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Gel properties of pork meat batter modulated by Gleditsia sinensis polysaccharide: Texture, viscoelasticity, water mobility, and microstructure

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Research Article

Keywords: Gleditsia sinensis polysaccharide, Microstructure, Pork meat batter gel, Textural properties, Viscoelasticity

Posted Date: November 5th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11432286/v1

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Additional Declarations: No competing interests reported.

Gel properties of pork meat batter modulated by *Gleditsia sinensis* polysaccharide: Texture, viscoelasticity, water mobility, and microstructure

Abstract

Natural polysaccharides are promising functional ingredients for improving meat gel properties, but the effects of *Gleditsia sinensis* polysaccharide (GSP) in pork meat batter remain unclear. We evaluated GSP effects on pork meat batter gels. GSP significantly enhanced cooking yield, water-holding capacity, and gel strength with optimal performance at 0.2%–0.4% addition. At 0.4% GSP, cooking yield increased by 15.68 % compared with the control, while springiness, chewiness, and microstructural uniformity also improved. GSP promoted a more compact gel network and higher immobilised water content, demonstrating its potential as an effective functional ingredient for producing pork products with superior water-holding capacity and texture.

Keywords *Gleditsia sinensis* polysaccharide · Microstructure · Pork meat batter gel · Textural properties · Viscoelasticity

Introduction

Meat and meat products constitute major dietary sources of saturated fatty acids (SFAs). However, from a nutritional and health perspective, the lipid profile of meat is inherently less favourable than that of vegetable oils. Long-term high intake of red and processed meats is consistently linked to a higher incidence of obesity, hypertension, and related metabolic disorders (Daba *et al*., 2021). The World Health Organization recommends limiting dietary intake of total fat, SFA, and cholesterol to reduce the risk of associated chronic diseases (Gálvez *et al*., 2019). Therefore, incorporating fat replacers into meat products to reduce SFA content and optimise the fatty acid profile has become an important strategy for enhancing nutritional quality. However, conventional fat replacers frequently impair critical processing properties of meat systems, particularly, gel formation capacity and thermal-structural stability (Pappa *et al*., 2000).

Hydrocolloids, widely used functional food additives, enhance the gel strength and water-holding capacity (WHC) of meat batter gels. This improvement is attributable to the ability of these hydrocolloids to simultaneously remodel the myofibrillar protein network and immobilise water within the gel matrix. The beneficial roles of polysaccharide hydrocolloids in meat products have been comprehensively reviewed, encompassing their effects on retarding lipid and protein oxidation, enhancing nutritional properties, and improving texture and colour quality, as well as their role as cryoprotectants (Bao *et al*., 2025). Commonly used hydrocolloids, such as carrageenan, xanthan gum, and gellan gum, have inherent limitations: carrageenan requires dissolution at temperatures above 70 ℃ to exert its full functionality, guar gum may accelerate lipid oxidation, and xanthan gum exhibits a narrow effective dosage range, where excessive addition can disrupt protein–protein interactions, thereby weakening the gel network structure (Yuan *et al*., 2026). Therefore, the development of novel, efficient, and safe natural hydrocolloids to address these limitations offers both significant practical value and theoretical insights into protein–polysaccharide interactions in meat gel systems.

Gleditsia sinensis polysaccharide (GSP) is a naturally occurring galactomannan isolated from the seeds of *G. sinensis*. Its molecular backbone is composed of mannose residues linked by β-(1→4)-glycosidic bonds, while galactose side chains are attached *via* α-(1→6)-glycosidic bonds (Ye *et al*., 2024). This molecular architecture, which differs from that of other common galactomannans, endows GSP with high viscosity, excellent hydration capacity, and diverse biological activities, with low-molecular-weight fractions exhibiting particularly pronounced effects (Wang *et al*., 2023). Accumulating evidence indicates that polysaccharides can effectively modulate protein gelation behaviour. For example, *Lycium barbarum* polysaccharides significantly enhance the whiteness, WHC, and textural properties of myofibrillar protein gels (Zhang *et al*., 2025c). Bacterial

