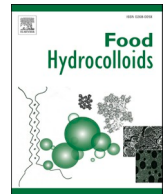


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Tuning the network structure and performance of pea protein–polysaccharide composite emulsion gels as bulk solid fat mimetics: Impact of biopolymer ratio

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ABSTRACT

The growing demand for low-fat and plant-based meat products has increased the need for effective fat substitutes. However, existing substitutes often exhibit limited similarity to animal fat in terms of texture and processing behavior, highlighting the need for structured alternatives with improved mechanical and functional properties. Here, pea protein isolate (PPI), konjac glucomannan (KGM), and xanthan gum (XG) were assembled into composite emulsion gels to clarify how the KGM/XG ratio regulates network formation and fat-mimetic performance. Oil droplets were entrapped within a PPI-polysaccharide matrix using a two-step homogenization process. Composite emulsion gels with KGM/XG mass ratios of 2:8, 4:6, 5:5, 6:4, and 8:2 were evaluated for appearance, texture, microstructure, rheology, thermal response, and water mobility. Among the formulations, the composite emulsion gels prepared with sequential addition of KGM and XG at a mass ratio of 6:4 exhibited the best overall performance, showing the highest hardness (448 g), storage modulus (569.9 Pa), and water-holding capacity (98.70%), together with restricted water mobility and improved heat tolerance. Confocal microscopy and electron microscopy revealed that this formulation exhibited relatively uniform oil droplet distribution and continuous network structure. These results suggest that the balanced KGM/XG ratio promoted the formation of an integrated protein–polysaccharide network through the complementary functionalities of KGM and XG, whereas excessive XG or KGM disrupted network organization and reduced gel cohesiveness. The PPI-KGM-XG composite emulsion gel therefore provides a tunable plant-based platform with potential for developing structured fat mimetics for low-fat meat products and plant-based foods.

1. Introduction

The increasing prevalence of obesity and cardiovascular disease has driven growing demand for low-fat and low-calorie food products (Wang et al., 2024). Fat replacers have therefore become important formulation tools for reducing lipid content while maintaining desirable texture and sensory quality (Syan et al., 2024). Among various fat-replacement strategies, emulsion gels have attracted considerable attention as solid fat mimetics because they combine the interfacial stabilization of emulsions with the structural integrity of gel networks.

In such systems, oil droplets are not merely dispersed lipid domains but can also function as active fillers that contribute to mechanical strength, mouthfeel, water retention, and processing stability (Zhang et al., 2025). In addition to technological performance, the development of plant-based fat mimetics is increasingly driven by environmental sustainability, clean-label trends, and the demand for healthier foods with reduced saturated fat content. These drivers have accelerated the search for naturally derived food ingredients capable of replacing animal fat while maintaining desirable processing and sensory properties.

Replacing animal fat with emulsion gels, especially plant protein-

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based emulsion gels, is also consistent with consumer interest in healthier and plant-based foods. Previous studies have demonstrated that plant proteins, such as soy protein and zein, can be used to develop emulsion gel-based fat substitutes (Choi et al., 2023; Li et al., 2022). For example, soy protein-based emulsion gels have been reported to exhibit textural properties comparable to pork backfat and improve the quality of reduced-fat meat products (Cui et al., 2022; Lin et al., 2020; Qin et al., 2024). Despite their excellent emulsifying and gel-forming properties, soy proteins may present challenges associated with allergenicity, characteristic beany flavor, and the growing need to diversify plant protein sources, thereby stimulating interest in alternative plant proteins (Zhang, Zhang, et al., 2024). However, many reported plant protein-based emulsion gels are still more suitable for soft or spreadable fats than for block-type animal fat analogues. Unlike spreadable fat substitutes, block-type solid fat mimetics must simultaneously provide firmness, elasticity, cohesiveness, shape retention, water-holding capacity, and resistance to heating or mechanical deformation. Therefore, the key challenge is not simply to prepare a plant-based gel, but to construct a coordinated composite network in which oil droplet organization, interfacial stabilization, continuous-phase gelation, and water immobilization are effectively integrated (Abdullah et al., 2022; Carvalho et al., 2025; Tatry et al., 2020).

Pea protein isolate (PPI), derived from legumes with a relatively low environmental footprint, has emerged as a promising alternative plant protein for structuring solid fat mimetics because of its favorable nutritional profile, sustainability, and excellent emulsifying potential. Nevertheless, PPI alone often forms emulsion gels with limited mechanical strength, poor water-holding capacity, and discontinuous microstructures, which restricts its direct application as a block-type fat analogue (Aryanti et al., 2025; Saget et al., 2021; Wang, Bai, et al., 2023). Incorporating polysaccharides is an effective strategy to overcome these limitations. In protein–polysaccharide systems, gel structure and functionality can be modulated through electrostatic interactions, hydrogen bonding, hydrophobic interactions, thermodynamic incompatibility, chain entanglement, depletion effects, and coupled gelation. The type and ratio of polysaccharides are therefore critical for regulating protein aggregation, oil droplet packing, continuous network formation, and water retention in PPI-based emulsion gels.

Konjac glucomannan (KGM) and xanthan gum (XG) are two widely used food hydrocolloids with complementary structural and functional characteristics. KGM is a non-ionic, water-soluble polysaccharide derived from konjac tubers and is known for its ability to improve gel firmness, chewiness, and water retention (Sun et al., 2023). XG is an anionic exopolysaccharide that produces highly viscous solutions at low concentrations and exhibits good stability under various processing conditions (Wang & Selomulya, 2022). More importantly, KGM and XG can interact synergistically, as the relatively rigid XG chains may promote the association and ordering of flexible KGM chains, thereby enhancing network formation (Yang et al., 2019). This synergistic interaction provides a potential route for constructing a more continuous and elastic hydrocolloid network in PPI-based emulsion gels.

However, the effect of KGM/XG balance on PPI-based emulsion gel formation remains insufficiently understood. Although KGM may provide skeletal support and water-binding capacity, insufficient KGM may fail to build a strong gel framework. Conversely, excessive XG may increase system viscosity and steric hindrance, disturb protein–polysaccharide association, and promote structural heterogeneity or phase separation. Thus, the KGM/XG ratio is expected to play a decisive role in controlling the spatial distribution of oil droplets, protein aggregates, and polysaccharide chains. Clarifying how this ratio regulates network continuity, water immobilization, and rheological behavior is essential for transforming weak PPI emulsion gels into cohesive block-type solid fat mimetics.

In this study, PPI-KGM-XG composite emulsion gels were fabricated using a two-step homogenization process to regulate the distribution of oil droplets, protein aggregates, and polysaccharide chains. The effects

of KGM/XG ratio on gel formation were systematically investigated by evaluating visual appearance, texture, microstructure, water-holding capacity, thermal behavior, linear and nonlinear rheological properties, and water mobility. This study aimed to clarify how polysaccharide balance modulates protein–polysaccharide association, oil droplet organization, continuous network formation, and water immobilization, thereby establishing structure–texture–function relationships for designing plant-based emulsion gels with potential applications as block-type solid fat mimetics.

2. Materials and methods

2.1. Materials

Pea protein isolate (PPI; protein content 85%, w/w) was purchased from Yantai Oriental Protein Technology Co., Ltd. (Shandong, China). Konjac glucomannan (KGM; purity 80%, w/w) obtained from Hubei Qiangsen Konjac Science and Technology Co., Ltd. (Hubei, China). Xanthan gum (XG) was obtained from Ordos Zhongxuan Biochemical Co., Ltd. (Inner Mongolia, China). Commercial corn oil was purchased from Shanshan Dongwang Foods Co., Ltd. (Shandong, China). Nile Blue and Nile Red were purchased from Sigma-Aldrich Chemical Company (St. Louis, MO, USA).

2.2. Preparation of PPI-KGM-XG composite emulsion gels

Powdered PPI (10%, w/v) was suspended in deionized water and subsequently heated with continuous agitation at 85 °C for 1 h. KGM or XG powder (8%, w/v) was gradually dispersed into deionized water under continuous stirring to promote uniform hydration and minimize the formation of undissolved aggregates. The dispersions were heated at 75 °C for 1 h and subsequently cooled to room temperature before storage at 4 °C. Excessive agitation was avoided during preparation to reduce potential air incorporation. After heating, all biopolymer dispersions were cooled to room temperature and stored at 4 °C for 12 h before composite emulsion gels preparation.

