Structural regulation and functional properties of Ficus pumila polysaccharide–egg white protein composite gels: Effects of pH and polysaccharide concentration

Wenjing Jia
Lingnan Normal University
Haojun Geng
Lingnan Normal University
Panpan Wang
Lingnan Normal University
Shengjian Ma
mashengjian1@163.com
Lingnan Normal University

Article

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Structural regulation and functional properties of *Ficus pumila* polysaccharide–egg white protein composite gels: Effects of pH and polysaccharide concentration

Wenjing Jia[1], Haojun Geng[2], Panpan Wang[3], Shengjian Ma（corresponding author）[4] ✉: mashengjian1@163.com

This study constructed a compound gel system using Ficus pumila polysaccharide and egg white protein as raw materials, and systematically investigated the regulatory effects of pH (5.0–9.0) and FPP concentration (0–0.4%) on the gel's structural and functional properties. Macroscopic and microscopic analytical methods were employed to elucidate the structural evolution mechanism of the compound gel at multiple scales. The results showed that the system exhibited optimal overall performance under neutral conditions (pH 7), possessing high structural homogeneity and freeze-thaw stability; acidic conditions promoted protein molecule aggregation, forming locally dense structures, while alkaline conditions resulted in a looser network structure due to enhanced charge repulsion. Furthermore, FPP concentration exhibited a significant dual regulatory effect on the system. With increasing FPP concentration (0%–0.4%), gel hardness and chewiness generally decreased, but freeze-thaw stability initially increased and then decreased, with the lowest water separation rate (7.49%) at 0.2% FPP. Sedimentation gradually decreased with increasing polysaccharide concentration. Microstructural analysis showed that FPP and EWP formed a stable non-covalent composite network system mainly through hydrogen bonding and electrostatic interactions; no new crystal structures or covalent cross-linking were observed. In summary, this study revealed the synergistic regulatory mechanism of pH and FPP concentration on the structure and properties of the composite gel and demonstrated that this natural composite system has good structural designability and functional development potential, making it a potential functional material in fields such as food gels, edible membrane materials, fruit and vegetable preservation coatings, and probiotic protective carriers.

Keywords: *Ficus pumila* seed polysaccharide; egg white protein; composite gel; pH regulation; hydrogen bond

[1] College of Life Science and Technology, Lingnan Normal University, Zhanjiang 524048, China. [2] College of Life Science and Technology, Lingnan Normal University, Zhanjiang 524048, [3]College of Life Science and Technology, Lingnan Normal University, Zhanjiang 524048, [4]College of Life Science and Technology, Lingnan Normal University, Zhanjiang 524048

corresponding author ✉email: mashengjian1@163.com

Introduction

Gel systems are an important structural form in food colloid science. They are three-dimensional networks constructed from biomacromolecules through non-covalent interactions, capable of binding water and imparting specific textural properties and stability. In food processing and functional material design, gel systems not only affect the sensory quality of products but also determine their storage stability and processing adaptability[1,2,3].

The construction of composite gel systems based on natural polysaccharides and proteins has become an important research direction in food structure design. Compared with single-component systems, protein-polysaccharide composite systems improve the uniformity, mechanical strength, and environmental stability of gel networks through intermolecular synergistic effects, exhibiting superior structure retention under conditions such as heat treatment, freeze-thaw cycles, and pH changes[2,4,5,6]. The interaction between proteins and polysaccharides mainly involves electrostatic interactions, hydrogen bonds, and hydrophobic interactions, and is constrained by the thermodynamic compatibility of the system[7,8,9,10,11]. The pH of the system is a key factor regulating the charge state of proteins and interfacial behavior, while the polysaccharide concentration directly affects the network structure formation and phase

separation behavior2[1, 8,12,13].

Ficus pumila polysaccharide (FPP) is a natural polysaccharide with a pectin-like structure, rich in galacturonic acid units, and possesses good hydration capacity and potential gelling properties. However, FPP exhibits insufficient mechanical strength and limited stability when gelled alone[5]. Egg white protein (EWP) is a typical heat-induced gelling protein, undergoing conformational unfolding and forming a cross-linked network upon heating. However, single EWP gels are prone to water separation and structural collapse during freeze-thaw cycles and long-term storage, limiting their application in highly stable food systems [4,14,15].

Previous studies have shown that polysaccharide-protein complex systems exhibit a dual mechanism of "structure enhancement-phase separation competition": low-concentration polysaccharides enhance the network structure through bridging, while high-concentration polysaccharides induce phase separation due to thermodynamic incompatibility, weakening system stability[5,8,13]. Although significant progress has been made in the structural design and functional regulation of protein-polysaccharide complexes, systematic research on the *Ficus pumila* polysaccharide (FPP) and egg white protein (EWP) complex remains limited, particularly regarding the synergistic regulation of gel structure formation, stability, and functional properties by environmental factors (pH) and polysaccharide concentration[5,13].

This study systematically investigated the structural evolution and mechanisms of the FPP-EWP complex under different pH and FPP concentrations. Combining macroscopic performance testing and microscopic structural characterization, the study systematically revealed the regulatory mechanisms of pH and FPP concentration on the structural formation and functional properties of the complex. The results not only provide a theoretical basis for the precise design of natural polysaccharide-protein complex gels but also offer a scientific foundation for their further development into novel food functional materials such as edible film materials, fruit and vegetable preservation coatings, and probiotic protective carriers.