exopolysaccharides stabilize protein networks through hydrogen bonding and electrostatic interactions (Lu *et al*., 2024). These findings collectively underscore the multifaceted mechanisms by which polysaccharides modulate protein gelation, thereby providing a robust foundation for the rational design of advanced colloidal systems. In addition to these direct interactions, the phase separation behaviour between proteins and polysaccharides is another critical factor governing the gelation properties of composite systems. In protein–polysaccharide mixed systems, thermodynamic incompatibility often leads to phase separation, which is further intensified during thermal processing (Zhang *et al*., 2017). A study demonstrated that the extent of phase separation in myofibrillar protein/κ-carrageenan mixtures increases with increasing polysaccharide ratio and temperature, and that the resulting gel networks are significantly influenced by polysaccharide concentration (Zhang *et al*., 2017). Understanding such phase behaviour is therefore essential for elucidating how polysaccharides modulate the microstructure and functional properties of meat protein gels (Zhang *et al*., 2017).

The spatial distribution of polysaccharides within the protein matrix also plays an important role in determining gel properties. Anionic hydrocolloids are distributed throughout the protein matrix *via* interactions with myofibrillar proteins, forming cavities of varying morphology that affect gel characteristics (Montero *et al*., 2000). This observation suggests that both the phase behaviour and the distribution pattern of polysaccharides contribute to the final gel properties (Montero *et al*., 2000). Despite these advances, the functional role of GSP in pork meat batter gels (PMBGs) remains underexplored. To this end, this study explored the impacts of varying GSP levels on PMBGs, determined the optimal dosage, and elucidated the molecular mechanism governing GSP–myofibrillar protein interactions. This study offers theoretical support for natural fat replacers and texture-modifying agents, promoting high-value utilisation of *G. sinensis*.

Materials and Methods

Materials

Pork tenderloin from three different carcasses was procured from a local market in Xinxiang, Henan, China. All other reagents were of analytical grade.

Extraction of GSP

GSP was isolated following the method of Zhang *et al*. (2025b), with slight modifications. *G. sinensis* seed powder was suspended in distilled water at a liquid-to-solid ratio of 240:1 (mL/g) and incubated in a water bath at 70 ℃ for 2 h. The suspension was centrifuged at 6 000 rpm for 10 min, and the supernatant was mixed with four volumes of anhydrous ethanol before precipitation at 4 ℃ overnight. After centrifugation (6 000 rpm, 10 min), the precipitate was redissolved in ultrapure water and lyophilized using a BenchTop Pro freeze dryer (SP

Scientific, Warminster, PA, USA) to obtain crude GSP, which was used in subsequent experiments.

Preparation of PMBGs

PMBGs were prepared according to Hou *et al*. with slight modifications (Hou *et al*., 2025). Fresh pork was trimmed, cut into pieces, pre-cooled to −4 ℃, and minced through a 6 mm sieve plate. Minced meat 400 g) was homogenized with 100 g ice-cold water, 10 g NaCl, and different GSP concentrations (T_0: 0 %, control; T_1: 0.1 %; T_2: 0.2 %; T_3: 0.4 %; T_4: 0.8 %) at 3000 rpm for 2 min. Aliquots of 35 g were transferred into 50 mL centrifuge tubes and degassed by centrifugation at 500 rpm for 3 min. Samples were heated in a water bath at 85 ℃ for 30 min, rapidly cooled in an ice–water bath to a core temperature of 20 ± 1 ℃, and stored at 0–4 ℃ for 16–18 h before analysis. Three independent batches (each from a different carcass) were produced for each treatment.

Determination of cooking yield

The method was adapted from Zhu *et al*. (2018). Approximately 50 g of meat batter (before heating; m_1, g) was vacuum-sealed in a heat-resistant bag, heated in a water bath at 85 ℃ for 30 min, cooled to room temperature, removed, blotted dry with filter paper, and reweighed (m_2, g). Cooking yield was calculated as:

$$\text{Cooking yield (\%)} = (m_2/m_1) \times 100 \qquad (1)$$

Determination of WHC

The method was adapted from Zhao *et al*. (2024). PMBGs were cut into 1 cm × 1 cm × 1 cm cubes. Each cube was weighed (m_3, g), wrapped in filter paper, and centrifuged at 4 ℃ and 5 000 rpm for 15 min. The cubes were then retrieved, blotted with dry filter paper and reweighed (m_4, g). WHC was calculated as:

$$\text{WHC (\%)} = (m_4/m_3) \times 100 \qquad (2)$$

Texture characterization

Texture profile analysis was characterised according to Zhao *et al*. (2025). PMBGs were cut into 2 cm × 2 cm × 2 cm cubes and analysed using a TA-XT Plus texture analyzer (Stable Micro Systems, Godalming, UK) equipped with a P/36R stainless-steel cylindrical probe. Test parameters were: pre-test, test, and post-test speeds at 2 mm/s; automatic trigger type; 5 g trigger force; 40 % compression ratio; and 5 s interval between cycles.

Determination of gel strength

Gel strength was determined following Qiao *et al*. (2024) using a TA-XT Plus texture analyzer (Stable Micro Systems, Godalming, UK) equipped with a P/0.5 stainless-steel cylindrical probe (12.7 mm diameter). Prior to testing, samples were equilibrated at room temperature for 2 h before testing. Test parameters were: gel strength

test mode, 1 mm/s test speed, 6 mm sample penetration distance, and 5 g trigger force.

Determination of viscoelastic properties

Rheological measurements were conducted using a rotational rheometer (Haake Mars III; Thermo Fisher Scientific GmbH, Karlsruhe, Germany) equipped with a parallel-plate geometry (50 mm diameter), according to Kang *et al*. with minor modifications (Kang *et al*., 2013). The plate gap was 0.5 mm, and the sample edge was sealed with silicone oil to minimize moisture loss. Samples were equilibrated at 80 ℃ for 5 min before testing. Strain sweep tests were first performed on separate fresh gel samples to determine the linear viscoelastic region (LVR), followed by frequency sweep tests (0.1–10 Hz) at 80 ℃, with the strain amplitude maintained within the determined LVR using fresh samples. The storage modulus (G') was recorded.

Analysis of water mobility

The method was adapted from Zhang *et al*. (2025a) using a benchtop nuclear magnetic resonance (NMR) analyzer (PQ001; Shanghai Newmai Technology Co., Ltd., China) with a Carr–Purcell–Meiboom–Gill sequence. Approximately 2.0 g of PMBGs was weighed and loaded into a standard 15 mm diameter NMR tube. Transverse relaxation time distributions were acquired at 32 ℃ and a proton resonance frequency of 22.6 MHz. The test parameters were: τ value (time between 90° and 180° pulses), 200 μs; number of scans, 32; repetition time, 6.5 s; number of echoes, 12 000. Water mobility and peak area ratios were obtained using the instrument software.

Microstructural properties

Microstructure was adapted from Guo *et al.* (2025). Samples (2 mm thick) were fixed in 2.5 % (v/v) glutaraldehyde prepared in a 0.1 mol/L phosphate-buffered saline (pH 7.0) at 4 ℃ for ≥48 h, and then rinsed three times with distilled water (30 min per rinse). Samples were dehydrated using a graded ethanol series (50 %, 70 %, 90 %, 95 %, and 100 % v/v), defatted with chloroform for 1 h, treated sequentially with h a 1:1 (v/v) mixture of anhydrous ethanol and *tert*-butanol for 15 min, and then with pure *tert*-butanol for 15 min. Samples were lyophilized, mounted onto aluminum stubs, sputter-coated with an approximately 10 nm thick gold–palladium alloy layer (MC1000; Hitachi High-Technologies Corporation, Tokyo, Japan), and imaged under a field-emission scanning electron microscope (SU8010; Hitachi High-Technologies Corporation, Tokyo, Japan).

Data analysis

Data from three independent gel batches ($n = 3$) were analysed and are presented as mean ± standard deviation. Data were analysed by one-way ANOVA followed by Tukey's HSD multiple comparison test using IBM SPSS Statistics (version 26.0). Statistical significance was set at $p < 0.05$. Data visualisto bation was performed using Origin 2021 (OriginLab Corp., Northampton, MA, USA).