PPI-KGM-XG composite emulsion gels were prepared according to the formulations shown in Table 1. All composite emulsion gel formulations contained a fixed corn oil content of 20% (w/w) and a constant total polysaccharide content, while only the KGM/XG mass ratio was varied among formulations. PPI and KGM dispersions were first mixed with corn oil and homogenized at 13,000 rpm for 3 min. XG was subsequently incorporated at the designated ratio, followed by a second homogenization step. The sequential addition of KGM before XG was adopted to facilitate the formation of a hydrated KGM-containing continuous phase prior to XG incorporation, thereby promoting more uniform polysaccharide distribution and network development. The mixtures were heated at 65 °C for 10 min with constant stirring to promote partial unfolding and rearrangement of PPI molecules and facilitate protein–polysaccharide network formation (Nakagawa & Ubbink, 2025). The samples were then cooled to room temperature and stored at 4 °C to form composite emulsion gels. Samples with KGM:XG mass ratios of 2:8, 4:6, 5:5, 6:4, and 8:2 were designated PK₂X₈EG,

Table 1
Final formulation composition of PPI-KGM-XG composite emulsion gels.

Emulsion gel	PPI (% w/w)	Corn oil (% w/w)	Total polysaccharides (% w/w)	KGM:XG (w/w)
PEG	4	20	0	0:0
PKEG	4	20	3.2	10:0
PXEG	4	20	3.2	0:10
PK ₂ X ₈ EG	4	20	3.2	2:8
PK ₄ X ₆ EG	4	20	3.2	4:6
PK ₅ X ₅ EG	4	20	3.2	5:5
PK ₆ X ₄ EG	4	20	3.2	6:4
PK ₈ X ₂ EG	4	20	3.2	8:2

PK₄X₆EG, PK₅X₅EG, PK₆X₄EG, PK₈X₂EG, respectively. Control samples were also prepared: PKEG (without XG), PXEG (without KGM), and PEG (without both KGM and XG).

No additional salts, buffers, acids, or alkalis were added during preparation. All formulations were prepared using deionized water under identical conditions to maintain comparable pH and ionic environments among samples.

2.3. Texture profile analysis (TPA)

Before texture measurement, composite emulsion gels were removed from refrigerated storage and equilibrated to 25 °C. Texture profile analysis was performed using a texture analyzer (TA-Xt.plus, Stable Micro Systems, UK) equipped with a cylindrical probe (P36R) (Chen et al., 2023). The pre-test and post-test speeds were 5 mm/s, the test speed was 1 mm/s, the compression strain was 50%, and the trigger force was 10 g. Hardness and springiness were calculated from the resulting force-distance curves using the instrument software.

2.4. Water-holding capacity (WHC)

Water-holding capacity was determined using a centrifugation-based method (Yang et al., 2025). Briefly, approximately 5.0 g of composite emulsion gels (m_0) was placed in a centrifuge tube and centrifuged at $4000 \times g$ for 15 min at 4 °C to remove weakly retained water. After centrifugation, the released water was carefully discarded and the remaining gel was weighed (m_1). WHC was calculated as $WHC (\%) = m_1/m_0 \times 100$.

2.5. Confocal laser scanning microscope (CLSM)

The microstructure of the composite emulsion gels was observed using a CLSM (LSM900, Zeiss, Germany) (Liu, Liang, et al., 2025). Nile Red (1 mg/mL) was used to stain the oil phase, which was detected in the green channel at an excitation wavelength of 488 nm. Nile Blue (1 mg/mL) was used to stain the protein phase, which was detected in the red channel at an excitation wavelength of 633 nm. The polysaccharides (KGM and XG) were not directly stained; therefore, their location and structural contribution were inferred from the spatial distribution of the oil droplets and protein-rich domains. This limitation was considered when interpreting the CLSM images.

2.6. Scanning electron microscope (SEM)

Scanning electron microscopy (SEM) was used to characterize the dried microstructures of the composite emulsion gels. Samples were freeze-dried, fractured, and sputter-coated with gold. Images were acquired using a JSM-7500 F Prime microscope (JEOL, Tokyo, Japan) at an accelerating voltage of 2 kV and magnifications of $\times 100$, $\times 80$, and $\times 50$ (Dong et al., 2023).

2.7. Cryo-scanning electron microscope (Cryo-SEM)

Cryo-SEM performed with minor modifications to a previously reported method (Cui et al., 2023). Briefly, the PK₆X₄EG and PEG samples were fixed on a sample stage using conductive carbon adhesive and rapidly frozen in liquid nitrogen for 30 s to preserve their native microstructure. The samples were transferred to a cryo-preparation system (PP3000T, Quorum, UK), fractured, sublimated at -90 °C for 10 min, and sputter-coated with gold at 10 mA for 60 s. The treated samples were then transferred to a cryogenic sample stage at -140 °C and observed using a Quanta 450 microscope (FEI, USA) at an accelerating voltage of 5 kV.

2.8. Rheological characterization

Rheological properties were measured using an MCR302 dynamic shear rheometer (Anton Paar, Austria) equipped with a 25 mm parallel-plate geometry. The linear viscoelastic region (LVR) was first determined using a strain-sweep test, and subsequent small-amplitude measurements were performed within the LVR.

2.8.1. Temperature scanning test

Thermal stability was evaluated by monitoring the temperature-dependent viscoelastic response of composite emulsion gels. Samples were heated from 20 to 95 °C at 3 °C/min, held at 95 °C for 10 min, and then cooled at 2 °C/min. Measurements were performed at an angular frequency of 6.28 rad/s and a strain of 0.1%, which was within the linear viscoelastic region (Wang, Bai, et al., 2023; Lee, Wi, & Choi, 2023).

2.8.2. Small amplitude oscillating shear test (SAOS)

For small-amplitude oscillatory shear (SAOS) measurements, composite emulsion gels were equilibrated to 20 °C before testing (Kogan & Gottlieb, 2025). The storage modulus (G') and loss modulus (G'') were recorded over an angular frequency range of 0.1–100 rad/s within the LVR.

2.8.3. Large amplitude oscillating shear test (LAOS)

For large-amplitude oscillatory shear (LAOS) measurements, composite emulsion gels were equilibrated to 25 °C before testing. Strain-sweep tests were conducted from 0.01% to 1000% at a frequency of 1 Hz. Elastic and viscous Lissajous curves were generated by plotting normalized stress against normalized strain and normalized shear rate, respectively (Wang & Selomulya, 2022).

2.9. Low-field nuclear magnetic resonance (LF-NMR)

Water mobility in the composite emulsion gels was analyzed using a low-field nuclear magnetic resonance (LF-NMR) analyzer (NMI120, Newman Electric Co., China) equipped with an NM120-040 V-I-40 mm magnet-probe configuration. Transverse relaxation times (T_2) were measured using the Carr-Purcell-Meiboom-Gill (CPMG) pulse sequence. Briefly, 5 g of composite emulsion gels was placed in a cylindrical glass tube (25 mm diameter) lined with polyethylene film. LF-NMR measurements were performed at 35 °C with an echo time (TE) of 0.500 ms, 4000 echoes, a spectral frequency of 20 MHz, and eight scans (Bao et al., 2024; Gilbert & Turgeon, 2026). Shorter T_2 values were interpreted as lower water mobility and stronger water confinement within the gel network.

2.10. Statistical analysis

All measurements were performed in triplicate unless otherwise stated, and results were expressed as mean $\pm$ standard deviation. Statistical differences among samples were evaluated by one-way analysis of variance (ANOVA) followed by Duncan's multiple-range test, with $P < 0.05$ considered statistically significant (Choi et al., 2023).

3. Results and discussion

3.1. Apparent morphology, texture profile and water-holding capacity analysis

3.1.1. Apparent morphology

The macroscopic appearance of PPI-based composite emulsion gels prepared with different formulations is shown in Fig. 1. Gels containing only PPI (PEG) exhibited a flattened and partially collapsed morphology, indicating that pea protein alone could not establish a continuous, load-bearing network. Incorporation of a single polysaccharide moderately improved gel integrity: PKEG maintained some



Fig. 1. Apparent morphology of PPI-KGM-XG composite emulsion gels with different KGM/XG ratios. Images were captured from planform (90°), oblique (45°), and front (0°) views.

shape but deformed readily, while PXEG appeared viscous and irregular, suggesting that increased continuous-phase viscosity alone does not guarantee self-supporting gel formation.

Interestingly, the macroscopic morphology of PPI-KGM-XG composite emulsion gels was strongly dependent on their ratio. The formulations with high XG (PK₂X₈EG) generated weak gels that were prone to collapse, likely due to excessive hydration and steric hindrance impeding effective protein–polysaccharide association. Increasing the KGM proportion enhanced shape retention by providing a more robust skeletal framework. However, excessive KGM (PK₈X₂EG) reduced cohesiveness and yielded a less integrated network. Notably, PK₆X₄EG maintained a regular cylindrical shape, indicating that a 6:4 KGM/XG ratio optimally balanced KGM-driven skeleton formation with XG-assisted network connectivity.

