

From binary to ternary: Synergistic interplay of guar gum and corn oil in glutinous rice/hydroxypropyl starch gels

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Abstract

This study investigated the influence of varying guar gum concentrations and corn oil addition on structural characteristics, rheological behavior, and multi-component interactions within glutinous rice starch (GRS)/ hydroxypropyl starch (HPS) blended gels. The results showed that guar gum incorporation promoted the formation of intramolecular and intermolecular hydrogen bonds, which disrupted short-range ordered structures and crystal structure. Consequently, gel texture was improved, as evidenced by an increase in springiness from 1.49 to 1.96, and water-holding capacity was enhanced, with T_{21} rising from 3.13% to 4.75%. The introduction of corn oil further weakened the short-range ordered structures and crystal integrity (with ΔH dropping from 8.92 to 5.90 J·g⁻¹). The gel prepared by the combined addition of guar gum and corn oil demonstrated enhanced elasticity and rigidity, and its deformation resistance and rapid recovery from shear deformation were significantly improved. These findings provide new insight into the interaction mechanisms underlying the GRS/HPS-guar gum-corn oil system.

1. Introduction

Starch-based composite materials have attracted growing interest in food research due to their ability to modulate texture, stability, and nutritional properties. Glutinous rice starch (GRS), in particular, is highly valued for its high viscosity, porous structure, and good water stability, making it suitable for a wide range of food formulations. However, when repeatedly frozen and thawed during storage or transportation, GRS gel foods often have several undesirable presentations, including moisture loss, cracking and surface collapse (Zhang et al., 2024). To overcome these limitations, a dual modification strategy-combining chemical modification with the physical blending of hydrocolloids-has emerged as a promising approach. Hydroxypropyl starch (HPS) is a modified starch that is considered safe, where a portion of the original hydroxyl groups have been replaced by hydroxypropyl groups. These large groups create steric hindrance, thereby preventing starch retrogradation (Jia et al., 2022).

The incorporation of hydrocolloids, such as guar gum (GG), is a well-established method for modulating the rheological characteristics of starch. The molecular structure of GG consists of d-mannose units, and its main chain is linked via β -1,4-glycosidic bonds (Zhang et al., 2024). GG possesses numerous branched structures and strong hydrogen bonding activity, endowing it with exceptional hydration capacity (Achayuthakan & Supphantharika, 2008). The presence of GG may interfere with water-starch interactions, leading to lower molecular mobility in the system and inhibited complexation of amylose and amylopectin. In addition, they may also interact with starch through van der Waals force and hydrogen bonding interaction, hindering their rearrangement (Huang et al., 2025).

Lipids are commonly found in starchy foods and are frequently used as additives to inhibit starch aging (Wang, Yan, Li, Chen, Gu, & Zhang, 2025). Free fatty acids interact with starch to form fatty acid-starch complexes, with fatty acids embedding into the hydrophobic cavities of the amylose helical structure through hydrophobic interactions (Chen et al., 2025; Sun et al., 2021). Corn oil (CO) has high nutritional value and contains tocopherols and plant sterols, which are natural antioxidants with anti-cancer, anti-

inflammatory, and other biological activities (Wang et al., 2025). The primary fatty acids in CO are linoleic acid (39–63%), oleic acid (20–42%), and palmitic acid (9–17%) (Stamenkovic et al., 2020). Lan et al. (2024) enhanced water-holding capacity through the combined addition of soybean oil and soybean polysaccharides, demonstrating the greatest aging inhibition effect on corn starch. This suggests that the combined application of oil and polysaccharides possesses great potential in retarding the retrogradation of starch-based products. Our previous work demonstrated that blending HPS and GRS at an appropriate ratio can significantly improve the gel properties and anti-aging performance of the starch gel (Huang et al., 2026). However, a deeper understanding of the detailed mechanisms governing the interactions between GG and GRS/HPS, as well as the effects of GG-CO combined addition on the structural characteristics and gelation properties of the GRS/HPS system, remains elusive. The regulatory mechanism and interaction within the starch-GG-CO ternary system also remain unclear.

This study examined how different levels of GG (0%, 0.5%, 1% and 1.5%) along with combinations of GG alone and GG-CO together, influenced multicomponent interactions, structural properties, gel behavior, anti-aging effects, and rheological characteristics in the GRS/HPS system. The findings help clarify how components interact in the GRS/HPS-GG-CO ternary system and offer new strategies for retarding starch retrogradation.

2. Material and methods

2.1 Material

HPS (model 240601) was sourced from Foshan Guonong Starch Co., Ltd. (Guangdong, China). It features a dry hydroxypropyl content of 3.50%, a molecular weight (M_w) of 1.74×10^6 g/mol, and an amylose fraction of roughly 18.18%, while its lipid, protein, and ash contents are each below 1.00%, and moisture is maintained at less than 13.00%. GRS (product code JNSL), supplied by Wuxi Jinnong Biotechnology Co., Ltd. (Jiangsu, China), presents a higher M_w of 1.97×10^6 g/mol alongside a markedly lower amylose level of 5.32%. Its compositional profile includes 0.68% protein, 0.11% lipids, 0.15% ash, and 7.86% moisture. CO was procured from Yihai Kerry Arawana Holdings Co., Ltd., based in Shandong, China. GG powders were both food-grade, with the M_w of 220 kDa and the purity of 84.70%, purchased from Zhengzhou Yufan Biotechnology Co., Ltd. (Henan, China). Fluorescein-5-isothiocyanate (FITC), Calcofluor white, and Nile Red were obtained from Congyuan Instrument Co. Ltd. (Guangdong, China). Distilled water was used in the experiment.

2.2 Sample preparation

A suspension containing 33 wt% solid content was made by dissolving a specific portion of the GRS/HPS mixture (3:7 ratio) in water. This suspension was then stirred for 2 min at 3000 rpm using the blender (KITCHEN IDEA, K2102, Zhejiang Tianshuo Yunchu Technology Co., Ltd., Zhejiang, China) to ensure proper dispersion. GG was then slowly added to the suspension to reach final concentrations of 0%, 0.5%, 1%, and 1.5% (w/v) in the system, followed by stirring at 4000 rpm for 2 min to achieve

complete dispersion and hydration. Finally, the mixture solution was heated to 95°C and stirred at 3000 rpm for 5 min to obtain GG- GRS/HPS gel samples. Following the same procedure, after adding GG at different concentrations, an additional 7.5% (w/w) CO was incorporated and stirred at 4000 rpm for 1 min. Subsequently, the same heating gelatinization process to obtain starch gels with GG-CO combined addition.

2.3 Structural properties

2.3.1 Short-range ordered structure

After rapid freezing in liquid nitrogen, the samples were freeze-dried and ground. The spectral characteristics of the sample's functional groups were examined using the attenuated total reflection Fourier transform infrared spectrometer (Nicolet IS50, ThermoFisher Corp., Waltham, MA, USA). Spectra were recorded 64 times from 4000 to 400 at 4 cm⁻¹ resolution, with air used as the background reference. Gaussian fitting was used to analyze the types and relative strengths of hydrogen bonds in the gel (Pan, Qi, Huang, Shen, Wen, & Xie, 2024).

2.3.2 Long-range ordered structure

Samples were analyzed using X-ray diffraction (XRD) with a PANalytical diffractometer (Almelo, Netherlands). Measurements were carried out over a 2 θ range of 4°-40° at a scanning speed of 12°/min. Relative crystallinity was determined by dividing the crystalline peak area by the total diffractogram area.

2.3.3 Thermal performance

A differential scanning calorimeter (DSC-Q100, TA Instruments, New Castle, DE, USA) was used to determine the thermal properties of the samples. 10 mg of mixture was sealed in an aluminum crucible, then allow it to equilibrate at 4°C for 12 h. Heating was carried out from 45 to 95°C at a rate of 10°C/min (Li et al., 2024). Empty crucible was used as the reference.

2.3.4 Scanning electron microscope (SEM)

A scanning electron microscope (S4800, Hitachi Ltd., Tokyo, Japan) was used to examine the microstructure of the samples at $\times 12,000$ magnification and 5.0 kV accelerating voltage. The cross sections of the freeze-dried gel were first coated with a thin gold layer before observation.

2.3.5 Confocal laser scanning microscope (CLSM)

The structure of samples was further examined using a confocal laser scanning microscope (LSM900, Zeiss, Jena, Germany). The samples were stained with FITC, Calcofluor white, and Nile Red solutions. FITC selectively labeled starch green, Calcofluor white selectively labeled GG blue, and Nile Red selectively labeled corn oil red. Approximately 50 mg sample was collected and transferred to a tube. Then, 50 μ l of FITC, Calcofluor white, and Nile red were added to the tube, followed by mixing for 1 min. After staining, the sample was transferred onto a microscope slide, sealed using aluminum foil (Gu et al.

2025). Following a 12 h equilibration at 25°C, the gel microstructures were observed under fluorescence mode using a 40× objective lens.

2.4 Gelation characteristics

2.4.1 Texture profile analysis (TPA)

10.00 g of each sample was placed into 10 mL beakers and stored at 4°C for 24 hours prior to TPA. A texture analyzer (TA-XT2i, Stable Microsystems Ltd., Surrey, UK) was used to perform the TPA. The test was conducted with the following settings: probe of P/0.25S, trigger force of 2 g, compressive strain of 30%, compression duration of 5 s, pre-test/test speed of 1 mm/s, and recovery distance of 2 cm. Four texture parameters, including hardness, springiness, cohesiveness, and resilience were recorded.

2.4.2 Water distribution

Water distribution was determined using a low-field nuclear magnetic resonance analyzer (MesoMR23-060H-1, Newman Technology Co., Ltd, Jiangsu, China). The transverse relaxation time of the samples was measured using the Carr-Purcell-Meiboom-Gill (CPMG) mode after performing water film correction in free induction decay (FID) mode.

Proton density images of samples were obtained using Magnetic Resonance Imaging software, with the FOV Read and FOV Phase of 50 mm, TE of 20 ms, and slice width of 3.0 mm.

2.5 Rheological behavior

Rheological characteristics of samples was characterized using the rheometer (MCR 102, Anton Paar, Austria). The rheometer is equipped with PP25 parallel plates and a plate gap of 1.0 mm.

2.5.1 Frequency sweep

Frequency sweeps were performed to assess the elastic modulus (G' , Pa) and viscosity modulus (G'' , Pa), using angular frequencies between 0.1 and 100 rad/s and a strain of 1%.

2.5.2 Flow behavior test

The apparent viscosity of the samples was investigated within the shear rate interval from 0.1 to 100 s⁻¹.

2.5.3 Creep and recovery test

Creep and recovery strains were determined based on the method of Yang, Zhang, Weng, Jiao, & Jin (2025), with minor modifications. For the creep recovery scanning, the test conditions were set by applying a constant stress of 50 Pa to the samples for 50 s. After this, the stress was stopped, and the samples were given 60 seconds to recover.

2.5.4 Three-interval thixotropy test

The stability of the samples was evaluated using a three-interval thixotropy test. This test was performed at 25°C. Samples were first sheared at a low rate of 1 s⁻¹ for 80 s, followed by a high-shear step at 100 s⁻¹ for 20 s. Finally allowed to recover under shear rate of 1 s⁻¹ for 40 s.