Results and Discussion

Cooking yield of PMBGs

Cooking yield is an important indicator for evaluating gel quality. Generally, a lower cooking yield indicates a looser gel structure and poorer WHC. The addition of GSP significantly enhanced the cooking yield of PMBGs (Table 1). Cooking yield exhibited a statistically significant biphasic response to GSP addition ($p < 0.05$): it increased progressively from 0 % to 0.4 % and then decreased at 0.8 %. The highest cooking yield of 82.06 ± 0.73 % was achieved with 0.4 % GSP, which represents a 15.68 % relative increase over the control (70.94 ± 0.75 %; $p < 0.05$). The improved cooking yield is primarily driven by hydrogen bonding and electrostatic interactions between GSP and myofibrillar proteins. The maximum cooking yield observed at 0.4 % GSP may be attributed to the formation of a dense gel network, which is likely to be driven by non-covalent interactions between GSP and myofibrillar proteins.

WHC

WHC is a key parameter for assessing gel quality as it directly influences flavour retention. The structural integrity of the gel matrix determines both WHC and textural properties (Chen *et al*., 2023). The WHC of PMBGs exhibited a concentration-dependent increase upon GSP addition (Table 1). It peaked in the 0.4 % and 0.8 % GSP groups, reaching 82.27 ± 0.80 % and 83.37 ± 0.70 %, respectively ($p > 0.05$). The improvement in WHC is likely due to the high density of hydrophilic hydroxyl groups (–OH) and other polar functional moieties present in GSP molecules, which can effectively bind water *via* hydrogen bonding, thereby minimising moisture loss during processing (Abubaker *et al*., 2025). Furthermore, GSP may promote protein aggregation and the formation of a more compact and uniform 3D network structure through non-covalent interactions, thereby improving water entrapment and gel stability, and consequently increasing WHC, as observed in other protein–polysaccharide systems (Cao *et al*., 2022).

Texture properties

Texture characteristics are key quality indicators for meat batter gels. In this study, hardness, springiness, cohesiveness, and chewiness were evaluated as textural parameters. Chewiness, calculated as the product of hardness, springiness, and cohesiveness, reflects the gel's resistance to mastication and its associated juiciness. Cohesiveness indicates the internal bond strength and structural integrity of the gel during deformation (Hou *et al*., 2025).

The springiness and cohesiveness of PMBGs initially increased and then slightly decreased with increasing GSP addition (Table 2). At 0.4 % GSP addition, springiness and chewiness peaked at 0.436 and 1.473 N,

respectively, showing increases of 21.45 % ($p < 0.05$) and 16.44 % ($p > 0.05$) relative to the control group. All GSP addition groups showed significantly higher cohesiveness than the control group, with the maximum value observed at 0.2 % level (0.431), which showed no significant difference from that at 0.4 % level (0.426, $p > 0.05$). Gel hardness was numerically lower in all GSP-treated groups than in the control group. Among the GSP-treated groups, hardness was highest at 0.8 % level (9.086 N), though it remained lower than that of the control group. This reduction in hardness may result from GSP-induced interference with the formation of a rigid, tightly interconnected protein matrix. GSP likely modifies the architecture of the protein network into a more deformable yet cohesive and elastic matrix, as evidenced by a significant increase in springiness at the 0.4 % addition level and significantly higher cohesiveness across all GSP-treated groups, but with chewiness showing no statistically significant differences among all samples ($p > 0.05$). Polysaccharides can reinforce the flexibility and structural integrity of the gel matrix through hydrogen bonding and electrostatic interactions, enhancing system hydration and stability, thereby improving springiness and cohesiveness (Bao *et al*., 2025). This mechanism is consistent with the effects of GSP observed in the present study. Chouikhi *et al*. (2023) similarly reported that the incorporation of a novel flaxseed polysaccharide into beef sausages induced pronounced texture-modulating effects; namely, reduced hardness and enhanced springiness at appropriate addition levels, a trend closely mirrored in this study.