These observations suggest that macroscopic gel integrity depended on the synergistic assembly of a continuous protein–polysaccharide network rather than on viscosity enhancement alone. Previous studies have shown that KGM and XG can form synergistic interaction gels through enthalpy-driven chain association and network cohesion, and that a balanced composition is important for translating molecular interactions into macroscopic gel strength (Qiao et al., 2024; Zhang, Liu, & Wang, 2024).

3.1.2. Texture profile analysis

Texture parameters, particularly hardness and springiness, are critical for evaluating the suitability of composite emulsion gels as block-type solid fat mimetics, as these properties determine resistance to cutting, mixing, and thermal processing while maintaining elastic recovery (Geng et al., 2023a, 2023b). Hardness increased as the KGM/XG ratio changed from XG-rich to moderately KGM-rich, but decreased when KGM became excessive (Fig. 2A). Specifically, the hardness increased from 201 g for PK₂X₈EG to 211 g for PK₄X₆EG and 335 g for

PK₅X₅EG. PK₆X₄EG exhibited a maximum hardness of 448 g, which was significantly higher than that of the other composite formulations and the single-component controls ($P < 0.05$). Further increasing KGM content to PK₈X₂EG decreased hardness to 341 g. This trend indicates that gel firmness is not determined solely by the content of a single polysaccharide but by the balance between skeleton formation and matrix cohesion. Compared with PEG, PKEG and PXEG, the incorporation of KGM/XG significantly improved gel firmness, suggesting that the synergistic interaction between the two polysaccharides contributed more effectively to network reinforcement than individual polysaccharide addition ($P < 0.05$). At the optimal ratio, the balanced KGM/XG composition may have facilitated the development of a continuous load-bearing network, with KGM contributing to framework formation and XG contributing to chain association and stress redistribution. Excessive XG produced a hydrated XG-rich phase that weakened force transmission, whereas excessive KGM led to network heterogeneity and reduced cohesiveness, diminishing the gel's compressive resistance.

Springiness followed a similar trend (Fig. 2B). It increased from 0.692 (PK₂X₈EG) to 0.824 (PK₄X₆EG), 0.842 (PK₅X₅EG), and peaked at 0.913 (PK₆X₄EG), before decreasing to 0.847 (PK₈X₂EG). PK₆X₄EG exhibited significantly higher springiness than the other formulations ($P < 0.05$), indicating improved elastic recovery after deformation. The parallel changes in hardness and springiness indicate that the 6:4 formulation not only enhances resistance to compression but also improves structural recovery after deformation. This behavior aligns with the functional requirements of animal fat in meat products, which contributes both firmness and resilience. Deviations from the optimal ratio generated either a weak XG-rich matrix or a less cohesive KGM-rich network, reducing elastic recovery.

Overall, these results suggest that the mechanical performance of PPI-based composite emulsion gels is governed by the synergistic

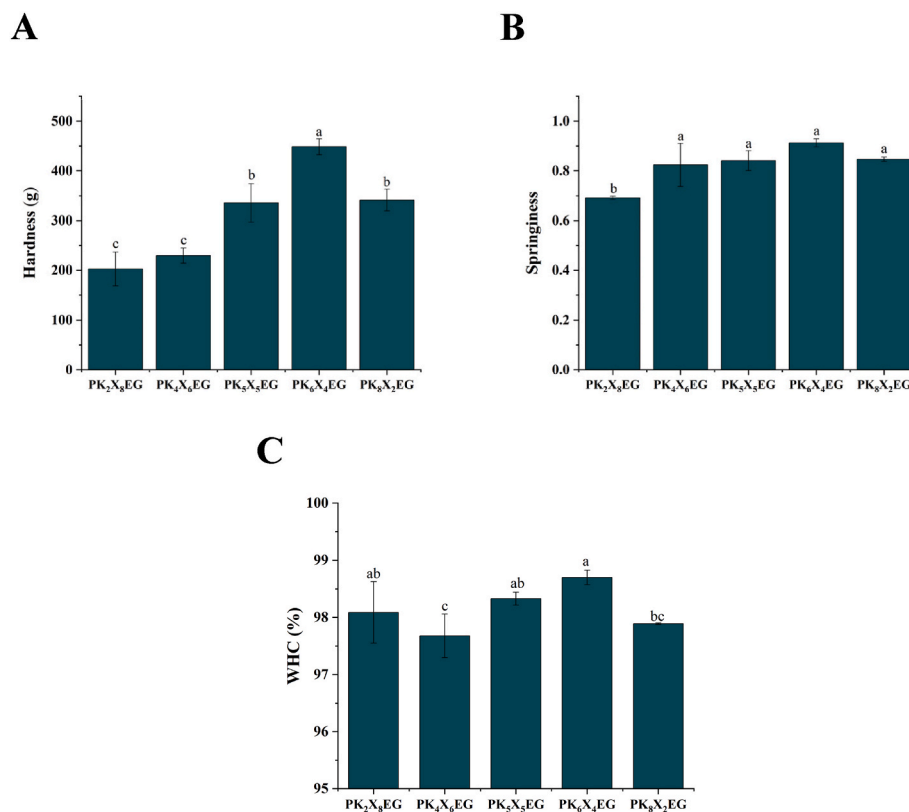


Fig. 2. Texture properties and water-holding capacity of PPI-KGM-XG composite emulsion gels with varying KGM/XG ratios: (A) hardness, (B) springiness, and (C) water-holding capacity (WHC). Different lowercase letters above the bars indicate significant differences among samples according to Duncan's multiple range test ($P < 0.05$).

formation of a continuous protein–polysaccharide network, in which KGM provides skeletal support and XG facilitates network connectivity and entanglement. This mechanism is consistent with recent reports showing that KGM/XG interactions can enhance gel cohesion, rheological stability, and structured emulsion performance when the polysaccharide balance is appropriate (Pan et al., 2025; Qiao et al., 2024; Yu et al., 2024).

3.1.3. Water-holding capacity analysis

The water-holding capacity of the composite emulsion gels was closely associated with their network continuity and pore structure. Significant differences in WHC were observed among the formulations (Fig. 2C, $P < 0.05$). PK₆X₄EG exhibited the highest WHC (98.70%), which was significantly higher than PEG, PKEG, PXEG, and other KGM/XG ratios ($P < 0.05$), indicating that the 6:4 ratio was most effective in restricting water migration within the protein-polysaccharide matrix (Fig. 2C). This enhanced water retention can be attributed to the combined effects of hydrogen bonding with hydroxyl-rich polysaccharide chains, capillary confinement within a continuous and well-organized porous network, and physical immobilization by embedded oil droplets. In contrast, XG-rich formulations likely retained water mainly through hydration but lacked sufficient skeletal support to resist water release under external stress, whereas excessive KGM promoted network heterogeneity and reduced uniform water confinement.

The lower WHC observed in PEG, PKEG, and PXEG further indicates that protein alone or single-polysaccharide incorporation was insufficient to construct a stable water-retaining network, whereas the balanced KGM/XG ratio promoted more effective water immobilization. These results indicate that WHC was governed not only by polysaccharide hydration capacity but also by the formation of a mechanically reinforced droplet-filled composite network under the tested conditions (Li et al., 2024; Wang et al., 2026; Yiu et al., 2025).

3.2. Microstructure analysis

3.2.1. Confocal laser scanning microscopy analysis

The spatial distribution of oil droplets and protein-rich domains in the PPI-KGM-XG composite emulsion gels was visualized by CLSM (Fig. 3). The green fluorescence assigned to oil droplets and the red fluorescence assigned to protein-rich domains confirmed the formation of oil-in-water composite emulsion gels systems. However, the droplet organization and the spatial distribution of protein-rich domains varied markedly with the KGM/XG ratio, indicating that polysaccharide balance affected not only emulsion stabilization during homogenization but also droplet immobilization during gel network formation (Pan et al., 2025; Yu et al., 2024).

PEG contained numerous oil droplets embedded in a weak protein-rich continuous phase, but the droplets were relatively large and densely packed, suggesting that PPI alone provided limited resistance to droplet rearrangement after homogenization. In PKEG and PXEG, single-polysaccharide addition altered the droplet distribution, but neither system produced an optimal droplet–matrix arrangement. PKEG exhibited scattered oil droplets within a protein-rich phase, while PXEG exhibited a relatively heterogeneous distribution of oil droplets, suggesting that either KGM- or XG-dominated systems were insufficient to simultaneously promote interfacial stabilization and continuous matrix reinforcement (Qiao et al., 2024).