2.5.5 Large-amplitude oscillatory shear (LAOS)

Strain sweep tests were conducted over a 1-1000% strain range at 0.5 Hz. Lissajous curves were generated by processing the data with Rheoplus software, illustrating the stress-strain relationship throughout each oscillation cycle. Based on the nonlinear strain response, the elastic and viscous components were separated using the theoretical decomposition method. Following the principles of Lissajous figures, these components were then used to construct the elastic (stress-strain) and viscous (stress-shear rate) Lissajous plots.

2.6 Statistical analysis

All experiments were replicated three times to ensure reproducibility. Data are reported as mean ± standard and were subjected to one-way ANOVA using SPSS 21.0 (SPSS Inc., Chicago, IL, USA). Differences were deemed significant at $p < 0.05$.

3. Results and discussion

3.1 Structural properties

3.1.1 Short-range ordered structure

The structures of the samples were characterized by FTIR spectroscopy (Fig. 1a). The FTIR spectra of both the GG-only and GG-CO samples exhibited comparable peak positions and shapes, implying that no new chemical compounds were formed. Across all spectra, the 990–1030 cm⁻¹ peak corresponded to O = C stretching vibration in the glucose ring, while the peak at 2920 cm⁻¹ corresponded to C-H stretching vibration (Zhao et al., 2023). A strong absorption peak at 1648 cm⁻¹ indicated the presence of carboxyl groups (Zhong et al., 2024). In the GG-only samples, a significant redshift was observed in the O-H stretching vibrations at 3000–3700 cm⁻¹, shifting from 3319 cm⁻¹ to 3299 cm⁻¹ with increased intensity as the GG proportion rose. This suggested that hydrogen bonds were formed between GG and starch, and the number of hydrogen bonds in the system increased with rising GG concentration. This could be attributed to primary and secondary hydroxyl groups on GG's outer branches, which readily interact with starch. (Xu, Ye, Zuo, & Fang, 2022). Samples with combined GG-CO addition exhibited three additional absorption peaks at 1745 cm⁻¹, 2850 cm⁻¹, and 3010 cm⁻¹. Two characteristic absorption peaks, located at 1745 cm⁻¹ and 2850 cm⁻¹, were assigned to the C = O stretching vibration of triglycerides (Chen et al., 2021) and the asymmetric stretching vibrations of -CH₃ and -CH₂ fatty acids (Wang, Wu, Wang, Yang, & Zhou, 2019). The peak at 3010 cm⁻¹, identified as the C-H stretching vibration associated with C = C double bonds in triglycerides, was detected (Zhang et al., 2024). For the GG-CO combined samples, the O-H stretching band (3000–3700 cm⁻¹) underwent a marked redshift with increasing GG concentration, a

phenomenon similarly observed in samples with only GG added. This peak shifted from 3336 cm^{-1} to 3320 cm^{-1} , indicating enhanced hydrogen bonding strength. Notably, the GG-CO combined samples exhibited narrower and weaker absorption bands in the range of 3000–3700 cm^{-1} compared with the samples with only GG added, indicating a reduction in the number of free -OH in the GRS/HPS matrix.

Gaussian fitting was used to examine specific types of hydrogen bonds (Table 1). As the GG ratio increased, the relative strength of intermolecular hydrogen bonds ($\text{OH}\cdots\text{O}$ and $\text{OH}\cdots\pi$) and intramolecular hydrogen bond ($\text{OH}\cdots\text{OH}$) grew, while the quantity of free hydroxyl groups decreased. The relative strength of intermolecular and intramolecular hydrogen bonds in samples with only GG added increased from 48.72% and 37.92% to 49.73% and 39.58%, while the free hydroxyl content dropped from 13.36% to 10.69%. A more pronounced shift was observed in the GG-CO combined samples, where intermolecular and intramolecular hydrogen bonds increased from 65.10% and 21.91% to 66.43% and 23.60%, accompanied by a decrease in free hydroxyl groups from 12.99% to 9.97%. This suggested that the addition of GG promoted more compact arrangement of starch molecules and conversion of free hydroxyl groups into other hydrogen bond types. Pan et al. (2024) reported that GG introduced extra hydrogen bond donors or acceptors, which facilitated the formation and reinforcement of hydrogen bonds in starch molecules. This conclusion was consistent with the results of our result. The GG-CO combined samples displayed enhanced intermolecular hydrogen bonds relative to the samples with GG-only added. This finding reinforced the notion that the presence of CO encouraged the development of intermolecular hydrogen bonds in the system.

FTIR spectra in the 800–1200 cm^{-1} were subjected to deconvolution (Fig. 1b). The ratios of 1048/1022 cm^{-1} ($R_{1048/1022}$) and 995/1022 cm^{-1} ($R_{995/1022}$) were calculated to evaluate the order and double helix structure of the starch molecules, respectively (Table 2). As the GG content increased, the $R_{995/1022}$ values of samples with only GG added and samples with GG-CO combined added slightly decreased from 1.06 and 1.07 to 0.96 and 0.96, respectively, with no significant difference. The $R_{1048/1022}$ decreased from 0.50 and 0.47 to 0.46 and 0.42, respectively. The $R_{1048/1022}$ of the samples with GG-CO combined addition were significantly lower than that of the samples with only GG added. While the addition of GG alone perturbed the ordered structure, the combined GG-CO system exerted a more pronounced effect, not only further disrupting the ordered structure but also reducing starch crystallinity.

Table 1
Hydrogen bond fitting results of starch gels with only GG added and GG-CO combined addition.

Samples	Hydrogen bond type	Abbreviations	Wavenumber(cm ⁻¹)	Relative strength (%)	
0% Guar	Intermolecular hydrogen bond	OH...O	3138	6.41	48.72
		OH...π	3373	42.31	
	Intramolecular hydrogen bond	OH...OH	3250	37.92	
	Free hydroxyl	-OH	3469	13.36	
0.5% Guar	Intermolecular hydrogen bond	OH...O	3101	2.51	48.92
		OH...π	3351	46.41	
	Intramolecular hydrogen bond	OH...OH	3206	38.57	
	Free hydroxyl	-OH	3503	12.51	
1% Guar	Intermolecular hydrogen bond	OH...O	3103	2.55	48.78
		OH...π	3350	46.23	
	Intramolecular hydrogen bond	OH...OH	3203	39.12	
	Free hydroxyl	-OH	3504	12.10	
1.5% Guar	Intermolecular hydrogen bond	OH...O	3126	4.88	49.73
		OH...π	3384	44.85	
	Intramolecular hydrogen bond	OH...OH	3244	39.58	
	Free hydroxyl	-OH	3511	10.69	
0% Guar + CO	Intermolecular hydrogen bond	OH...O	3130	2.56	65.10
		OH...π	3364	62.54	
	Intramolecular hydrogen bond	OH...OH	3232	21.91	
	Free hydroxyl	-OH	3491	12.99	
0.5% Guar + CO	Intermolecular hydrogen bond	OH...O	3131	2.15	65.28
		OH...π	3359	63.13	
	Intramolecular hydrogen bond	OH...OH	3224	22.83	

Samples	Hydrogen bond type	Abbreviations	Wavenumber(cm ⁻¹)	Relative strength (%)	
	Free hydroxyl	-OH	3500	11.89	
1% Guar + CO	Intermolecular hydrogen bond	OH...O	3119	2.53	65.81
		OH...π	3364	63.28	
	Intramolecular hydrogen bond	OH...OH	3218	23.17	
	Free hydroxyl	-OH	3517	11.02	
1.5% Guar + CO	Intermolecular hydrogen bond	OH...O	3140	3.90	66.43
		OH...π	3378	62.53	
	Intramolecular hydrogen bond	OH...OH	3237	23.60	
	Free hydroxyl	-OH	3517	9.97	

Table 2

The short-range ordered structure and thermodynamic properties of starch gels with only GG added and GG-CO combined addition.

0% Guar	R _{995/1022}	R _{1048/1022}	To/°C	Tp/°C	Tc/°C	ΔH/J·g ⁻¹
	1.06 ± 0.02^a	0.50 ± 0.04^a	53.52 ± 0.57^a	69.81 ± 0.23^c	79.54 ± 0.14^c	8.92 ± 0.03^a
0.5% Guar	1.05 ± 0.02 ^a	0.47 ± 0.02 ^{ab}	53.97 ± 0.30 ^a	69.99 ± 0.45 ^{bc}	80.76 ± 0.32 ^{abc}	7.87 ± 0.70 ^a
1% Guar	1.04 ± 0.03 ^a	0.48 ± 0.03 ^a	54.08 ± 0.85 ^a	70.55 ± 0.55 ^{abc}	81.04 ± 0.03 ^{ab}	7.32 ± 0.88 ^{abc}
1.5% Guar	0.96 ± 0.05 ^a	0.46 ± 0.00 ^{ab}	54.62 ± 0.23 ^a	71.49 ± 0.48 ^{ab}	81.56 ± 0.58 ^a	6.01 ± 1.30 ^{bc}
0% Guar + CO	1.07 ± 0.01 ^a	0.47 ± 0.03 ^{ab}	53.50 ± 0.50 ^a	70.28 ± 0.94 ^{abc}	79.87 ± 0.41 ^{bc}	8.63 ± 0.59 ^a
0.5% Guar + CO	1.02 ± 0.05 ^a	0.43 ± 0.01 ^b	54.35 ± 0.08 ^a	70.95 ± 0.94 ^{abc}	81.02 ± 0.77 ^{ab}	7.76 ± 0.79 ^{ab}
1% Guar + CO	1.00 ± 0.09 ^a	0.43 ± 0.01 ^b	54.85 ± 0.32 ^a	71.30 ± 0.49 ^{abc}	81.09 ± 0.82 ^{ab}	7.27 ± 0.49 ^{abc}
1.5% Guar + CO	0.96 ± 0.08 ^a	0.42 ± 0.01 ^b	54.90 ± 1.01 ^a	71.75 ± 0.42 ^a	81.59 ± 0.34 ^a	5.90 ± 0.34 ^c

Data are expressed as the mean $\pm$ standard deviation ($n = 3$). Means annotated with different letters (a-c) within the same column are significantly different ($p < 0.05$).

