang, Y.H., 2015. Effects of galactomannan addition on rheological, pasting and physical properties of water chestnut starch: rheology of starch and galactomannan. J. Texture Stud. 46, 58–66. https://doi.org/10.1111/jtxs.12113.

Leloup, V.M., Colonna, P., Ring, S.G., Roberts, K., Wells, B., 1992. Microstructure of amylose gels. Carbohydr. Polym. 18, 189–197. https://doi.org/10.1016/0144-8617(92)90063-V.

Li, H., Cui, B., Janaswamy, S., Guo, L., 2019. Structural and functional modifications of kudzu starch modified by branching enzyme. Int. J. Food Prop. 22, 952–966. https://doi.org/10.1080/10942912.2019.1619576.

Lin, S., Liu, X., Cao, Y., Liu, S., Deng, D., Zhang, J., Huang, G., 2021. Effects of xanthan and konjac gums on pasting, rheology, microstructure, crystallinity and in vitro digestibility of mung bean resistant starch. Food Chem. 339, 128001 https://doi.org/10.1016/j.foodchem.2020.128001.

Liu, D., Li, Z., Fan, Z., Zhang, X., Zhong, G., 2019a. Effect of soybean soluble polysaccharide on the pasting, gels, and rheological properties of kudzu and lotus starches. Food Hydrocolloids 89, 443–452. https://doi.org/10.1016/j.foodhyd.2018.11.003.

Liu, Q., Lawrence, A.J., Liang, J.-H., 2011. Traditional Chinese medicine for treatment of alcoholism: from ancient to modern. Am. J. Chin. Med. 39, 1–13. https://doi.org/10.1142/S0192415X11008609.

Liu, S., Xiao, Y., Shen, M., Zhang, X., Wang, W., Xie, J., 2019b. Effect of sodium carbonate on the gelation, rheology, texture and structural properties of maize starch-Mesona chinensis polysaccharide gel. Food Hydrocolloids 87, 943–951. https://doi.org/10.1016/j.foodhyd.2018.09.025.

Lutfi, Z., Nawab, A., Alam, F., Hasnain, A., Haider, S.Z., 2017. Influence of xanthan, guar, CMC and gum acacia on functional properties of water chestnut (Trapa bispinosa) starch. Int. J. Biol. Macromol. 103, 220–225. https://doi.org/10.1016/j.ijbiomac.2017.05.046.

McClements, D.J., 2017. The future of food colloids: next-generation nanoparticle delivery systems. Curr. Opin. Colloid Interface Sci. 28, 7–14. https://doi.org/10.1016/j.cocis.2016.12.002.

Nawab, A., Alam, F., Haq, M.A., Hasnain, A., 2016. Effect of guar and xanthan gums on functional properties of mango (Mangifera indica) kernel starch. Int. J. Biol. Macromol. 93, 630–635. https://doi.org/10.1016/j.ijbiomac.2016.09.011.

Rong, L., Shen, M., Wen, H., Xiao, W., Li, J., Xie, J., 2022. Effects of xanthan, guar and Mesona chinensis Benth gums on the pasting, rheological, texture properties and microstructure of pea starch gels. Food Hydrocolloids 125, 107391. https://doi.org/10.1016/j.foodhyd.2021.107391.

Saartrat, S., Puttanlek, C., Rungsardthong, V., Uttapap, D., 2005. Paste and gel properties of low-substituted acetylated canna starches. Carbohydr. Polym. 61, 211–221. https://doi.org/10.1016/j.carbpol.2005.05.024.

Sciarini, L.S., Maldonado, F., Ribotta, P.D., Pérez, G.T., León, A.E., 2009. Chemical composition and functional properties of Gleditsia triacanthos gum. Food Hydrocolloids 23, 306–313. https://doi.org/10.1016/j.foodhyd.2008.02.011.

Shahzad, S.A., Hussain, S., Alamri, M.S., Mohamed, A.A., Ahmed, A.S., Ibraheem, M.A., Abdo Qasem, A.A., 2019a. Use of hydrocolloid gums to modify the pasting, thermal, rheological, and textural properties of sweet potato starch. International Journal of Polymer Science 1–11. https://doi.org/10.1155/2019/6308591, 2019.

Shahzad, S.A., Hussain, S., Mohamed, A.A., Alamri, M.S., Ibraheem, M.A., Qasem, A.A.A., 2019b. Effect of hydrocolloid gums on the pasting, thermal, rheological and textural properties of chickpea starch. Foods 8, 687. https://doi.org/10.3390/foods8120687.

Shahzad, S.A., Hussain, S., Mohamed, A.A., Alamri, M.S., Qasem, A., Osman, M.A., n.d. PASTING, THERMAL, TEXTURAL AND RHEOLOGICAL PROPERTIES OF RICE STARCH BLENDED WITH 6 DIFFERENT HYDROCOLLOID GUMS 56, 781–791. https://doi.org/10.21162/PAKJAS/19.6901..