For the composite PPI-KGM-XG systems, the CLSM images exhibited a non-monotonic dependence on KGM/XG ratio. XG-rich PK₂X₈EG contained more aggregated and unevenly distributed sized oil droplets, implying that excessive XG may increase local viscosity heterogeneity and restrict uniform droplet breakup or redistribution during homogenization. As the KGM proportion increased, oil droplets appeared to be more effectively confined within the surrounding protein-rich regions. In particular, PK₆X₄EG exhibited a relatively uniform droplet-filled architecture, in which oil droplets were surrounded and immobilized by a

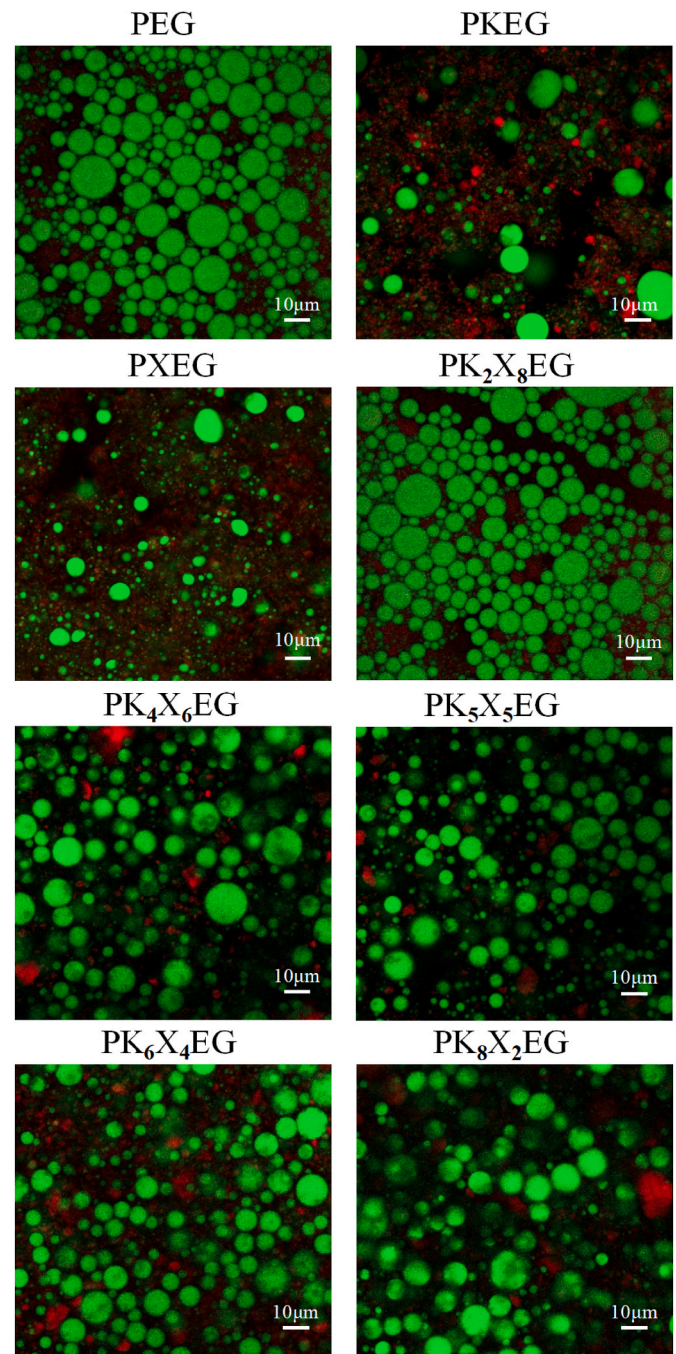


Fig. 3. Confocal laser scanning microscopy (CLSM) images of PPI-KGM-XG composite emulsion gels with varying KGM/XG ratios. Proteins and oil droplets were stained with Nile Blue (red) and Nile Red (green), respectively. Scale bars represent 10 μ m.

protein-rich continuous phase. This structure is favorable for stress transfer because oil droplets can behave as active fillers rather than isolated dispersed domains. However, further increasing the KGM proportion in PK₈X₂EG resulted in a less uniform droplet arrangement with localized aggregation, suggesting that excessive KGM may promote matrix heterogeneity or partial phase separation (Li et al., 2024).

3.2.2. Scanning electron microscopy analysis

SEM analysis revealed significant variations in the microstructures of the various composite emulsion gels (Fig. 4). The microstructures differed substantially among formulations, confirming that the KGM/XG

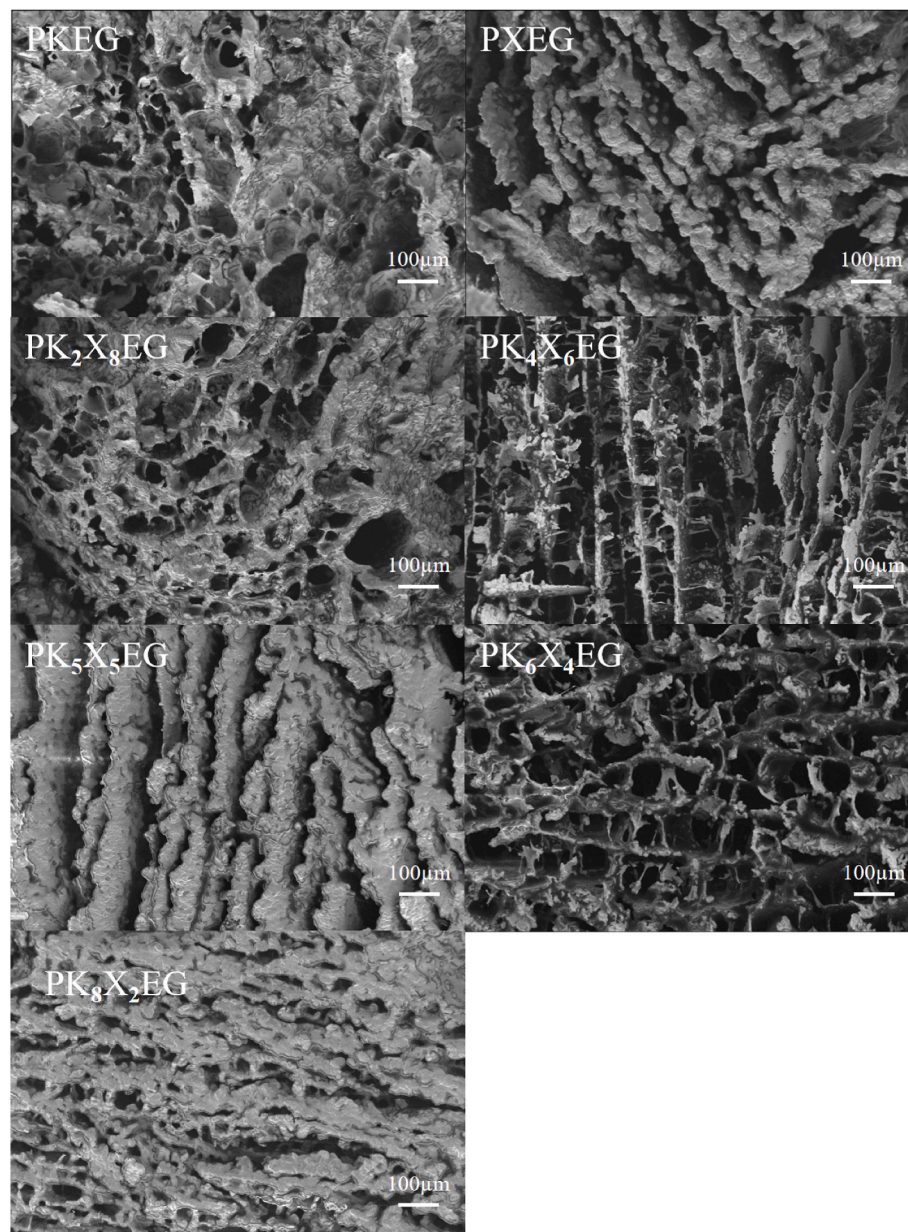


Fig. 4. Scanning electron microscopy (SEM) images of PPI-KGM-XG composite emulsion gels with varying KGM/XG ratios. Scale bars represent 100 μm .

ratio was a key determinant of the protein–polysaccharide network architecture (Pan et al., 2025).

PXEG exhibited an oriented, lamellar-like structure with limited transverse connectivity, indicating that XG mainly contributed to thickening and structural alignment during drying rather than forming an integrated load-bearing network. PKEG displayed an irregular porous structure with large voids, suggesting that KGM alone could provide partial framework support but was insufficient to generate a more continuous and uniform matrix. These observations explain why the single-polysaccharide gels exhibited only limited improvement in macroscopic integrity (Qiao et al., 2024).