3.1.2 Long-range ordered structure

Figure 1c presented the XRD patterns of the GRS/HPS starch gel samples with only GG added and GG-CO combined addition. All samples exhibited characteristic diffraction peaks near 15° , 17° , 18° , 20° , and 23° . The peak appearing at 20° represented the crystalline region of GG, and all samples displayed a typical A-type crystal structure (Pan, Liu, Li, Chen, Yu, & Xie, 2023). As the GG ratio increased, no new diffraction peaks were detected, indicating that adding GG did not alter the crystal structure of the composite starch gel. As the GG proportion increased, the crystalline peaks in the XRD spectrum gradually diminished. When the GG content reached 1.5%, the samples exhibited a near-complete loss of crystalline order. As the GG proportion increased, the relative crystallinity of the sample with only GG added decreased from 3.15% to 0.54%, while the sample with GG-CO combined added decreased from 2.46% to 0.40%. This decrease in relative crystallinity can be explained to the disruption of the arrangement ordered structure caused by the addition of GG (Table 2). And intermolecular interactions between GG and amylose and amylopectin molecules of GRS/HPS that further inhibited the formation of new crystalline structures (von Borries-Medrano, Jaime-Fonseca, & Aguilar-Méndez, 2016). Furthermore, highly hydrophilic colloids may reduce the available water for starch molecules, hindering recrystallization and lowering relative crystallinity (Fu, Zhang, Chen, Peng, & Kan, 2025). The relative crystallinity of the samples with GG-CO combined addition were slightly lower than that of the samples with only GG added. This may be attributed to interactions between starch and lipids, which disrupted hydrogen bond formation between amylopectin chains (Dun, Liang, Li, Li, & Geng, 2021). This aligns with the observations of Wang, You, Ke, Wu, Lao, & Zhao (2025), who proposed that the long carbon chains of fatty acids in oil interfere with the lattice organization of starch polymers, thus preventing the formation of long-range helical structures.

3.1.3 Thermal properties

The gelatinization enthalpy (ΔH), onset temperature (T_o), peak temperature (T_p), and conclusion temperature (T_c) were summarized in Table 2, and the DSC curve displayed in Fig. 1d. The T_o , T_p , and T_c of the sample without added GG and CO were the lowest, at 53.52°C , 69.81°C , and 79.54°C , respectively. As the GG proportion increased, a slight shift to higher temperatures was observed, indicating a gradual rise in gelatinization temperature. When the GG content was 1.5%, the T_o increased to 54.62°C without significant difference, while T_p and T_c significantly increased to 71.49°C and 81.56°C , respectively. Samples with GG-CO combined addition exhibited consistent trend. The T_o , T_p , and T_c increased from 53.50°C , 70.28°C , and 79.87°C to 54.90°C , 71.75°C , and 81.59°C , respectively. This may be due to GG exhibiting higher solubility at lower temperature, leading to increased system viscosity. With higher viscosity, the movement and rearrangement of starch granules face greater resistance, requiring a higher temperature to break through, thus raising the gelatinization temperature (Dong et al., 2025). Compared with the samples with only GG added, the T_o , T_p , and T_c of the samples with GG-CO combined addition showed increase without significant differences. This may be attributed to CO coating the starch granule surface,

restricting water penetration into the granules. This reduced solubility and dissolution capacity of starch, thereby inhibiting starch gelatinization. Dai et al. (2025) found that defatting starch reduced its gelatinization temperature. Research has found that lipids exerted little influence on starch gelatinization temperature, but it reduced the enthalpy of heat (Dun, Liang, Li, Li, & Geng, 2021).

The ΔH value decreased significantly with increasing GG ratio. For the samples with only GG added, the ΔH significantly decreased from 8.92 J/g to 6.01 J/g. For the samples with GG-CO combined added, it markedly decreased from 8.92 J/g to 5.90 J/g. This may be attributed to the disruption of ordered structures (Table 2) and decrease in crystallinity (Fig. 1c). These results demonstrated that the addition of GG-CO combination effectively reduced ΔH and diminished the crystalline integrity of the samples significantly.

3.1.4 SEM

The microstructure of samples with only GG added and GG-CO combined addition were shown in Fig. 2a-h. The microstructure of the sample without added GG and CO (Fig. 2a) showed a honeycomb-like network structure with limited pore count. Pores showed uneven size and spatial distribution, with maximum apertures reaching 3.2 μm . As the GG proportion increased, the connections between starches became stronger, leading to smaller pore sizes and the formation of a continuous, ordered network structure. (Fig. 2b-d). When the GG content reached 1.5%, the gel network structure became denser, the number of pores increased significantly, the inner wall of pores became thinner, and the pore size in the network structure was significantly reduced to 0.1–0.4 μm . This may be attributed to stronger hydrogen bonds within the system and intermolecular interactions between GG and the amylose and amylopectin chains of GRS/HPS during gelation (Lu, Chan, Li, & Li, 2025). The highly flexible molecular structure of GG may also play a role, as its galactose side chains can become more tightly intertwined with GRS/HPS amylose and amylopectin chains through topological entanglement. This physical interlocking effectively reduces the distance between molecules. They together formed an interpenetrating three-dimensional polymer network throughout the entire system. The network structure of the samples with GG-CO combined addition became denser with the increase of GG ratio. Interestingly, the surface of the GG-CO combined samples was shinier, which may be due to the adhesion of oil. (Zhai et al., 2025). The surface of the sample with only CO added (Fig. 2e) showed obvious oil droplets attached. As the GG proportion increased, the CO particle size decreased, and the oil droplets gradually filled the network voids, making the surface smooth and uniform. This could be ascribed to the emulsifying behavior of GG, which adsorbed at the oil-water interface to reduce interfacial tension. Its hydrophilic moieties formed strong hydrogen bonds with water molecules, while the hydrophobic moieties interacted with the oil droplet surfaces to form a stable film, thereby minimizing droplet aggregation and coalescence. Another possible reason was that GG increased the viscosity of the system, effectively reducing the aggregation and collision of oil droplets. The samples with GG-CO combined addition showed slightly larger pores than the samples with only GG added. This may be attributed to oil droplets potentially inserting between the GRS/HPS and GG molecular chains,

affecting the tightness of intermolecular bonds. Consequently, the originally compact network structure became slightly loosened, leading to an increase in network porosity.

3.1.5 CLSM

CLSM images can be used to visualize the distribution of starch, GG, and oil droplet components within the sample. The CLSM images of the samples were shown in Fig. 2a1-h1. The GRS/HPS molecules of the sample without GG were uniformly stained green (Fig. 2a1), indicating complete gelatinization of starch and the presence of individual larger pores on the surface. GG was stained blue and embedded in the GRS/HPS matrix. With the addition of GG, a cyan zone (between green and blue) observed in the mixture of GG and starch (Fig. 2b1-d1 and Fig. 2f1-h1), indicating that GG has interacted with starch. As the GG ratio increased, the system showed a stronger cyan, and the blue area gradually expanded. This further demonstrated the physical entanglement between GG and GRS/HPS molecular chains, which insert and cross-link with each other, thereby promoting the formation of a denser gel matrix. Bright green represented ungelatinized starch granules. When the GG addition reached 1.5%, the number of ungelatinized starch granules gradually increased, suggesting that GG suppressed starch gelatinization, which agreed with the DSC results. In the GG-CO samples with 0% GG, numerous red oil droplets with uneven size were observed, matching the large droplets seen in the SEM. After adding GG, it can be observed that oil droplets did not aggregate with GRS/HPS or GG. Instead, they were embedded as spherical droplets within the cross-linked gel network structure formed by GRS/HPS and GG, thus favoring the formation of a continuous network structure. Instead, they existed as spherical droplets embedded within the cross-linked gel network formed by GRS/HPS and GG, thus favoring the formation of a continuous network structure. As the GG proportion increased, the droplet size gradually decreased, and the distribution became more uniform. This effect may be attributed to the formation of coating around the oil droplets by polysaccharides, which made the aqueous phase gel, thus preventing the oil droplets from gathering (Meng, Qi, Guo, Wang, & Liu, 2018). Owing to the complex spatial structure of oil, most lipid adsorbed on the starch surface (Zhao et al., 2023). The results illustrated the importance of GG in the GRS/HPS gel matrix structure and oil droplet stability.

3.2 Gelation properties

3.2.1 Textural properties

The textural properties of the GG-only and GG-CO combined samples were shown in Table 3. Hardness, springiness, and cohesiveness all trended upward in response to rising GG levels. The GG-CO combined samples exhibited higher hardness, springiness, and cohesiveness than the GG-only samples, thus enhancing the entire textural performance of the system. Specifically, the hardness of the samples with only GG added increased from 43.42 g to 75.28 g. Springiness and cohesiveness rose from 1.49 and 0.81 to 1.96 and 0.85, respectively. The hardness of the samples with GG-CO combined addition significantly increased from 56.11 g to 109.02 g. The springiness and cohesiveness increased from 1.58 and 0.85 to 1.97 and 0.88, respectively. This can be attributed to enhanced hydrogen bond strength

between GG and GRS/HPS molecule hydroxyl groups (Fig. 1a) and the more compact gel matrix (Fig. 2d and h), ultimately improving the hardness of the entire system. The rise in hardness was consistent with the work of Xie, Yuan, Zhang, Wu, & Ai (2023), who found that GG could form stronger gels with corn starch molecules. The increase in springiness may be due to the interpenetration and cross-linking of GG and GRS/HPS molecular chains (Fig. 2d1 and h1), which have a uniform porous network structure (Fig. 2d and h). This has better resistance to starch aging, as rapid aging of starch often accelerates the loss of springiness. Polysaccharides have been reported to promote the formation of three-dimensional network structure in starch, thereby increasing its springiness (Zhao et al., 2021). The improved cohesiveness may result from the tight bonding and strong interactions between the molecular chains of GG and starch (Fig. 2d1 and h1), forming a robust network structure that can resist external force. The hardness of the GG-CO combined samples increased significantly, probably due to the enhanced supporting role of oil droplets within the system. The interaction between oil droplets and GG molecules, together with the dispersion and cross-linking of oil droplets, can enhance the structural stability of gel and improve the hardness of the system. Springiness and cohesiveness slightly increased compared to the samples with only GG added, with no significant difference. Wang, Yiu, Kim, Vongsvivut, Zhou, & Selomulya (2026) observed that the hardness of gel increased with rising oil content, reaching the peak at the highest level of the test, while springiness and cohesiveness were largely independent of the oil content.

Table 3
Textural properties and T₂ peak areas proportion of starch gels with only GG added and GG-CO combined addition.

0% Guar	Hardness/g	Springiness	Cohesiveness	T ₂₁	T ₂₂	T ₂₃
	43.42 ± 4.34^d	1.49 ± 0.10^d	0.81 ± 0.02^f	3.13 ± 0.82^d	9.53 ± 0.78^a	87.33 ± 0.57^{ab}
0.5% Guar	47.64 ± 1.71 ^d	1.68 ± 0.01 ^{bc}	0.83 ± 0.01 ^{ef}	4.52 ± 0.43 ^b	9.07 ± 0.43 ^{abc}	86.74 ± 0.73 ^{ab}
1% Guar	51.06 ± 1.12 ^d	1.95 ± 0.01 ^a	0.84 ± 0.01 ^{de}	4.63 ± 0.65 ^{ab}	8.76 ± 0.49 ^{abc}	86.61 ± 0.36 ^{ab}
1.5% Guar	75.28 ± 8.79 ^b	1.96 ± 0.01 ^a	0.85 ± 0.03 ^{cde}	4.75 ± 0.15 ^{ab}	8.83 ± 0.04 ^{abc}	86.41 ± 0.15 ^b
0% Guar + CO	56.11 ± 4.63 ^{cd}	1.58 ± 0.11 ^{cd}	0.85 ± 0.00 ^{bcd}	3.23 ± 0.88 ^{cd}	9.34 ± 0.71 ^{ab}	87.43 ± 0.28 ^a
0.5% Guar + CO	62.44 ± 4.20 ^c	1.76 ± 0.03 ^b	0.86 ± 0.00 ^{abc}	4.35 ± 0.44 ^{bc}	8.51 ± 0.38 ^{abc}	87.14 ± 0.08 ^{ab}
1% Guar + CO	84.71 ± 8.46 ^b	1.96 ± 0.02 ^a	0.87 ± 0.00 ^{ab}	4.97 ± 0.37 ^{ab}	8.13 ± 0.57 ^{bc}	86.90 ± 0.20 ^{ab}
1.5% Guar + CO	96.90 ± 9.43 ^a	1.97 ± 0.02 ^a	0.88 ± 0.01 ^a	5.64 ± 0.59 ^a	7.96 ± 1.12 ^c	86.39 ± 0.86 ^b

Data are expressed as the mean ± standard deviation (n = 3). Means annotated with different letters (a-f) within the same column are significantly different ($p < 0.05$).