Gel strength

Gel strength is a key parameter for assessing the mechanical stability and textural properties of meat batter gels, directly affecting elasticity, sliceability, and overall sensory acceptability. Higher gel strength typically reflects a denser protein network, stronger intermolecular interactions (*e.g*., hydrophobic interactions and disulfide bonds), and a more cohesive gel system, contributing to superior product quality (Qiao *et al*., 2024). Gel strength increased with GSP addition up to 0.4 %, with no significant difference between the 0.2 % and 0.4 % groups ($p > 0.05$), and then declined at 0.8 % (Figure 1). The numerically highest gel strength was 238.36 ± 6.08 g at 0.4 % GSP, representing a significant 54.07 % increase compared to the control group (154.71 ± 7.57 g; $p < 0.05$). This enhancement may be due to synergistic interactions between GSP at low addition levels and myofibrillar proteins *via* hydrogen bonding and electrostatic forces, which enhance G' and structural integrity of the gel network (Bao *et al*., 2025). Concurrently, the high water-binding capacity of GSP contributes to the immobilization of water within the gel matrix, thereby reducing purge loss during heating and promoting the formation of a more uniform and stable protein network capable of retaining water more effectively (Cao *et al*., 2022). During this process, GSP molecules were likely entrapped within the interstitial spaces of the protein

network, thereby promoting the formation of a more homogeneous and stable 3D gel network and enhancing the synergistic thickening effect (Gao *et al*., 2022). However, when the GSP addition level increased to 0.8 %, gel strength declined to 178.46 ± 5.59 g, still above that of the control group but below the peak value. This decline may be attributed to excessive polysaccharide content surpassing the optimal threshold, leading to a coarser and less uniform network structure, competition with the protein network for water, and disruption of normal myofibrillar protein cross-linking, thereby weakening gel network stability. Moreover, high GSP addition levels significantly increase system viscosity, hindering protein unfolding and ordered aggregation, and resulting in a looser or more fragile gel structure and reduced mechanical strength (Zhuang *et al*., 2020).

Viscoelastic properties

G' is a key viscoelastic parameter for characterising the gelation process of meat batter gels, and its dynamic evolution effectively reflects the kinetic behaviour associated with protein unfolding, aggregation, and subsequent formation of a 3D network structure, and it indicates the gel system's ability to store elastic energy (Ren *et al*., 2023). Although all samples exhibited a similar frequency-dependent G' trend, visible differences in G' values were observed among the GSP addition levels at the same tested frequency (Figure 2). The influence of the GSP addition level on G' followed a triphasic pattern: an initial decrease followed by an increase and then a subsequent decline. Specifically, G' decreased upon addition of 0.1 % GSP relative to the control group. This initial decrease suggests that at low GSP levels, the partial disruption of native protein–protein contacts by GSP molecules is not yet offset by the formation of new stabilizing protein–polysaccharide interactions. In contrast, when the GSP addition level increased to 0.2–0.4 %, G' values rose significantly, reaching a maximum at 0.4 %. At this level, sufficient interactions between proteins and polysaccharides promote a denser and mechanically robust 3D network, thereby enhancing both the elasticity and mechanical strength of the gels. However, further increasing GSP to 0.8 % led to lower G'; although the value remained greater than in the control, it fell below the peak value at 0.4 %. This reduction may result from excessive polysaccharide content inducing phase separation or pronounced steric effects within the protein matrix, disrupting network homogeneity and structural continuity, thus compromising overall gel performance (Chen *et al*., 2023).

Water mobility

LF-NMR analysis revealed three distinct transverse relaxation time (T_2) peaks within 0.1–1 000 ms for all samples. The T_{2b} peak (0.1–10 ms) corresponds to bound water, which is strongly associated with polar functional groups on macromolecules, including proteins, *via* hydrogen bonding. The T_{21} peak (10–100 ms) corresponds to immobilised water, specifically water confined within the myofibrillar network. The T_{22} peak

(100–1 000 ms) corresponds to free water located in the interstitial spaces between muscle fibers (Guo *et al*., 2020).