For the composite gels, XG-rich $\text{PK}_2\text{X}_8\text{EG}$ exhibited a coarse and heterogeneous porous network with more apparent void regions, suggesting insufficient network cohesion and possible local phase separation. $\text{PK}_4\text{X}_6\text{EG}$ and $\text{PK}_5\text{X}_5\text{EG}$ exhibited more developed structures, but their networks were still relatively discontinuous or directionally aggregated. In contrast, $\text{PK}_6\text{X}_4\text{EG}$ displayed a more continuous and integrated network morphology with fewer apparent structural defects,

supporting higher mechanical strength and water-holding capacity (Li et al., 2024; Yu et al., 2024). When the KGM proportion was further increased to $\text{PK}_8\text{X}_2\text{EG}$, the network became less uniform, with locally aggregated regions, suggesting an imbalance between network formation and structural compatibility.

3.2.3. Cryo-SEM analysis

Cryo-SEM was used to observe the hydrated structure of selected composite emulsion gels with reduced artifacts from dehydration (Fig. 5). PEG exhibited a weaker and less organized hydrated network, confirming that protein alone cannot immobilize droplets or form an effective load-bearing network.

Overall, the CLSM, SEM, and Cryo-SEM results consistently demonstrate that the KGM/XG ratio governs the multiscale structure of PPI-based composite emulsion gels, and the 6:4 ratio produces the most favorable microstructure, characterized by more effectively embedded oil droplets and a continuous protein–polysaccharide matrix.

Interestingly, $\text{PK}_6\text{X}_4\text{EG}$ exhibited a continuous porous matrix in

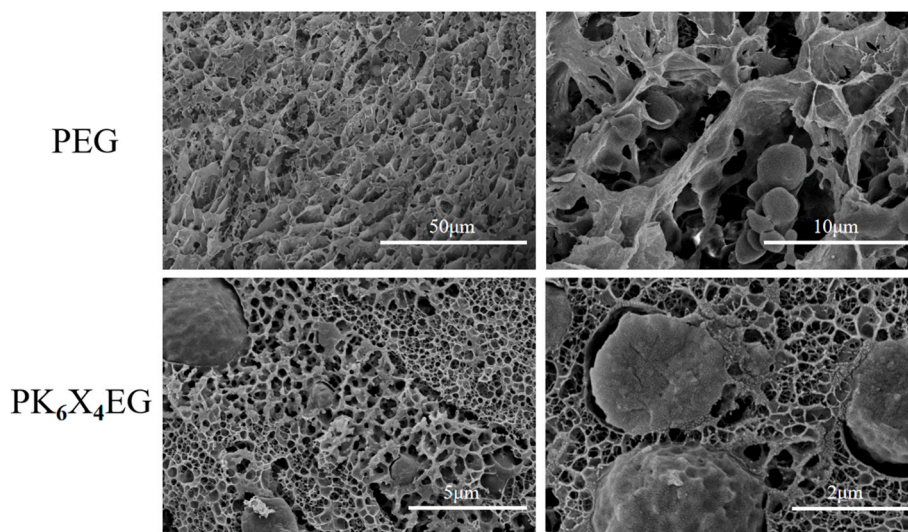


Fig. 5. Cryo-scanning electron microscopy (Cryo-SEM) images of selected PPI-KGM-XG composite emulsion gels: PK₆X₄EG and PEG (protein-only emulsion gel without KGM/XG).

which spherical oil droplets were embedded within a well-organized biopolymer network, demonstrating a hierarchical droplet-filled composite network. The matrix surrounding the oil droplets exhibited better structural continuity, suggesting effective spatial integration of the oil phase with the protein–polysaccharide network. This structural organization explains the improved hardness, springiness, and macroscopic stability observed for PK₆X₄EG (Wang et al., 2026; Yiu et al., 2025).

3.3. Rheological analyses

3.3.1. Temperature sweep analysis

The thermal rheological behavior of the PPI-KGM-XG composite emulsion gels was evaluated by monitoring the storage modulus (G') during heating (Fig. 6). The temperature-dependent variation in G' reflected the dynamic evolution of the protein–polysaccharide network, including thermal weakening of pre-existing physical interactions, protein unfolding and aggregation, polysaccharide chain association, and partial network disruption at elevated temperatures (Liu, Liang, et al.,

2025).

PEG maintained a low G' throughout heating, indicating that PPI alone was unable to construct a thermally reinforced load-bearing network under the present conditions. PKEG and PXEG exhibited more pronounced temperature-induced increases in G' , suggesting that single-polysaccharide systems underwent thermal thickening or transient network formation. However, these high G' peaks should not be interpreted simply as superior gel performance, because the corresponding macroscopic morphology and texture results exhibited limited shape retention and cohesiveness. This suggests that thermal rheological enhancement in a single-polysaccharide system does not necessarily translate into a stable block-type composite emulsion gels.

For the composite PPI-KGM-XG systems, the thermal response depended strongly on the KGM/XG ratio. XG-rich formulations exhibited limited thermal reinforcement and less stable G' profiles, suggesting that excessive XG may increase hydration and steric hindrance, thereby weakening effective protein–KGM association and reducing stress transfer within the network. In contrast, increasing the KGM proportion favored the development of a stronger polysaccharide-associated network structure. The synergistic interaction between KGM and XG has been shown to be strongly affected by the fine structure of XG, which controls enthalpy-driven assembly behavior and gel strength (Qiao et al., 2024). Therefore, an appropriate KGM/XG balance is essential for promoting effective chain association and network cohesion.

Among the composite gels, PK₆X₄EG exhibited the most favorable thermal viscoelastic response, maintaining a relatively stable G' during the later heating stage. This behavior suggests that the 6:4 KGM/XG ratio promoted a balanced physical network in which KGM-derived skeletal support, XG-assisted chain association, protein aggregation, and oil droplet filling were effectively coupled. The thermal behavior of KGM is also closely related to its molecular structure and deacetylation state, which can influence chain aggregation, interfacial activity, and interaction with other food biopolymers (Jiang et al., 2026; Michel et al., 2026). Thus, the optimized formulation likely reduced excessive network rearrangement during heating by promoting more compatible protein–polysaccharide organization.

The initial decrease in G' at lower temperatures may be attributed to the weakening of weak physical interactions and increased molecular mobility. The subsequent increase in G' likely resulted from thermally induced protein unfolding and aggregation, together with enhanced association between KGM and XG chains. At higher temperatures, the decline in G' indicated partial disruption or rearrangement of the physical network, including weakening of hydrogen bonding and

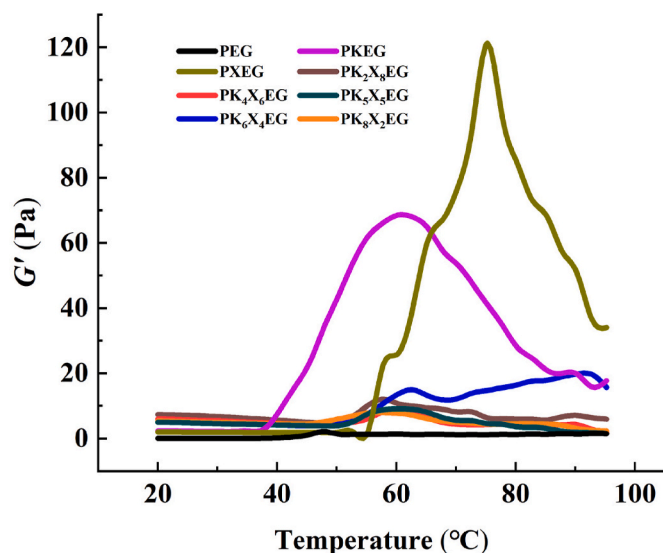


Fig. 6. Temperature sweep profiles of PPI-KGM-XG composite emulsion gels with varying KGM/XG ratios. The storage modulus (G') was monitored as a function of temperature during heating.

reduced chain association. Therefore, the temperature sweep results suggest that the optimized KGM/XG ratio improved thermal network integrity by balancing thermally induced reinforcement and network stability, rather than simply increasing continuous-phase viscosity.

3.3.2. Small-amplitude oscillatory frequency sweep analysis

The frequency dependence of G' and G'' was used to evaluate the linear viscoelastic behavior of the composite emulsion gels (Fig. 7). For most samples, G' was higher than G'' over the tested angular frequency range, indicating that the gels exhibited predominantly elastic, solid-like behavior. The weak frequency dependence of G' further suggests the formation of a percolated biopolymer network with relatively long relaxation times (Pan et al., 2025; Wang et al., 2023).