3.2.2 Water status and distribution analysis

The time ranges T₂₁ (0.1–10 ms), T₂₂ (10–100 ms), and T₂₃ (100–1000 ms) represent bound water, fixed water confined within the gel structure, and the free water outside the gel matrix, respectively. LF-NMR results of both GG-only and GG-CO combined samples displayed three distinct relaxation peaks (Fig. 3a). Table 3 summarized the corresponding proportion of T₂ relaxation peak areas. The sample without added GG and CO exhibited the lowest bound water content and the highest fixed water and free water peak contents, indicating a relatively weak water-binding capacity. For samples with only GG added, the percentage of peak area for T₂₁ increased notably from 3.13% to 4.63% ($p < 0.05$) as the GG ratio increased to 1%. With further increase to 1.5% GG, it rose to 4.75% ($p > 0.05$), showing no significant difference. Meanwhile, T₂₂ and T₂₃ reduced from 9.53% and 87.33% to 8.83% and 86.41% respectively with increasing GG ratio, with no significant difference. This indicated a reduction in water mobility, with free water converting to bound water. The addition of GG promoted the transition of water in the system toward lower degree of freedom. This is likely due to the addition of GG forming a more compact gel network structure (Fig. 2d and h), which restricted water molecule mobility. This was in accordance with

the findings of Han et al. (2024), who observed that GG addition could control water migration by absorbing free water in rice noodles, thereby inhibiting ice crystal growth, improving the water retention capacity of rice noodles. For samples with GG-CO combined addition, T_{21} peak area percentage rose notably from 3.23% to 5.64% ($p < 0.05$) as the GG proportion increased. And T_{22} and T_{23} reduced from 9.34% and 87.43% to 7.96% and 86.39%, respectively. Compared with the samples with only GG added, the samples with GG-CO combined addition showed an increase in T_{21} and a decrease in T_{22} and T_{23} . This may be due to the incorporation of CO, which attracted some water molecules to the vicinity of the hydrophilic groups of GG and GRS/HPS, thereby forming more bound water with the GG and GRS/HPS molecules and enhancing the proportion of T_{21} . Su, Li, Wang, & Wang (2024) also observed that the oil-deprived gel had lower T_{22} and higher T_{23} values.

MRI can be used to determine the distribution of water. The signal intensity scales with the pseudocolor map, where redder shades signify greater signal strength and thus a larger concentration of water and protons. In contrast, a bluer appearance is linked to a weaker signal, suggesting diminished quantities. Figure 3b showed the low-field NMR spectra of samples with only GG added and GG-CO combined addition. As the GG content rose, the red areas in the images of samples were increasing, while the blue-green areas were decreasing, indicating that GG incorporation can effectively reduce water loss (Gong, Dong, Zhang, Li, & Hu, 2021) and significantly improve the water holding capacity of GRS/HPS gel. This is primarily because the GG molecular chains exhibit strong hydrophilicity, enabling them to form hydrogen bonds with water molecules, thereby absorbing and binding moisture. Higher GG content provided extra binding sites for water molecules in the starch gel, leading to stronger water retention within the gel structure. Compared with the GG-only samples, the GG-CO combined samples showed a slight increase in the red region, suggesting that the combination of GG and CO improved the ability to retain water and reduce water loss. The dense network structure formed by GG crosslinking with GRS/HPS prevented oil droplet aggregation (Fig. 2f1-h1), ensuring complete mixing of oil and water.

3.3 Rheological behavior

3.3.1 Frequency sweep

The results in Fig. 4a and b showed the relationship between G' and G'' and frequency for the mixed starch gel with only GG added and GG-CO combined addition. Across all samples, G' exceeded G'' , and higher GG levels caused a gradual increase in both G' and G'' . The G' and G'' of the samples with only GG added increased from 1206.50 and 694.16 Pa to 1619.30 and 901.95 Pa, respectively. The G' and G'' of the samples with GG-CO combined addition increased from 1441.50 and 707.96 Pa to 1728.70 and 823.85 Pa, respectively, suggesting that GG incorporation enhanced the formation of a more compact and elastic gel. This likely arises from the highly flexible coiled conformation of GG (Rong, Shen, Wen, Xiao, Li, & Xie, 2022), which physically entangled with GRS/HPS molecules to form a denser three-dimensional network structure in the matrix (Fig. 2). The G' and G'' for the GG-CO combined samples were slightly higher than those for the GG-only samples, indicating that the strength of gel was higher. This can be attributed to the interaction between oil droplets and GG, which improved molecular

interconnectivity and reinforced the overall gel structure. Su et al. (2024) also observed that CO addition increased G' and G'' in emulsion gel, yielding high-strength emulsion gel. In general, the combined addition of GG and CO strengthened the internal structure of the GRS/HPS blended starch gel, leading to a system with improved strength and stability.

3.3.2 Flow behavior test

Figure 4c and d showed the apparent viscosity of samples with only GG added and GG-CO combined addition. Shear force disrupted the network structure of the samples, causing viscosity to decrease as the shear rate increased. At a constant shear rate, the incorporation of GG resulted in a steady rise in viscosity. The initial viscosity of the samples with only GG added increased from 1.6×10^6 mPa·s to 2.4×10^6 mPa·s, and the initial viscosity of the samples with GG-CO combined addition increased from 1.9×10^6 mPa·s to 3.1×10^6 mPa·s, indicating that adding GG could increase the apparent viscosity of GRS/HPS blended starch gel. This can be attributed to the increased concentration of GG leading to more intensive entanglement with GRS/HPS molecular chains, resulting in increased gelation or thickening. This formed a denser three-dimensional network structure (Fig. 2), thereby increasing flow resistance and resulting in samples with higher viscosity. The apparent viscosity of samples with GG-CO combined addition was higher than that of samples with only GG added, likely due to structural reinforcement after oil droplets embedded into the network structure, where they cross-link with starch and GG chains, increasing the internal friction of the system. According to zhai et al. (2025), soybean oil notably improved the viscosity of starch gel, which was attributed to the strengthened interaction between soybean oil and starch at high temperature.

3.3.3 Creep and recovery test

As shown in Fig. 4e and f, all samples exhibited significant creep recovery behavior. As GG content increased, maximum creep strain decreased. The maximum creep strain of the GG-only samples decreased from 65.4% to 28.3%, whereas for the GG-CO combined samples, it decreased from 38.8% to 21.0%. This indicated that the addition of GG increased the deformation resistance of the samples. This finding can be attributed to the increased viscoelasticity of the samples (Fig. 4a and b). The maximum creep strain of the GG-CO combined samples decreased significantly, indicating that the oil reinforced the gel matrix and made the network more elastic and rigid. Overall, the combined addition of GG-CO endowed GRS/HPS blended starch gel with stronger elasticity and rigidity, increased the deformation resistance of the samples, and provided enhanced advantages in both stability and transport.

3.3.4 Three-interval thixotropy

In the three-interval thixotropy test of GRS/HPS blended gels with only GG added and GG-CO combined addition, the viscosity curves as a function of time were presented in Fig. 4g and h. At a low shear rate (the first and third stages), the viscosity increased markedly with rising GG content, consistent with the results for apparent viscosity (Fig. 4c and d). When shear stress was applied during the second interval, the interconnected structures inside the sample were partially disrupted, leading to a sharp drop in

viscosity. Once reversible reconstruction (i.e. the third interval) was achieved, the polymer backbone rearranged as the structure entered a new equilibrium state, restoring its original structure (Cui, Yang, Wang, Blennow, Li, & Liu, 2024). The viscosity of samples in the third stage was significantly lower than that in the first stage. Further quantitative analysis of structural recovery revealed that as the GG proportion increased, the recovery rate of samples with only GG added rose from 63.79% to 66.25%, while that of samples with GG-CO combined addition increased from 64.58% to 66.99%. Increased structural recovery rate reflected weaker thixotropic behavior and enhanced rheological stability (Wang et al., 2021). Results showed that GG addition shortened relaxation time of sample, implying the structure can recover rapidly. This may be due to the interaction between GG and GRS/HPS chains, which may increase the overall stiffness of the chain, thereby reducing relaxation time. The recovery rate of samples with GG-CO combined addition were higher than that of samples with only GG added, indicating that the GG-CO combined addition resulted in a stronger, highly viscoelastic network. This finding aligned with frequency sweep and creep and recovery test results. Consequently, the results demonstrated that the network structure of the samples was dynamic and recoverable, and the samples with GG-CO combined addition had a stronger ability to quickly recover from shear deformation.

3.3.5 LAOS

Figure 5a and b presented the Lissajous curves for elasticity and viscosity of GRS/HPS blended gels with only GG added and GG-CO combined addition, over strain amplitudes ranging from 1% to 1000%. In the linear strain range, all gels showed elliptical elastic Lissajous curves and circular viscosity curves, highlighting elasticity-dominated viscoelasticity. When the strain entered the nonlinear viscoelastic zone, the elastic Lissajous traces shifted from smooth ellipses to a quadrilateral shape (Fig. 5a), indicating the onset of a shift away from elasticity toward viscosity dominance. The viscous Lissajous curves gradually narrowed from elliptical shape, demonstrating shear thinning characteristics in the samples. As the GG ratio increased, the area within the Lissajous curves expanded, revealing that energy dissipation intensified and deformation became more substantial at high strains, in agreement with the results of creep recovery. This implied that accomplishing oscillatory shear required consuming more energy, which proved that the system had higher mechanical properties. One likely explanation is that the higher GG concentration increased polymer density, thereby promoting hydrogen bond formation between GG and GRS/HPS. Regarding the rheological response, the GG-CO combined samples exhibited larger Lissajous curve areas than the GG-only samples, implying both a rise in dissipated energy and an increase in strain-induced deformation at elevated strain

amplitudes.

Figure 5. Elastic Lissajous curves (a) and viscous Lissajous curves (b) of starch gels with only GG added and GG-CO combined addition.