Shrivastava, M., Yadav, R.B., Yadav, B.S., Dangi, N., 2018. Effect of incorporation of hydrocolloids on the physicochemical, pasting and rheological properties of colocasia starch. Food Measure 12, 1177–1185. https://doi.org/10.1007/s11694-018-9731-6.

Silva Costa, R.A., Bonomo, R.C.F., Rodrigues, L.B., Santos, L.S., Veloso, C.M., 2020. Improvement of texture properties and syneresis of arrowroot (*Maranta arundinacea*) starch gels by using hydrocolloids (guar gum and xanthan gum). J. Sci. Food Agric. 100, 3204–3211. https://doi.org/10.1002/jsfa.10356.

Slattery, C.J., Kavakli, I.H., Okita, T.W., 2000. Engineering starch for increased quantity and quality. Trends Plant Sci. 5, 291–298. https://doi.org/10.1016/S1360-1385(00)01657-5.

Song, X., Dong, H., Zang, Z., Wu, W., Zhu, W., Zhang, H., Guan, Y., 2021. Kudzu resistant starch: an effective regulator of type 2 diabetes mellitus. Oxid. Med. Cell. Longev. 2021, 1–15. https://doi.org/10.1155/2021/4448048.

Soni, P.L., Agarwal, A., 1983. The starch of pueraria tuberosa - comparison with maize starch. Starch Staerke 35, 4–7. https://doi.org/10.1002/star.19830350103.

Sun, D., Yoo, B., 2015. Effect of tapioca starch addition on rheological, thermal, and gelling properties of rice starch. LWT - Food Sci. Technol. (Lebensmittel-Wissenschaft -Technol.) 64, 205–211. https://doi.org/10.1016/j.lwt.2015.05.062.

Tang, M., Hong, Y., Gu, Z., Zhang, Y., Cai, X., 2013. The effect of xanthan on short and long-term retrogradation of rice starch. Starch Staerke 65, 702–708. https://doi.org/10.1002/star.201200170.

Varela, M.S., Navarro, A.S., Yamul, D.K., 2016. Effect of hydrocolloids on the properties of wheat/potato starch mixtures: effect of hydrocolloids on the properties. Starch - Stärke 68, 753–761. https://doi.org/10.1002/star.201400257.

Von Borries-Medrano, E., Jaime-Fonseca, M.R., Aguilar-Méndez, M.A., 2019. Tapioca starch-galactomannan systems: comparative studies of rheological and textural properties. Int. J. Biol. Macromol. 122, 1173–1183. https://doi.org/10.1016/j.ijbiomac.2018.09.067.

Xiao, W., Shen, M., Ren, Y., Rong, L., Liu, W., Chen, X., Yang, J., Li, J., Xie, J., 2021. Mesona chinensis polysaccharides promote molecular crosslinking and gel formation of debranched waxy maize starch. LWT 148, 111773. https://doi.org/10.1016/j.lwt.2021.111773.

Yang, K., Luo, X., Zhai, Y., Liu, J., Chen, K., Shao, X., Wu, X., Li, Y., Chen, Z., 2021. Influence of sodium alginate on the gelatinization, rheological, and retrogradation properties of rice starch. Int. J. Biol. Macromol. 185, 708–715. https://doi.org/10.1016/j.ijbiomac.2021.06.207.

Zhang, Y., Gu, Z., Zhu, L., Hong, Y., 2018. Comparative study on the interaction between native corn starch and different hydrocolloids during gelatinization. Int. J. Biol. Macromol. 116, 136–143. https://doi.org/10.1016/j.ijbiomac.2018.05.011.

Zhang, Z., Lam, T.-N., Zuo, Z., 2013. Radix *puerariae* : an overview of its Chemistry, pharmacology, pharmacokinetics, and clinical use: the journal of clinical pharmacology. J. Clin. Pharmacol. 53, 787–811. https://doi.org/10.1002/jcph.96.

Zhao, Y., Zhu, X., Fang, Y., 2021. Structure, properties and applications of kudzu starch. Food Hydrocolloids 119, 106817. https://doi.org/10.1016/j.foodhyd.2021.106817.

Zheng, Y., Sun, W., Yang, W., Chen, S., Liu, D., Tian, J., Ye, X., 2020. The influence of xanthan gum on rheological properties and in vitro digestibility of kudzu (*Pueraria lobata*) starch. Starch - Stärke 72, 1900139. https://doi.org/10.1002/star.201900139.

Zhou, S., Hong, Y., Gu, Z., Cheng, L., Li, Z., Li, C., 2020. Effect of heat-moisture treatment on the in vitro digestibility and physicochemical properties of starch-hydrocolloid complexes. Food Hydrocolloids 104, 105736. https://doi.org/10.1016/j.foodhyd.2020.105736.