Among the composite systems, PK₆X₄EG exhibited the highest G' over the frequency range, confirming that this formulation developed the strongest elastic network. This result agrees well with the macroscopic morphology, texture profile, CLSM, SEM, and Cryo-SEM observations, in which PK₆X₄EG displayed the best shape retention, highest hardness and springiness, and the most integrated droplet-filled network. Recent studies on KGM/XG-regulated O/W emulsions have shown that controlled aggregation of these polysaccharides in the aqueous phase can markedly alter rheological behavior, microstructural evolution, and emulsion stability (Pan et al., 2025). Similarly, KGM/XG has been reported to synergistically improve the rheological and 3D-printing properties of high internal phase emulsions stabilized by protein microgels, further supporting the role of KGM/XG interactions in constructing structured emulsion systems (Yu et al., 2024).

The enhanced G' of PK₆X₄EG can be associated with the synergistic contribution of three structural elements: a KGM/XG-associated continuous biopolymer network, polysaccharide-mediated chain interactions, and oil droplets embedded as active fillers within the protein–polysaccharide matrix. In contrast, PEG exhibited much lower moduli, indicating insufficient network formation by PPI alone. PKEG and PXEG exhibited improved viscoelasticity compared with PEG but were less effective than the optimized composite system, suggesting that a single polysaccharide could not simultaneously provide skeletal support, network connectivity, and droplet immobilization. Similar structure–mechanics relationships have been observed in pea protein isolate emulsion-filled gels, where polysaccharide incorporation modulated microstructure, mechanical strength, and gel functionality (Li et al., 2024). Therefore, the frequency sweep results confirm that the mechanical strength of PPI-KGM-XG composite emulsion gels was governed

by the balance between continuous-phase gelation and droplet-filled matrix reinforcement.

3.3.3. Large-amplitude oscillatory shear analysis

Large-amplitude oscillatory shear (LAOS) analysis was performed to investigate the nonlinear viscoelastic response and structural breakdown of the composite emulsion gels under large deformation (Figs. 8–10). In the low-strain region, G' remained higher than G'' for the composite gels, confirming that the intact protein–polysaccharide network behaved as an elastic-dominant material. As strain increased, G' gradually decreased and eventually approached or fell below G'' , indicating the transition from a solid-like network to a flow-dominated state. This strain-induced softening reflects progressive disruption of physical cross-links, chain entanglements, droplet–matrix interactions, and protein–polysaccharide associations.

PK₆X₄EG maintained a higher G' and a broader elastic-dominant region than the other formulations, suggesting stronger resistance to deformation and delayed network breakdown. Compared with the other formulations, PK₆X₄EG exhibited a slower decrease in elastic modulus under increasing strain, indicating enhanced structural resilience and a greater ability to preserve network integrity during nonlinear deformation. This indicates that the 6:4 KGM/XG ratio produced a more resilient network capable of distributing stress across the continuous matrix and embedded oil droplets. Such behavior is highly relevant to the design of structured composite emulsion gels for plant-based fat mimetics, because these materials must tolerate cutting, mixing, and deformation while maintaining block-like integrity. This nonlinear resistance can be attributed to the hierarchical organization of the composite network, where the KGM-rich framework provides mechanical support, while XG contributes additional chain connectivity and energy dissipation pathways.

Double-network and droplet-filled emulsion gels have recently been proposed as effective design strategies for structuring food emulsion gels and improving their mechanical robustness (Yiu et al., 2025). Although the present system does not represent a classical double-network gel, the cooperative contribution of KGM and XG resembles a double-network-like reinforcement mechanism, in which different structural components contribute to load bearing and deformation tolerance. Moreover, oil droplets encapsulated within double polysaccharide networks have been shown to function as animal fat analogues by combining lipid structuring with network reinforcement (Wang et al., 2026).

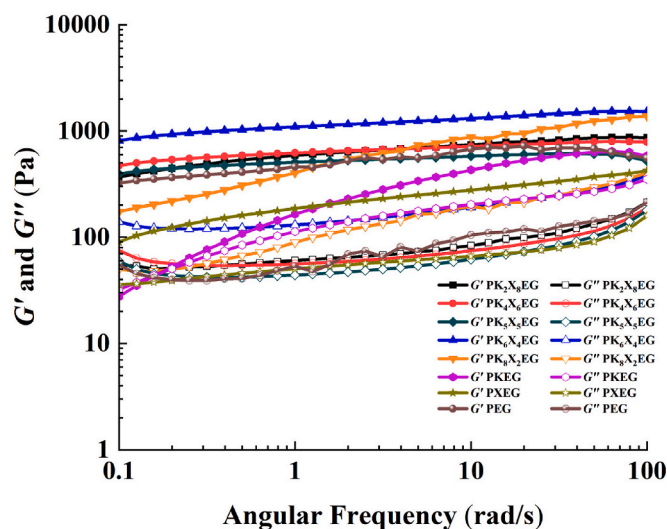


Fig. 7. Frequency sweep profiles of PPI-KGM-XG composite emulsion gels with varying KGM/XG ratios. The storage modulus (G') and loss modulus (G'') were measured as functions of angular frequency.

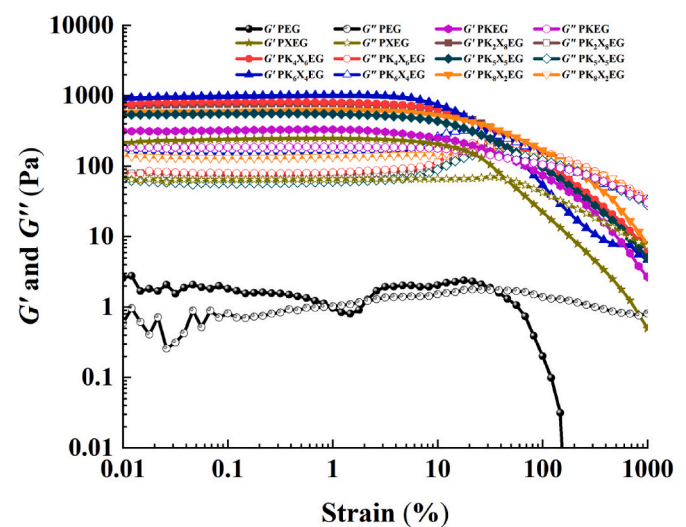


Fig. 8. Strain sweep profiles of PPI-KGM-XG composite emulsion gels with varying KGM/XG ratios. The storage modulus (G') and loss modulus (G'') were measured as functions of strain amplitude.