3.4 Mechanisms underlying the interaction among GRS/HPS, GG, and CO

Figure 6 illustrated the formation mechanism of GRS/HPS composite gels at varying GG concentrations, as well as with the combined addition of GG and CO. The GRS/HPS gel system without GG and CO exhibited a loose network structure, where amylose formed double helices, making it prone to aging during storage. After adding GG, its highly flexible molecular conformation allowed the galactose side chains to become topologically entangled, physically interweaving more tightly with the amylose and amylopectin of GRS/HPS. The effect shortened intermolecular distance, densifying the network structure and preventing the formation of the double helices. Upon the addition of CO, the complex spatial structure of large oil droplets occupied physical space, confining GG and GRS/HPS chains to cross-link and assemble within a more restricted volume. This promoted intermolecular hydrogen bond formation and physically hindered the proximity of amylose chains. When GG and CO were added in combination, the increased concentration of GG reduced oil droplet size and made the distribution more uniform. GG and GRS/HPS are competitively attached to the interface of oil and water, which lowered the interfacial tension. The hydrophilic regions of these components formed strong hydrogen bonds with water, while the hydrophobic portions anchored to the oil droplet surface. This dual interaction created a stable interfacial film that prevented droplet aggregation and coalescence. Oil droplets were embedded as spherical microdroplets within the dense network formed by GRS/HPS and GG crosslinking. This further strengthened intramolecular hydrogen bonding within the system and facilitated physical entanglement among GRS, HPS, and GG. This system contained more numerous, smaller cavities, which increased the fixed water content (from 3.13% to 5.64%).

4. Conclusion

This study compared the impact of individual GG addition at varying levels and GG-CO combined addition on the structural, gelling, and rheological characteristics of the GRS/HPS blend gel system. The results found that the highly flexible molecular conformation of GG enabled the galactose side chain to form tighter topological entanglements with the amylose and amylopectin chains of GRS/HPS, as well as the hydroxypropyl groups of HPS, thereby inhibiting recrystallization. The combined addition of GG-CO promoted intermolecular hydrogen bonds and physical intertwining with GRS/HPS, effectively preventing the establishment of double-helical ordering. GG acted as both a thickener and an emulsifier, which reduced oil droplet size and improved their uniform distribution. GG and GRS/HPS cross-linked and competitively adsorbed at the oil-water interface. The hydrophilic chains extended sufficiently into the aqueous phase, whereas the hydrophobic segments adsorbed onto the oil droplet surfaces. This amphiphilic arrangement created a steric barrier that suppressed droplet aggregation and coalescence. Spherical oil microdroplets were embedded within the dense cross-linked network of GRS/HPS and GG, forming a compact and continuous gel structure that contained more and smaller cavities. The texture characteristics of the GRS/HPS blend gel were improved, and the combination with water was closer, so that the water distribution was more uniform. These changes help alleviate the effects of starch aging. In addition, the gel structure with GG-CO combined addition has stronger rigidity and elasticity, which improved the resistance to deformation ability of system and its ability to rapidly recover from shear deformation. This study demonstrated that the GRS/HPS/GG/CO system provides an ideal texture for

preparing highly stable polysaccharide gels, exhibiting properties such as high viscoelasticity, deformation resistance, and rapid recovery, thereby effectively delaying starch aging. This work provides some new insights into the mechanisms and interfacial interactions of binary and ternary starch/colloid/lipid composite gels.

Declarations

Declaration of competing interest

The authors declare that they have no known economic interests or personal relationships that may affect the work reported in this paper.

Author Contribution

Lu Huang: Conceptualization, Methodology, Investigation, Data curation, Writing-Original Draft, Writing-review & editing. Yilin Liang: Validation, Methodology, Formal analysis, Conceptualization. Siqi Gao: Methodology, Conceptualization. Yanzhen Qu: Methodology, Formal analysis. Siyuan Shao: Validation, Conceptualization. Yongjian Cai: Writing-review & editing. Mouming Zhao: Project administration, Resources. Qiangzhong Zhao: Supervision, Funding acquisition, Writing-review & editing.

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Data Availability

All data supporting the findings of this study are available from the corresponding author upon reasonable request.

References

1. Achayuthakan, P., & Supphantharika, M. (2008). Pasting and rheological properties of waxy corn starch as affected by guar gum and xanthan gum. *Carbohydrate Polymers*, 71(1), 9–17. <https://doi.org/10.1016/j.carbpol.2007.05.006>
2. Chen, H. J., Zhong, S. L., Chi, G. X., Li, H. Y., Chen, K. W., Wang, Z. R., & Kan, J. Q. (2025). Preparation and functional characteristics of starch-lipid complexes with different oleic acid-rich glycerolipids. *Food Chemistry*, 476, 143450. <https://doi.org/10.1016/j.foodchem.2025.143450>

3. Chen, L., McClements, D. J., Yang, T. Y., Ma, Y., Ren, F., Tian, Y. Q., & Jin, Z. Y. (2021). Effect of annealing and heat-moisture pretreatments on the oil absorption of normal maize starch during frying. *Food Chemistry*, 353, 129468. <https://doi.org/10.1016/j.foodchem.2021.129468>
4. Cui, Y., Yang, F., Wang, C. S., Blennow, A., Li, C. Y., & Liu, X. X. (2024). 3D Printing windows and rheological properties for normal maize starch/sodium alginate composite gels. *Food Hydrocolloids*, 146, 109178. <https://doi.org/10.1016/j.foodhyd.2023.109178>
5. Dai, Z., Lin, Z., Gao, L., Bereka, T. Y., Xu, D., Wu, F., et al. (2025). A comparative study of starch granule-associated proteins/lipids on short-term and long-term retrogradation of normal and waxy corn starches. *International Journal of Biological Macromolecules*, 302, 140479. <https://doi.org/10.1016/j.ijbiomac.2025.140479>
6. Dun, H., Liang, H., Li, S., Li, B., & Geng, F. (2021). Influence of an O/W emulsion on the gelatinization, retrogradation and digestibility of rice starch with varying amylose contents. *Food Hydrocolloids*, 113, 106547. <https://doi.org/10.1016/j.foodhyd.2020.106547>
7. Gong, Y., Dong, R., Zhang, K., Li, Y., & Hu, X. (2021). The modulatory effect of guar gum on freeze-thaw stability of cooked oat roll. *Food Hydrocolloids for Health*, 1, 100032. <https://doi.org/10.1016/j.fhfh.2021.100032>
8. Gu, Y., Xu, R., McClements, D. J., Liu, T. X., Li, Q. Y., Su, G. W., et al. (2025). Effect of preheating-induced structural changes of mung bean starch and protein on the phase behavior, physicochemical properties, and digestibility of composite hydrogels. *Food Hydrocolloids*, 166, 111346. <https://doi.org/10.1016/j.foodhyd.2025.111346>
9. Han, X., Liang, Q. F., Rashid, A., Qayum, A., Rehman, A., Zhong, M. M., et al. (2024). The effects of different hydrocolloids on lotus root starch gelatinization and gels properties. *International Journal of Biological Macromolecules*, 257, 128562. <https://doi.org/10.1016/j.ijbiomac.2023.128562>
10. Han, Z., Ye, Z. Q., Xu, X. D., Zeng, X. A., Liu, J. Y., Woo, M. W., & Luo, D. H. (2024). Mechanistic study on the effect of hydroxypropyl corn starch, guar gum and compound phosphates on the freeze-thaw quality of quick-frozen kuey teow. *International Journal of Biological Macromolecules*, 279, 135237. <https://doi.org/10.1016/j.ijbiomac.2024.135237>
11. Huang, F., Hu, H., Ouyang, K. F., Zhang, Q., Li, G. Y., Zhong, J. Z., et al. (2025). The processing quality characteristics, freeze-thaw stability, and retrogradation properties of rice cakes affected by four hydrocolloids: Xanthan gum, guar gum, carrageenan, and konjac gum. *International Journal of Biological Macromolecules*, 315, 144471. <https://doi.org/10.1016/j.ijbiomac.2025.144471>
12. Huang, L., Shao, S. Y., Liang, Y. L., Zhao, Q. Z., & Zhao, M. M. (2026). Strategy to enhance the texture, anti-aging property, and rheological property of starch gel: Blending of glutinous rice starch with hydroxypropyl starch. *Food Chemistry*, 509, 148567. <https://doi.org/10.1016/j.foodchem.2026.148567>
13. Jia, Y. Z., Zhang, Z., Li, M., Ji, N., Qin, Y., Wang, Y. F., et al. (2022). The effect of hydroxypropyl starch on the improvement of mechanical and cooking properties of rice noodles. *Food Research International*, 162, 111922. <https://doi.org/10.1016/j.foodres.2022.111922>

14. Lan, G. W., Xie, S. M., Duan, Q. F., Huang, W. J., Huang, W., Zhou, J. F., et al. (2024). Effect of soybean polysaccharide and soybean oil on gelatinization and retrogradation properties of corn starch. *International Journal of Biological Macromolecules*, 264, 130772. <https://doi.org/10.1016/j.ijbiomac.2024.130772>
15. Li, R. B., Tao, H. T., Tan, C. P., Yuan, F., Guo, L., Cui, B., et al. (2024). The structural and functional properties of a novel enzyme-modified starch as an alternative to hydroxypropyl starch ether. *Food Hydrocolloids*, 148, 109448. <https://doi.org/10.1016/j.foodhyd.2023.109448>
16. Lu, W. C., Chan, Y. J., Li, Z. E., & Li, P. H. (2025). Influence of different hydrocolloids on the pasting, rheological, and morphological characteristics of heat gelatinized cassava starch. *Food Chemistry*, 463, 140933. <https://doi.org/10.1016/j.foodchem.2024.140933>
17. Meng, W. H., Ren, Y. Q., & Miao, S. (2025). Advancing salt reduction technologies: AI-assisted structural design of starch-based emulsion gel systems for next-generation low sodium food formulations. *Trends in Food Science & Technology*, 164, 105234. <https://doi.org/10.1016/j.tifs.2025.105234>
18. Meng, Z., Qi, K., Guo, Y., Wang, Y., & Liu, Y. (2018). Effects of thickening agents on the formation and properties of edible oleogels based on hydroxypropyl methyl cellulose. *Food Chemistry*, 246, 137–149. <https://doi.org/10.1016/j.foodchem.2017.10.154>
19. Pan, W. T., Liu, W. M., Li, J. W., Chen, Y., Yu, Q., & Xie, J. H. (2023). The role of guar gum in improving the gel and structural characteristics of germinated highland barley starch. *International Journal of Biological Macromolecules*, 238, 124052. <https://doi.org/10.1016/j.ijbiomac.2023.124052>
20. Pan, W. T., Qi, X., Huang, Z. B., Shen, M. Y., Wen, H. L., & Xie, J. H. (2024). Effect of three polysaccharides with different charge characteristics on the properties of highland barley starch gel. *International Journal of Biological Macromolecules*, 281, 136267. <https://doi.org/10.1016/j.ijbiomac.2024.136267>
21. 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>
22. Stamenkovic, O. S., Kostic, M. D., Tasic, M. B., Djalovic, I. G., Mitrovic, P. M., Biberdzic, M. O., & Veljkovic, V. B. (2020). Kinetic, thermodynamic and optimization study of the corn germ oil extraction process. *Food and Bioproducts Processing*, 120, 91–103. <https://doi.org/10.1016/j.fbp.2019.12.013>
23. Su, C. Y., Li, D., Wang, L. J., & Wang, Y. (2024). Development of corn starch-sodium alginate emulsion gels as animal fat substitute: Effect of oil concentration. *Food Hydrocolloids*, 157, 110439. <https://doi.org/10.1016/j.foodhyd.2024.110439>
24. Sun, S. L., Jin, Y. Z., Hong, Y., Gu, Z. B., Cheng, L., Li, Z. F., & Li, C. M. (2021). Effects of fatty acids with various chain lengths and degrees of unsaturation on the structure, physicochemical properties and digestibility of maize starch-fatty acid complexes. *Food Hydrocolloids*, 110, 106224. <https://doi.org/10.1016/j.foodhyd.2020.106224>