The peak area ratio statistics (Figure 3) showed that immobilised water (T_{21}) was the main water component in all gel samples, accounting for >94 % of the total water content. No significant differences were observed in the proportions of bound water (T_{2b}), immobilised water (T_{21}), and free water (T_{22}) among all groups (all $p > 0.05$). The immobilised water fraction was 94.51 ± 0.57 % in the control group and 96.68 ± 0.52 % in the 0.4 % GSP group, indicating that GSP addition within the tested concentration range did not significantly alter the existing forms of water in the gel system. Notably, although the proportion of immobilised water did not change significantly, the WHC of the gels significantly improved after GSP addition (Table 1). This difference arises because LF-NMR detects all water with restricted mobility in the intact gel, whereas WHC measures only the water retained after centrifugation, a process that expels a fraction of the T_{21} water. This may be because GSP did not change the mobility of water in different binding states, but it rather enhanced the stability of the gel network structure through interactions with myofibrillar proteins, reducing the exudation of immobilised water during centrifugation and thereby increasing the WHC measured by the centrifugal method. These results suggest that the improvement in WHC induced by GSP is primarily attributable to the stabilization of the gel network architecture rather than alterations in the binding states of water molecules within the gel.

Microstructural properties

SEM (2 000×; Figure 4) revealed that the control PMBGs exhibited a coarse and heterogeneous microstructure with large, irregular pores. In contrast, increasing the GSP addition level to 0.4 % resulted in a more compact and uniform protein network with smaller pore sizes. At 0.4 % GSP, the gel displayed a compact and continuous architecture with reduced pore size and pore density compared to the control. However, at 0.8 % GSP, larger pores reappeared and the network became less uniform. These microstructural observations are consistent with the gel strength results, indicating that an appropriate level of GSP addition can improve the structural integrity of PMBGs, as observed in similar protein–polysaccharide gel systems (Zhuang *et al*., 2021). In the present study, the homogeneous and compact network observed at 0.4 % GSP suggests that GSP, when added at an appropriate concentration, may act as a dispersed filler phase within the myofibrillar protein matrix (Gravelle *et al*., 2016), similar to the behaviour of anionic hydrocolloids reported in myosystem protein gels (Montero *et al*., 2000). The immobilization of water by GSP through hydrogen bonding likely reduces irregular moisture channels that would otherwise hinder protein aggregation during heating, as directly observed in myofibrillar protein-polysaccharide systems (Zhuang *et al*., 2020). At 0.8 % GSP, however, the reappearance of larger pores

and less uniform structures may indicate that excess polysaccharide induces a transition from dispersed phase behaviour to a more pronounced phase-separated structure (Chen *et al*., 2023), where the polysaccharide-rich phase competes with the protein network for available water and disrupts normal protein cross-linking (Zhuang *et al*., 2020).

Conclusions

This study demonstrated that GSP addition effectively improved the physicochemical and functional properties of PMBGs. The phase behaviour between GSP and myofibrillar proteins, as reflected by the microstructural transitions from a homogeneous network at 0.4 % GSP to a less uniform structure at 0.8 % GSP, underscores the importance of optimising polysaccharide addition levels to maintain a balanced protein–polysaccharide interaction. The addition of GSP significantly enhanced gel strength, increased cooking yield and WHC, and improved the springiness and cohesiveness of gel texture. At the optimal addition level of 0.4 %, GSP yielded PMBGs with a fine, uniform, and well-organized 3D network structure characterized by smaller pore sizes and enhanced structural integrity, resulting in superior elasticity and stability. In conclusion, GSP incorporated at the experimentally optimised addition level of 0.4 % functioned as an effective natural quality-modifying agent, enhancing gel performance by improving the microstructural uniformity and density of the protein–polysaccharide network, which in turn contributed to improved macroscopic functional properties such as WHC and gel strength. These findings underscore the potential of GSP as a novel, natural hydrocolloid for developing healthier meat products with improved technological and sensory properties, while promoting the high-value utilization of *G. sinensis* resources.