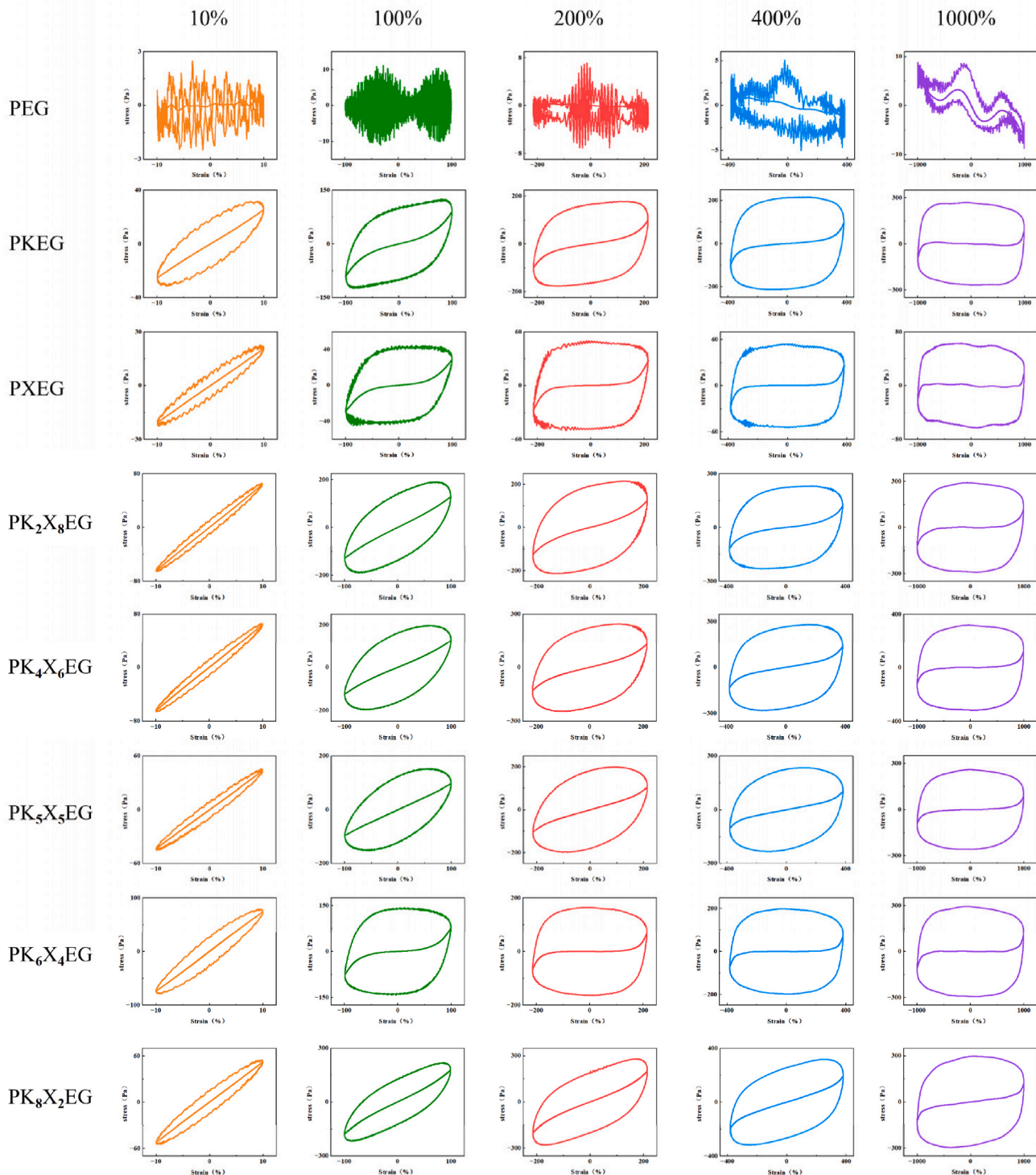


Fig. 9. Elastic Lissajous plots of PPI-KGM-XG composite emulsion gels with varying KGM/XG ratios obtained from large-amplitude oscillatory shear (LAOS) measurements.

The elastic Lissajous plots (Fig. 9) further revealed the intra-cycle nonlinear behavior of the gels. At lower strain amplitudes, the curves were close to elliptical, indicating predominantly linear viscoelastic behavior. With increasing strain amplitude, the curves became increasingly distorted, reflecting nonlinear elastic responses associated with network stretching, rearrangement, and partial rupture. Notably, PK₆X₄EG retained a relatively broader and more regular elastic response compared with the other formulations, suggesting that its network could

withstand larger deformation before extensive structural disruption. This behavior indicates improved deformation tolerance rather than simply increased rigidity.

The viscous Lissajous plots (Fig. 10) exhibited increasingly open and distorted loops at high strain amplitudes, indicating enhanced energy dissipation. The enlarged loop area of the composite gels reflects greater mechanical energy dissipation through reversible and irreversible structural rearrangements. In PK₆X₄EG, the balanced KGM/XG ratio

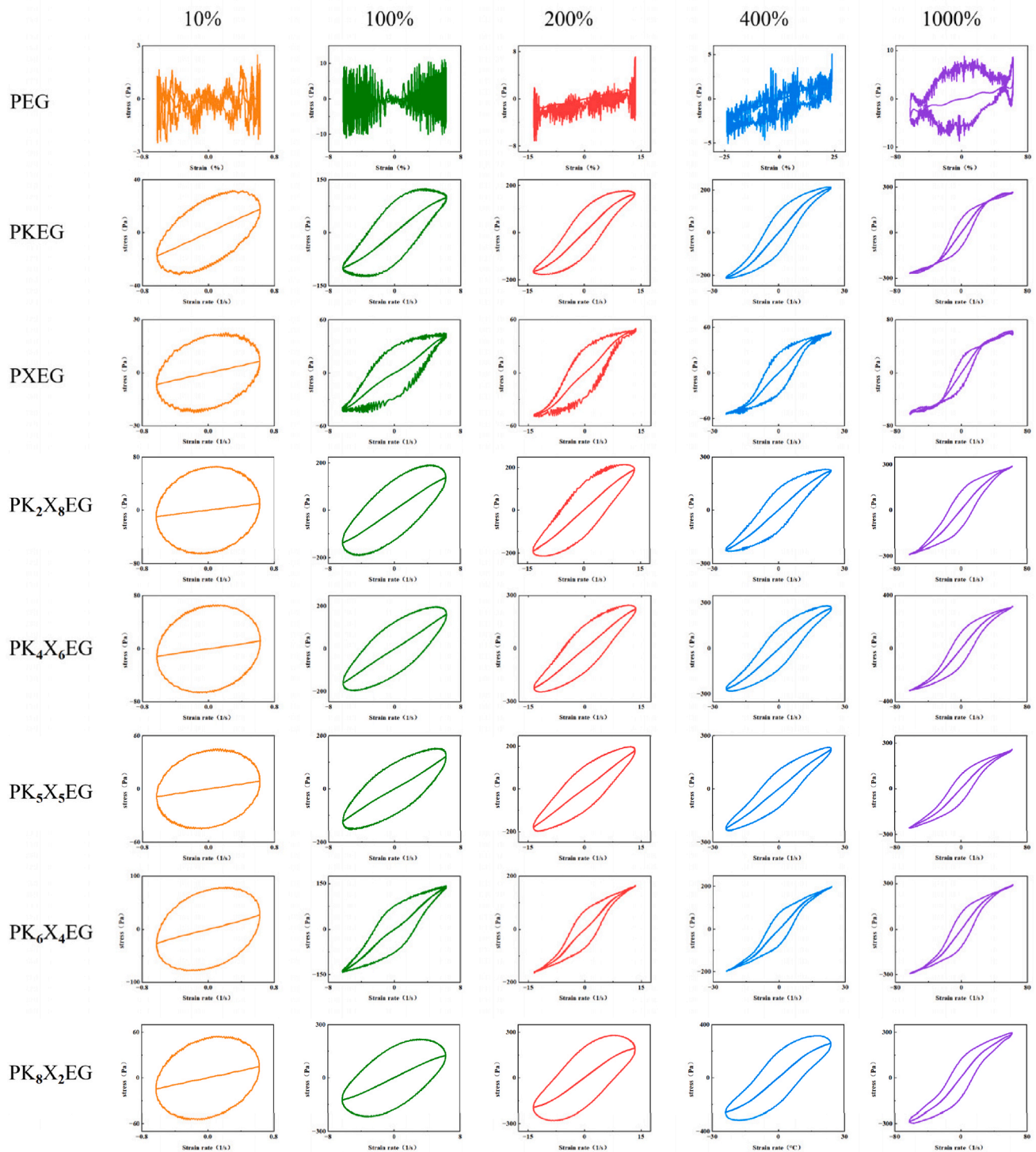


Fig. 10. Viscous Lissajous plots of PPI-KGM-XG composite emulsion gels with varying KGM/XG ratios obtained from large-amplitude oscillatory shear (LAOS) measurements.

likely enabled simultaneous stress resistance and energy dissipation by combining a load-bearing polysaccharide framework with flexible chain rearrangement. These changes suggest that, under large deformation, the composite emulsion gels dissipated mechanical energy through disruption of non-covalent interactions, disentanglement of polysaccharide chains, rearrangement of protein aggregates, and movement of oil droplets within the matrix.

Compared with unbalanced formulations, PK₆X₄EG exhibited a more stable nonlinear viscoelastic response, indicating that the optimized protein-polysaccharide-oil network was more resistant to structural collapse. The LAOS response therefore demonstrates that PK₆X₄EG achieved a balance between rigidity and adaptability, which is a desirable feature for solid fat mimetics requiring both shape retention and mechanical processability. The superior LAOS behavior of PK₆X₄EG is

consistent with the concept that plant-based composite emulsion gels require not only droplet stabilization but also a reinforced continuous biopolymer network to achieve solid fat-like functionality (Hou et al., 2022; Yiu et al., 2023). Overall, the LAOS results demonstrate that the KGM/XG ratio not only determined the small-deformation elasticity of the composite emulsion gels but also controlled their resistance to nonlinear deformation and structural failure.