25. von Borries-Medrano, E., Jaime-Fonseca, M. R., & Aguilar-Méndez, M. A. (2016). Starch-guar gum extrudates: Microstructure, physicochemical properties and in-vitro digestion. *Food Chemistry*, 194, 891–899. <https://doi.org/10.1016/j.foodchem.2015.08.085>
26. Wang, H., Wu, Y., Wang, N., Yang, L., & Zhou, Y. (2019). Effect of water content of high-amylose corn starch and glutinous rice starch combined with lipids on formation of starch-lipid complexes during deep-fat frying. *Food Chemistry*, 278, 515–522. <https://doi.org/10.1016/j.foodchem.2018.11.092>
27. Wang, J. Y., You, X. L., Ke, W. H., Wu, C., Lao, Z. Z., & Zhao, F. (2025). Sand frying-induced assembly of coix seeds starch with oils into stable structures: A comprehensive investigation based on starch-lipid interaction. *International Journal of Biological Macromolecules*, 308, 142453. <https://doi.org/10.1016/j.ijbiomac.2025.142453>
28. Wang, Y., Yan, Q., Li, Z., Chen, W. T., Gu, W. J., & Zhang, W. B. (2025). Microstructure and emulsifying properties of rice starch-fatty acid complexes prepared by ultra-high pressure treatment. *Food Hydrocolloids*, 158, 110486. <https://doi.org/10.1016/j.foodhyd.2024.110486>
29. Wang, Y., Yiu, C. C. Y., Kim, W., Vongsivut, J., Zhou, W. B., & Selomulya, C. (2026). Emulsion gels of oil encapsulated in double polysaccharide networks as animal fat analogues. *Food Hydrocolloids*, 171, 111807. <https://doi.org/10.1016/j.foodhyd.2025.111807>
30. Wang, Y. J., Xu, L. L., Zong, A. Z., Du, F. L., Xie, D. Y., Wen, Y. Q., & Xu, T. C. (2025). Variations in 3-chloropropanol esters, glycidyl esters, and lipid accompaniments during the simulated moderate decolorization process of maize germ oil. *Food Chemistry*, 479, 143567. <https://doi.org/10.1016/j.foodchem.2025.143567>
31. Xie, F., Yuan, C. M., Zhang, H., Wu, Y., & Ai, L. Z. (2023). Structure-function relationship between galactomannans and their effects on freeze-thaw stability, retrogradation, and texture of corn starch gels during cold storage. *Food Chemistry*, 398, 133915. <https://doi.org/10.1016/j.foodchem.2022.133915>
32. Xu, X. J., Ye, S. H., Zuo, X. B., & Fang, S. (2022). Impact of guar gum and locust bean gum addition on the pasting, rheological properties, and freeze-thaw stability of rice starch gel. *Foods*, 11(16), 2508. <https://doi.org/10.3390/foods11162508>
33. Yang, Y. Y., Zhang, Q., Weng, Y. X., Jiao, A. Q., & Jin, Z. Y. (2025). Effects of xanthan gum and hydroxypropyl methylcellulose on the structure and physicochemical properties of triticale gluten during fermentation. *International Journal of Biological Macromolecules*, 294, 139413. <https://doi.org/10.1016/j.ijbiomac.2024.139413>
34. Zhai, H. B., Lan, G. W., Duan, Q. F., Huang, W. J., Zhu, L. Y., Xie, F. W., & Chen, P. (2025). Synergistic enhancement of corn starch gel functionality: Soluble soybean polysaccharide and soybean oil enhance texture and improve water retention during partial gelatinization. *Food Hydrocolloids*, 168, 111541. <https://doi.org/10.1016/j.foodhyd.2025.111541>
35. Zhang, G. P., Chen, Y. T., Pan, J. X., Qiu, Y., Cui, P. B., Lyu, F., & Zhang, J. Y. (2024). Effect of guar gum on the physicochemical properties and in vitro digestive characteristics of extruded starches.

International Journal of Biological Macromolecules, 275, 133176.

<https://doi.org/10.1016/j.ijbiomac.2024.133176>

36. Zhang, J. Y., Li, X. T., Wang, K., Zhu, Y., Guo, L., Cui, B., & Lu, L. (2024). Effects of different oil additives on water resistance of corn starch straws. *Carbohydrate Polymers*, 334, 122027.
<https://doi.org/10.1016/j.carbpol.2024.122027>
37. Zhang, L., Zhang, J., Zhang, K., Xie, C., Yang, R. Q., Li, G. H., & Zhang, C. (2024). Effects of protein-glutaminase on the properties of glutinous rice flour, paste, and gel food: Based on the interactions between the deamidated protein and starch. *Food Chemistry*, 459, 140387.
<https://doi.org/10.1016/j.foodchem.2024.140387>
38. Zhao, K. F., Jia, Z. Y., Hou, L. L., Yang, H., Xiao, S. S., Ding, W. P., et al. (2023). Interpretation of the effects of hydroxypropyl starch and hydroxypropyl distarch phosphate on frozen raw noodles quality during frozen storage: Studies on water state and starch-gluten network properties. *International Journal of Biological Macromolecules*, 242. <https://doi.org/10.1016/j.ijbiomac.2023.124783>. Article 124783.
39. Zhao, Q. Z., Tian, H., Chen, L., Zeng, M. M., Qin, F., Wang, Z. J., et al. (2021). Interactions between soluble soybean polysaccharide and starch during the gelatinization and retrogradation: Effects of selected starch varieties. *Food Hydrocolloids*, 118, 106765.
<https://doi.org/10.1016/j.foodhyd.2021.106765>
40. Zhao, X. Y., Li, X. X., Guo, R. T., Wang, X. F., Zeng, L. J., Wen, X., & Huang, Q. L. (2023). Different oil-modified cross-linked starches: *In vitro* digestibility and its relationship with their structural and rheological characteristics. *Food Chemistry*, 418, 135991.
<https://doi.org/10.1016/j.foodchem.2023.135991>
41. Zhong, Y. L., Zeng, S. Y., Lv, Y. Q., Lv, W. Q., Xiao, H. W., & Sheng, S. Y. (2024). Effect of guar gum on the rheological properties, microstructure and 3D printing performance of egg yolk powder-potato starch composite gel. *Food Hydrocolloids*, 153, 110018.
<https://doi.org/10.1016/j.foodhyd.2024.110018>

Figures

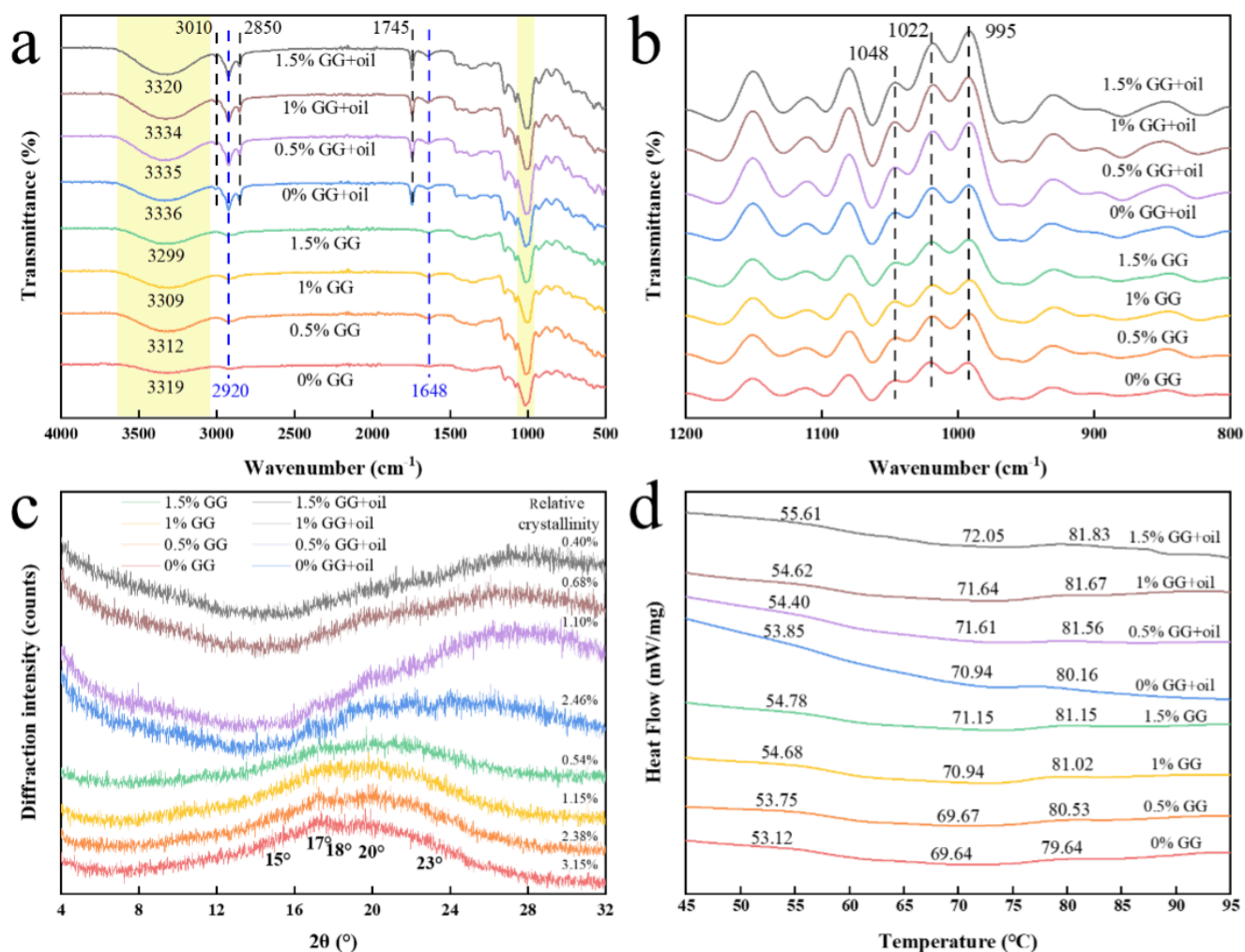


Figure 1

FTIR curves (a), deconvoluted FTIR curves (b), XRD patterns (c), and DSC profiles (d) of starch gels with only GG added and GG-CO combined addition.