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Table 1 Effect of GSP addition level on cooking yield and WHC of PMBGs

Sample group	Cooking yield (%)	WHC (%)
T_0	70.94±0.75^{d}	77.10±0.70^{b}
T_1	75.99±0.36^{c}	78.50±0.56^{b}
T_2	78.17±0.63^{bc}	81.50±1.11^{a}
T_3	82.06±0.73^{a}	82.27±0.80^{a}
T_4	79.34±0.49^{b}	83.37±0.70^{a}

* Different superscript letters within the same column indicate statistically significant differences ($p < 0.05$)

Table 2 Effect of GSP addition level on texture properties of PMBGs

Sample group	Hardness (N)	Springiness	Cohesiveness	Chewiness (N)
T_0	9.26±0.00^{a}	0.36±0.01^{b}	0.36±0.01^{b}	1.27±0.18^{a}
T_1	7.94±0.04^{ab}	0.39±0.00^{ab}	0.41±0.00^{a}	1.29±0.02^{a}
T_2	7.41±0.49^{b}	0.38±0.00^{ab}	0.43±0.02^{a}	1.17±0.00^{a}
T_3	7.50±0.47^{ab}	0.44±0.04^{a}	0.43±0.01^{a}	1.47±0.09^{a}
T_4	9.09±0.23^{ab}	0.39±0.00^{ab}	0.40±0.01^{a}	1.32±0.06^{a}

* Different superscript letters within the same column indicate statistically significant differences ($p < 0.05$)

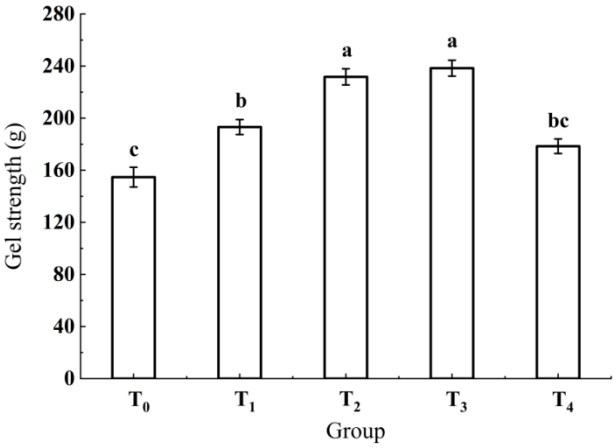


Fig. 1 Effect of GSP addition level on gel strength of PMBGs

* Different superscript letters indicate statistically significant differences ($p < 0.05$)