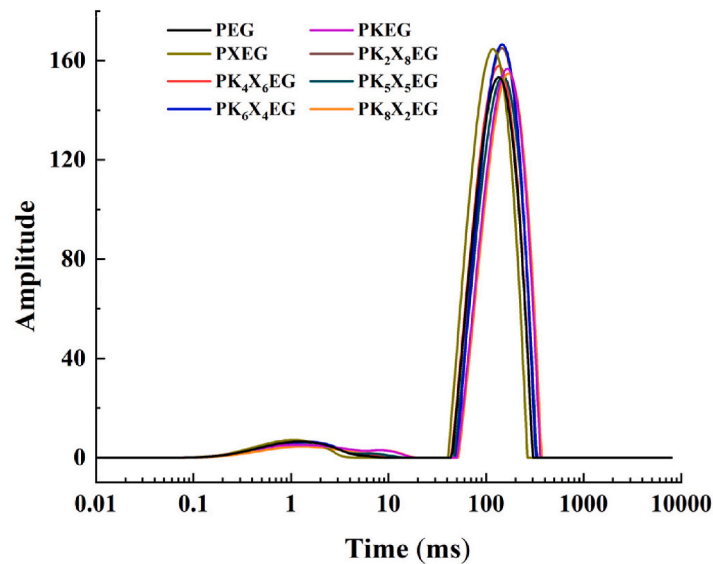
3.4. Low-field nuclear magnetic resonance (LF-NMR) analysis

LF-NMR was used to characterize water mobility and water distribution in the PPI-KGM-XG composite emulsion gels (Fig. 11). The

transverse relaxation time (T_2) distribution provides information on the degree of water immobilization within the gel network. Typically, the shorter relaxation component (T_{21}) is associated with tightly bound water interacting with protein-polysaccharide networks, whereas the longer relaxation component (T_{22}) corresponds to more mobile water with weaker interactions within the gel matrix. Therefore, a lower T_2 value and a reduced proportion of T_{22} water indicate stronger water immobilization (Gilbert & Turgeon, 2026).

The T_2 profiles exhibited that the KGM/XG ratio markedly affected water mobility in the composite emulsion gels. Compared with weak or unbalanced samples, composite emulsion gels with an appropriate KGM/XG ratio exhibited a stronger contribution from low-mobility

A



B

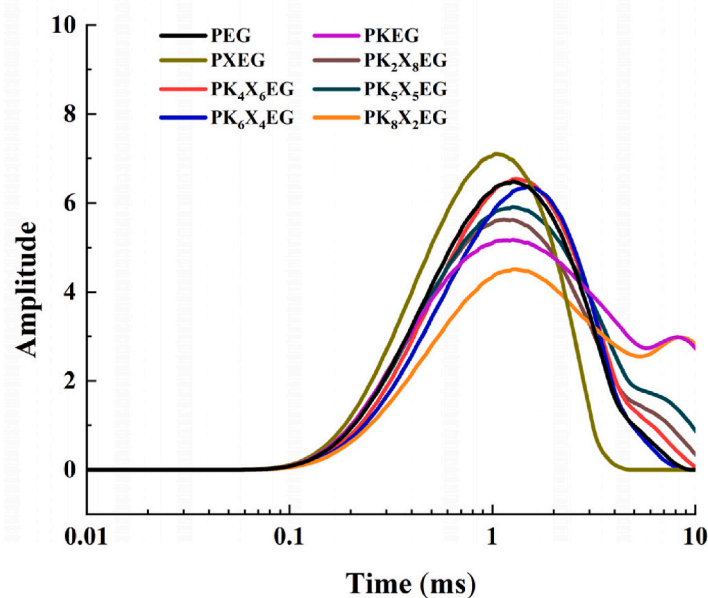


Fig. 11. Low-field nuclear magnetic resonance (LF-NMR) relaxation profiles of PPI-KGM-XG composite emulsion gels with varying KGM/XG ratios: (A) overall T_2 relaxation time distribution and (B) magnified view of the low-mobility water region. The shorter relaxation component (T_{21}) represents tightly bound water, whereas the longer relaxation component (T_{22}) corresponds to more mobile water within the gel matrix.

water populations, reflected by a higher proportion of T_{21} -associated water and a reduced proportion of mobile T_{22} water. The shift of relaxation signals toward shorter T_2 values indicated enhanced restriction of water movement within the composite network. This indicated that water molecules were more effectively restricted within the protein–polysaccharide network. Such water immobilization can be attributed to hydrogen bonding with hydroxyl-rich polysaccharide chains, physical entrapment within smaller pores, and restriction of water diffusion by the continuous gel matrix. PK₆X₄EG exhibited a more favorable water mobility profile, consistent with its compact microstructure, higher hardness, higher springiness, and better macroscopic shape retention. The optimized 6:4 ratio likely promoted a more integrated porous network, where the complementary functionalities of KGM and XG may contribute to water retention and network continuity. The role of KGM in regulating water mobility is closely associated with its molecular aggregation behavior and polysaccharide network-forming ability. Deacetylation-induced KGM aggregates have recently been shown to possess potential interfacial and structuring functions, indicating that KGM molecular organization can strongly influence emulsion and gel stability.

In contrast, XG-rich formulations may retain water through hydration but lack sufficient skeletal support, resulting in a weak matrix that cannot effectively resist water release under external stress. Excessive KGM may also be unfavorable because KGM-rich domains can induce network heterogeneity and enlarged pores, weakening the uniform confinement of water. Therefore, the LF-NMR results support the conclusion that water-holding behavior was not simply determined by polysaccharide hydration capacity, but by the ability of the protein–polysaccharide network to immobilize water within a continuous and mechanically stable structure. Overall, the LF-NMR results connect the microstructure to the macroscopic behavior of the gels. A continuous matrix with fewer structural defects limited water mobility, improved WHC, and contributed to better texture. This relationship is particularly relevant for fat mimetic design because controlling water mobility and retention is important for maintaining desirable texture during subsequent food processing and application. It should be noted that WHC and LF-NMR measurements reflect water retention and mobility under the tested conditions and do not directly represent long-term storage stability, water loss during thermal processing, or freeze–thaw resistance.

4. Conclusion

In this study, PPI-KGM-XG composite emulsion gels were developed as plant-based emulsion gel systems with potential as solid fat mimetics by regulating the KGM/XG ratio. The results demonstrated that the polysaccharide ratio played a decisive role in controlling macroscopic integrity, texture, microstructure, rheological behavior, water-holding capacity, and water mobility. Among all formulations, PK₆X₄EG, with a KGM/XG ratio of 6:4, exhibited the best overall performance, including the highest hardness, springiness, storage modulus, and water-holding capacity. Microscopic analyses revealed that this formulation exhibited improved droplet organization and a more continuous protein–polysaccharide network, as supported by CLSM, SEM, and Cryo-SEM observations, while LF-NMR indicated restricted water mobility within the gel matrix.

The improved performance of PK₆X₄EG may be associated with the complementary contributions of KGM and XG. KGM may facilitate framework development and water retention, whereas XG may contribute to network continuity, chain association, and stress redistribution. Excessive XG weakened the KGM-supported framework and led to insufficient load transfer, while excessive KGM reduced network cohesiveness and promoted structural heterogeneity. Therefore, the formation of a block-type emulsion gel was governed not by polysaccharide content alone, but by the coordinated organization of protein aggregates, polysaccharide chains, oil droplets, and water within a continuous composite network. It should be noted that the identified 6:4

KGM/XG ratio represents the most favorable formulation within the specific PPI concentration, oil content, and total polysaccharide level investigated in this study, rather than a universal optimum for all PPI-based emulsion gel systems. Further systematic optimization involving multiple formulation variables, including protein concentration, oil phase content, and polysaccharide concentration, will be necessary to establish broader design principles for plant-based solid fat mimetics.

These findings establish a structure–texture–function relationship for PPI-KGM-XG composite emulsion gels and provide a practical strategy for designing plant-based solid fat mimetics with desirable firmness, elasticity, shape retention, and water-holding capacity. From a processing perspective, the developed system shows potential for scale-up because it relies on food-grade ingredients and a conventional high-shear homogenization process commonly used in emulsion-based food manufacturing. However, further pilot-scale studies are required to evaluate the effects of processing parameters, energy input, storage stability, and large-scale production conditions on the final product performance. It should be emphasized that the present study mainly focused on structural and physicochemical performance, and the nutritional consequences, gastrointestinal fate, and consumer perception of the developed emulsion gels require further validation. Future studies should further investigate the application performance of the optimized emulsion gel in real food systems, such as reduced-fat meat products and plant-based meat analogues, including direct comparison with animal fats (e.g., pork back fat), cutting behavior, cooking stability, freeze–thaw resistance, sensory acceptance, gastrointestinal digestion behavior, lipid release characteristics, and compatibility with other food ingredients. Such studies will help advance the application of protein–polysaccharide composite emulsion gels as sustainable and functional alternatives to animal fat.

CRedit authorship contribution statement

Xueting Zhou: Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Yifan Wang:** Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Chi Zhang:** Methodology, Supervision, Writing – review & editing. **David Julian McClements:** Conceptualization, Writing – review & editing. **Xingfeng Xu:** Formal analysis, Methodology, Validation. **Qiang Wang:** Methodology, Writing – review & editing. **Wan-shu Zhu:** Methodology, Writing – review & editing. **Qingjie Sun:** Funding acquisition, Project administration. **Lei Dai:** Conceptualization, Funding acquisition, Project administration, Writing – review & editing.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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