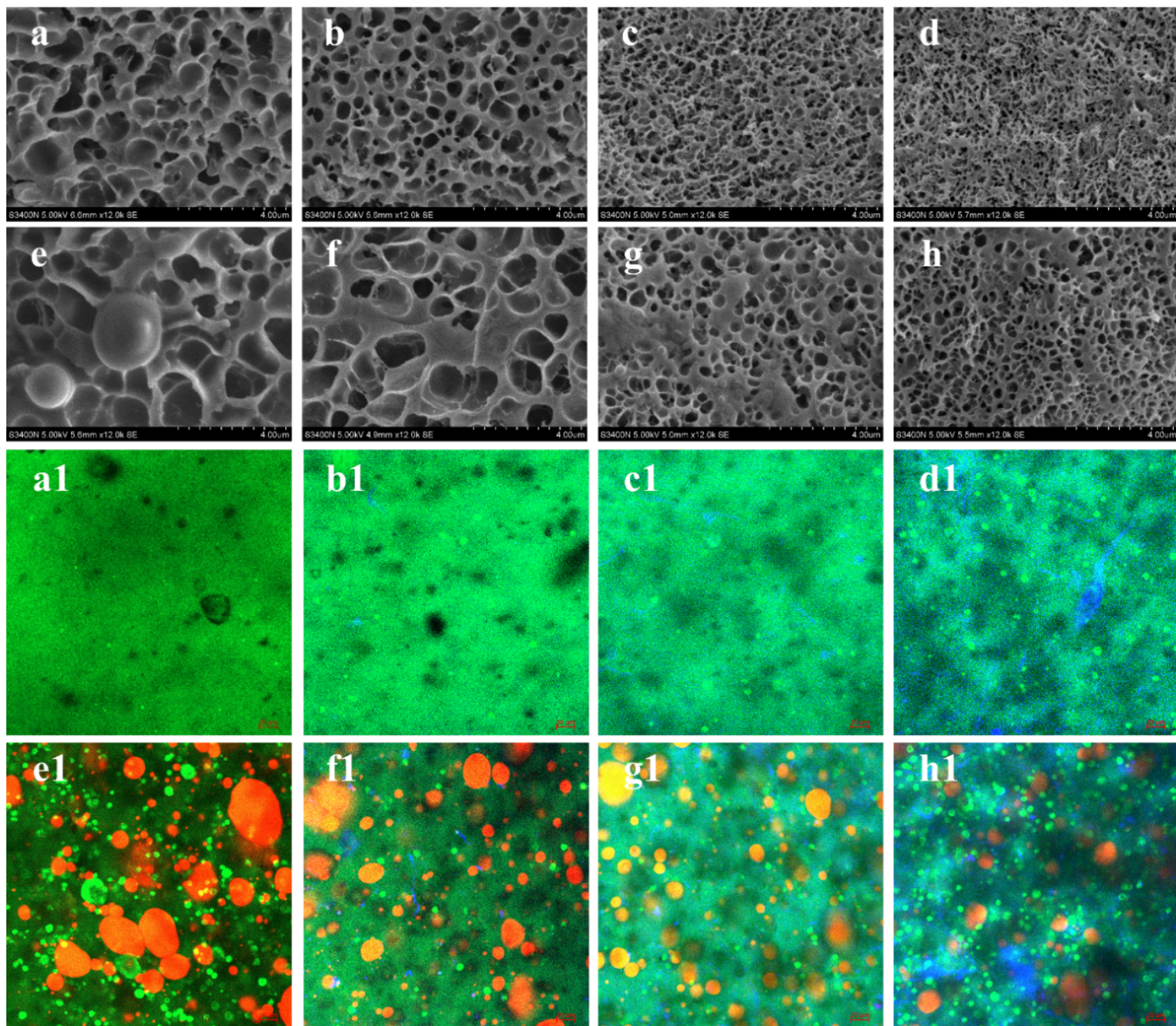


Figure 2

The cross-sectional SEM images and CLSM images of starch gels with only GG and the combined addition of GG and CO. a-d: SEM images of starch gels with only GG added (0%, 0.5%, 1%, and 1.5%); e-h: SEM images of starch gels with GG (0%, 0.5%, 1%, and 1.5%) - CO combination addition; a1-d1: CLSM images of starch gels with only GG added (0%, 0.5%, 1%, and 1.5%); e1-h1: CLSM images of starch gels with GG (0%, 0.5%, 1%, and 1.5%) - CO combination addition.

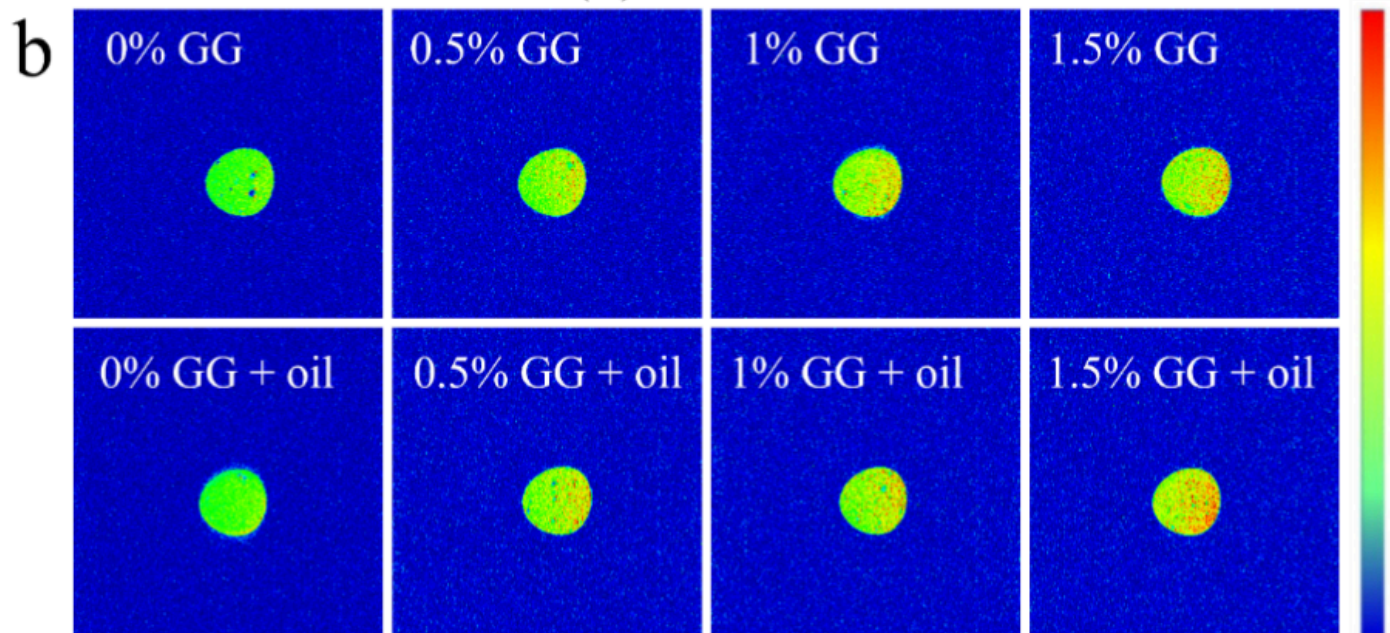
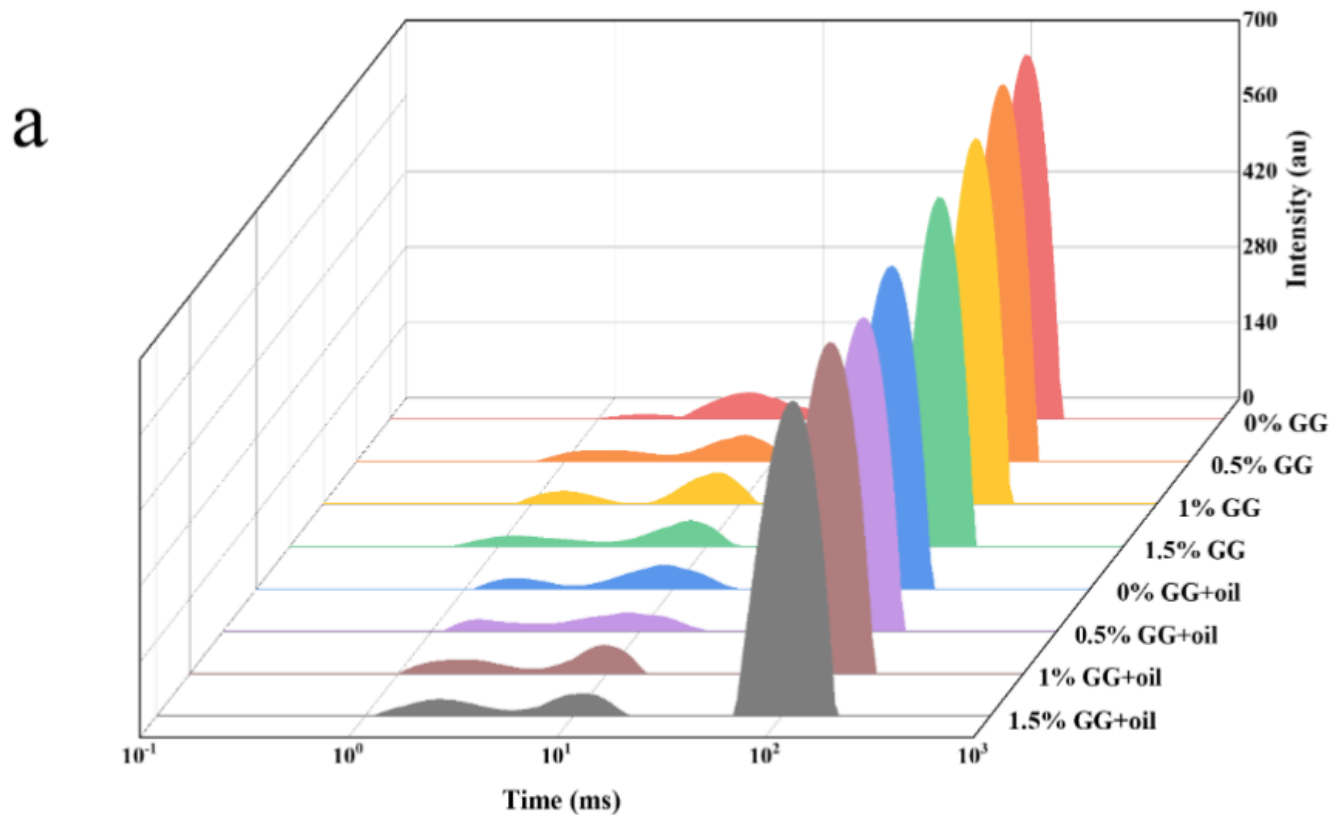


Figure 3

Water distribution (a) and the H- proton response images (b) of starch gels with only GG added and GG-CO combined addition.