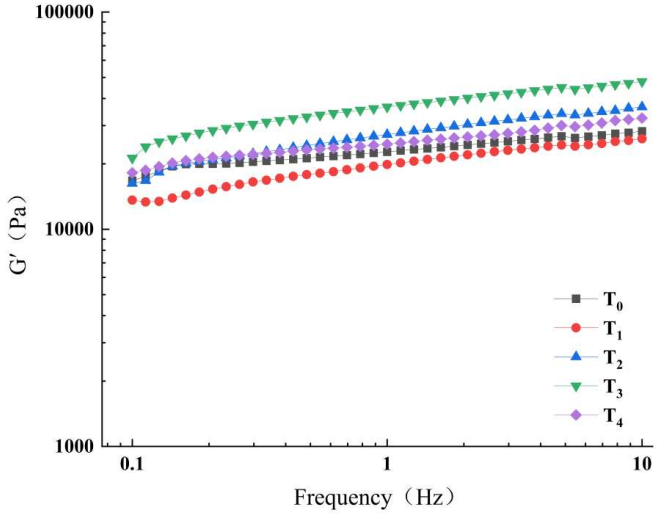


Fig. 2 Effect of GSP addition level on viscoelastic properties of PMBGs

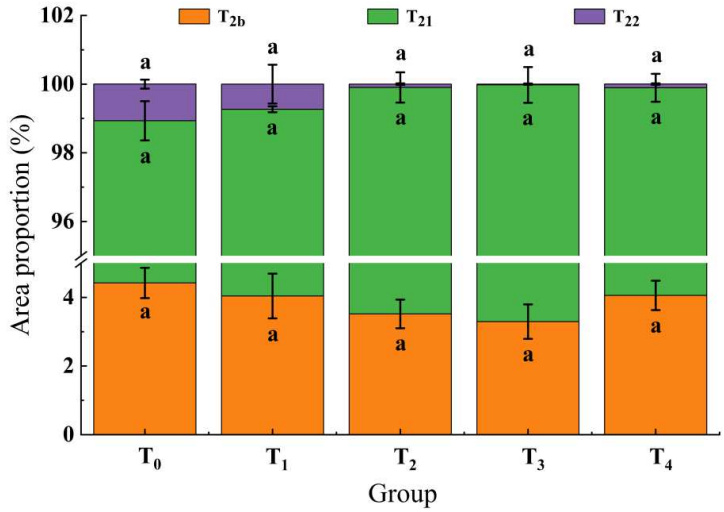
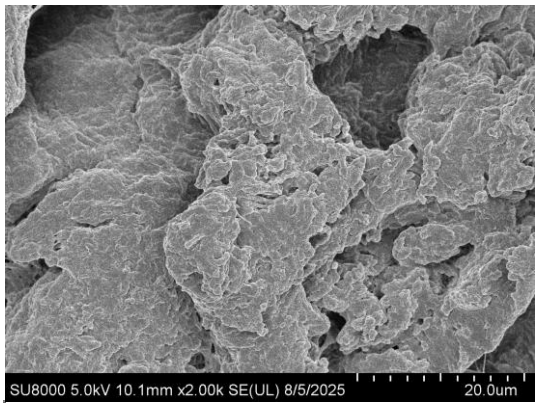


Fig. 3 Effect of GSP addition level on water mobility in PMBGs

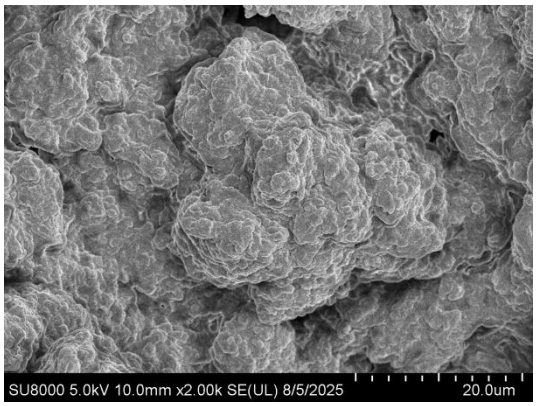
* T_{2b} peak: bound water. T_{21} peak: immobilized water. T_{22} peak: free water. Different superscript letters indicate statistically significant differences ($p < 0.05$)



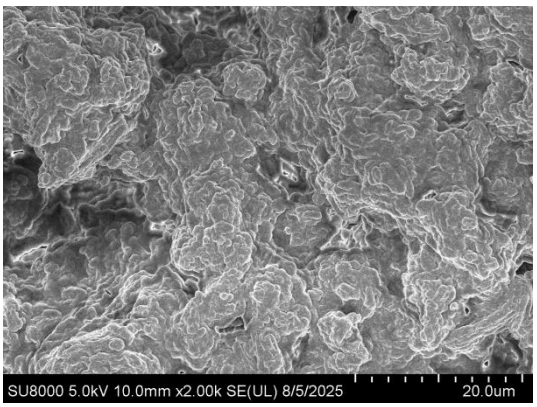
(a)



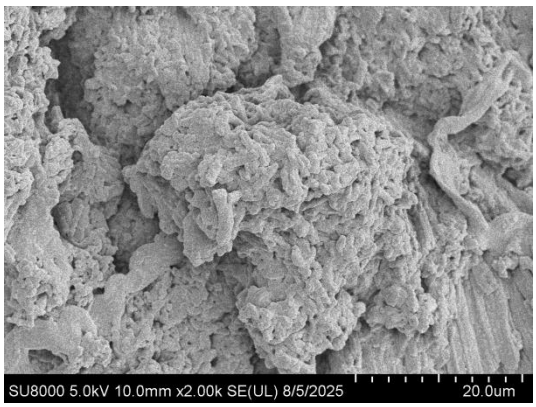
(b)



(c)



(d)



(e)

Fig. 4 Effect of GSP addition level on microstructure of PMBGs

* GSP addition: (a) control, (b) 0.1 %, (c) 0.2 %, (d) 0.4 %, and (e) 0.8 %

Magnification: 2000×. Scale bar: 20 μm