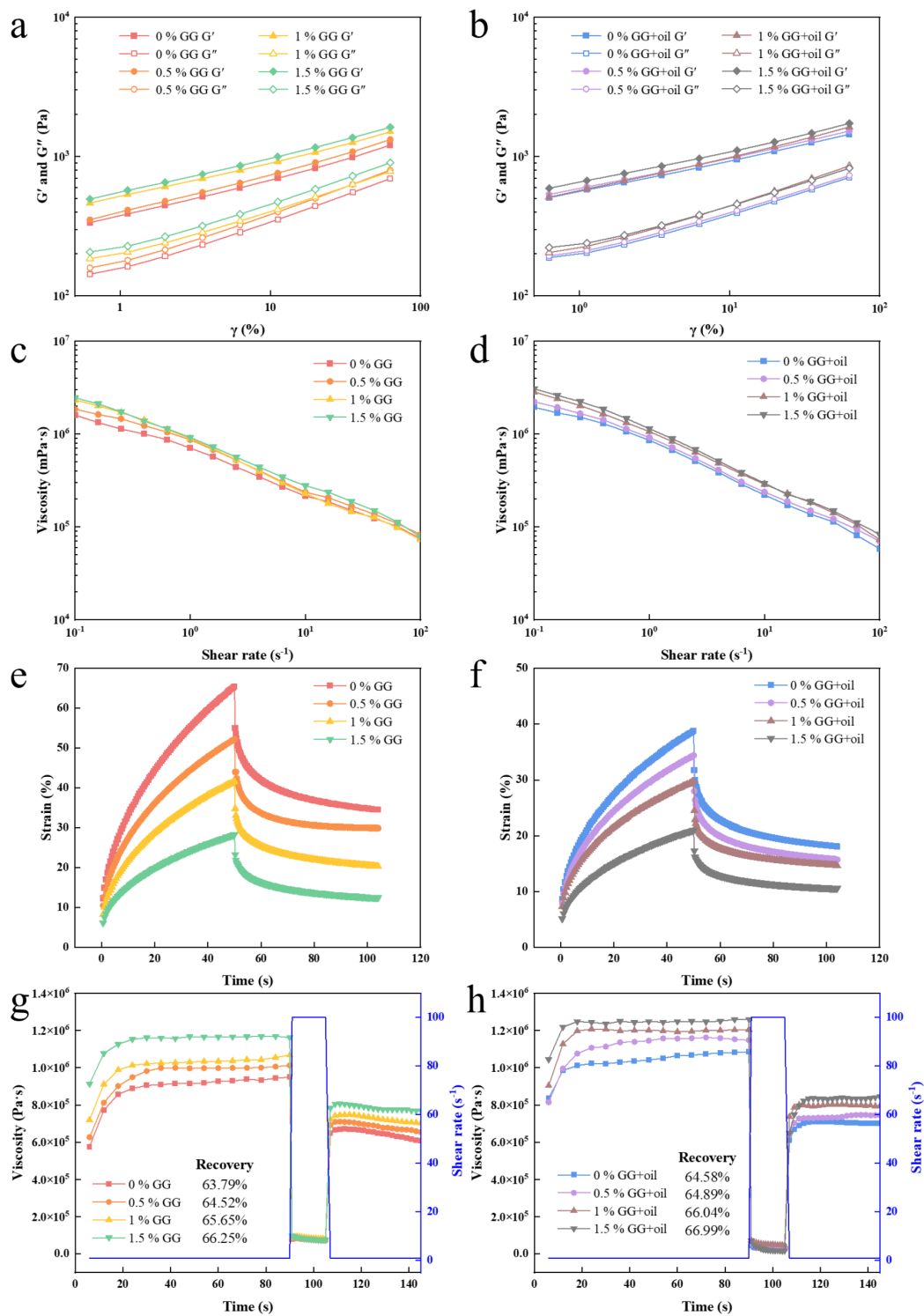


Figure 4

Frequency sweep (a and b), viscosity (c and d), creep and recovery curves (e and f), and three-interval thixotropic curves (g and h) of starch gels with only GG added and GG-CO combined addition.

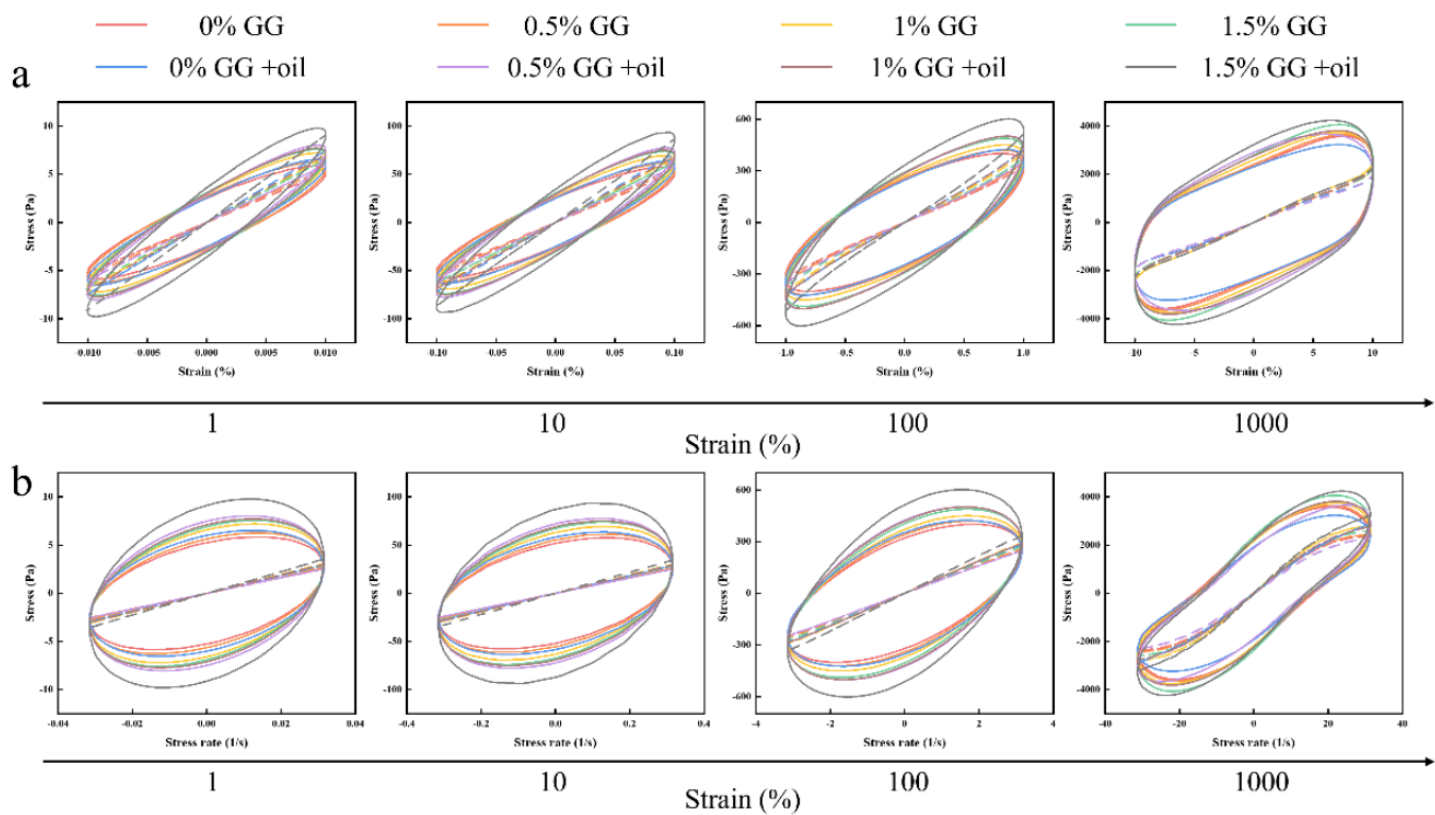


Figure 5

Elastic Lissajous curves (a) and viscous Lissajous curves (b) of starch gels with only GG added and GG-CO combined addition.

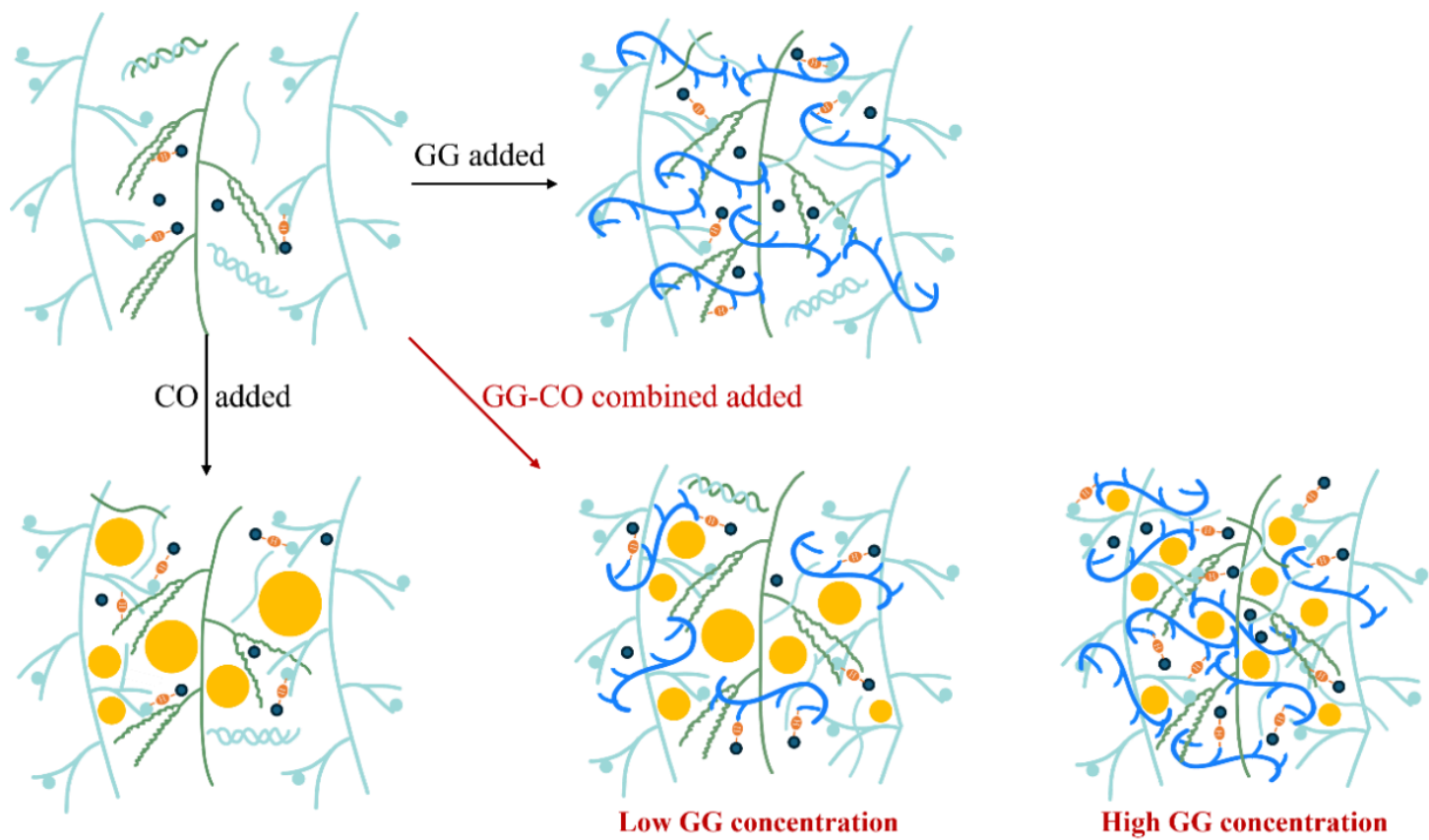


Figure 6

Mechanisms underlying the interaction among GRS/HPS, GG, and CO