Materials and Methods

Materials

Ficus pumila seeds purchased online from Guiyang City, Guizhou Province, China, and were authenticated as mature seeds of *Ficus pumila* by the School of Life Science and Technology, Lingnan Normal University.

Fresh chicken eggs were purchased from a local commercial supermarket in Zhanjiang, Guangdong Province, China. They were Grade A table eggs, with a production date within 3 days at the time of purchase.

Ficus pumila polysaccharide (FPP) was extracted from *Ficus pumila* seeds by water extraction and alcohol precipitation; egg white protein (EWP) was

prepared by mechanical separation from fresh eggs. All chemical reagents were of analytical grade and could be used without further purification.

Deionized water used in the experiment was prepared using a Milli-Q ultrapure water system.

Preparation of the Composite Gel System

The method of Hu et al.[16] was followed with appropriate modifications. FPP was dissolved in deionized water and stirred at room temperature until completely dissolved to prepare polysaccharide solutions with mass fractions of 0%, 0.1%, 0.2%, 0.3%, and 0.4%, respectively. The egg white protein solution was filtered through gauze to remove impurities before use. The FPP solution and EWP solution were mixed according to the designed ratio. The pH of the system was precisely adjusted to 5.0, 6.0, 7.0, 8.0, or 9.0 using 0.1 mol/L HCl or 0.1 mol/L NaOH, and monitored using a calibrated pH meter. The mixture was heated in a 95 ℃ water bath for 30 min to induce protein denaturation and gel network formation, followed by rapid cooling to room temperature to complete the gelation process.

Texture Profile Analysis (TPA)

A texture analyzer (probe P/0.5) was used to perform double compression tests on the gel samples. The compression rate was 1.0 mm/s, the compression ratio was 50%, and the interval between the two compressions was 5 s. Each group was measured in triplicate, and the hardness, breaking

force, springiness modulus, and adhesiveness were recorded. The results were taken as mean ± standard deviation.

Sensory Evaluation

A sensory evaluation panel of 10 trained evaluators scored the appearance, texture, elasticity, and overall acceptability of the gel (10 = poor, 100 = excellent). The average value was taken.

Freeze-Thaw Stability

Determination Following the method of Lee et al. (2002)[17], the gel sample was frozen at −20 ℃ for 24 h and then thawed at 25 ℃ for 12 h, defined as one freeze-thaw cycle. Three cycles were performed. The freeze-thaw water separation capacity (WSC) of the compound system was determined using the following formula:

$$W\ (\%) = \left(1 - \frac{m}{M}\right) \times 100$$

Where W is the water separation capacity (%); m is the mass of the sample after thawing (g), and M is the mass of the sample before freeze-thaw (g).

Sedimentation and Water Holding Capacity Determination

The gel sample was placed at 4 ℃ and allowed to stand for 8 h, 20 h, 32 h, 44 h, 56 h, 68 h, and 80 h. The mass of the separated liquid at each time point was recorded to assess storage stability. Water holding capacity (WHC) was determined by centrifugation (4000 rpm, 15 min) and

calculated using the following formula:

$$\text{WHC}\ (\%) = \frac{W_{\text{d}}}{W_{\text{w}}} \times 100$$

Ww is the gel mass (g) before centrifugation, and Wd is the gel mass (g) after removing the supernatant.

Fourier Transform Infrared Spectroscopy (FTIR) Analysis

The lyophilized gel samples were characterized using an FTIR spectrometer with a scanning range of 400–4000 cm^{-1} and a resolution of 4 cm^{-1}. The peak positions and intensity changes of the amide A band, amide I band (C=O stretching), and amide II band (N–H bending) were analyzed to investigate the molecular interactions between FPP and EWP and changes in the protein's secondary structure.

X-ray Diffraction (XRD) Analysis

The crystal structure of the lyophilized samples was characterized using an X-ray diffractometer (Cu-Kα radiation source) with a scanning range of $2\theta = 5°–40°$ and a scan rate of 2°/min. The crystallization behavior and molecular packing state of the system were analyzed by examining the changes in diffraction peak positions and intensities[5] (Liu et al., 2018).

Scanning Electron Microscopy (SEM) Observation

Lyophilized samples were fixed on the sample stage, sputter-coated with gold (approximately 10 nm thick), and then their surface morphology was

observed under an accelerating voltage of 10 kV. The three-dimensional microstructure and pore distribution characteristics of the composite gel were analyzed.

Data Processing and Analysis:

All experimental data are expressed as mean ± standard deviation. One-way ANOVA and Tukey multiple comparisons were performed using SPSS software. The significance level was set at $p < 0.05$.

3. Results and Analysis

3.1 Effect of pH on Gel Properties of FPP-EWP Composite System

3.1.1 Textural Properties and Sensory Evaluation

The textural properties of the FPP–EWP composite gel differed significantly under different pH conditions (Fig. 1. a-e). Gel hardness decreased monotonically with increasing pH (5→9), with the highest hardness at pH 5 and the lowest at pH 9; the initial modulus showed a similar trend to hardness. The breaking force increased with increasing pH; the gel's resistance to breakage was higher under alkaline conditions than under acidic conditions, indicating that the high pH system has a larger elastic deformation space. Adhesion was strongest at pH 9, decreasing sequentially with decreasing pH in the other groups.

Considering all textural indices, the pH 5 and pH 6 systems exhibited moderate hardness and good structural integrity; the pH 7 system showed the most balanced indices and the most stable gel network structure; the pH 8 and pH 9 systems showed high adhesion and enhanced interfacial interactions.

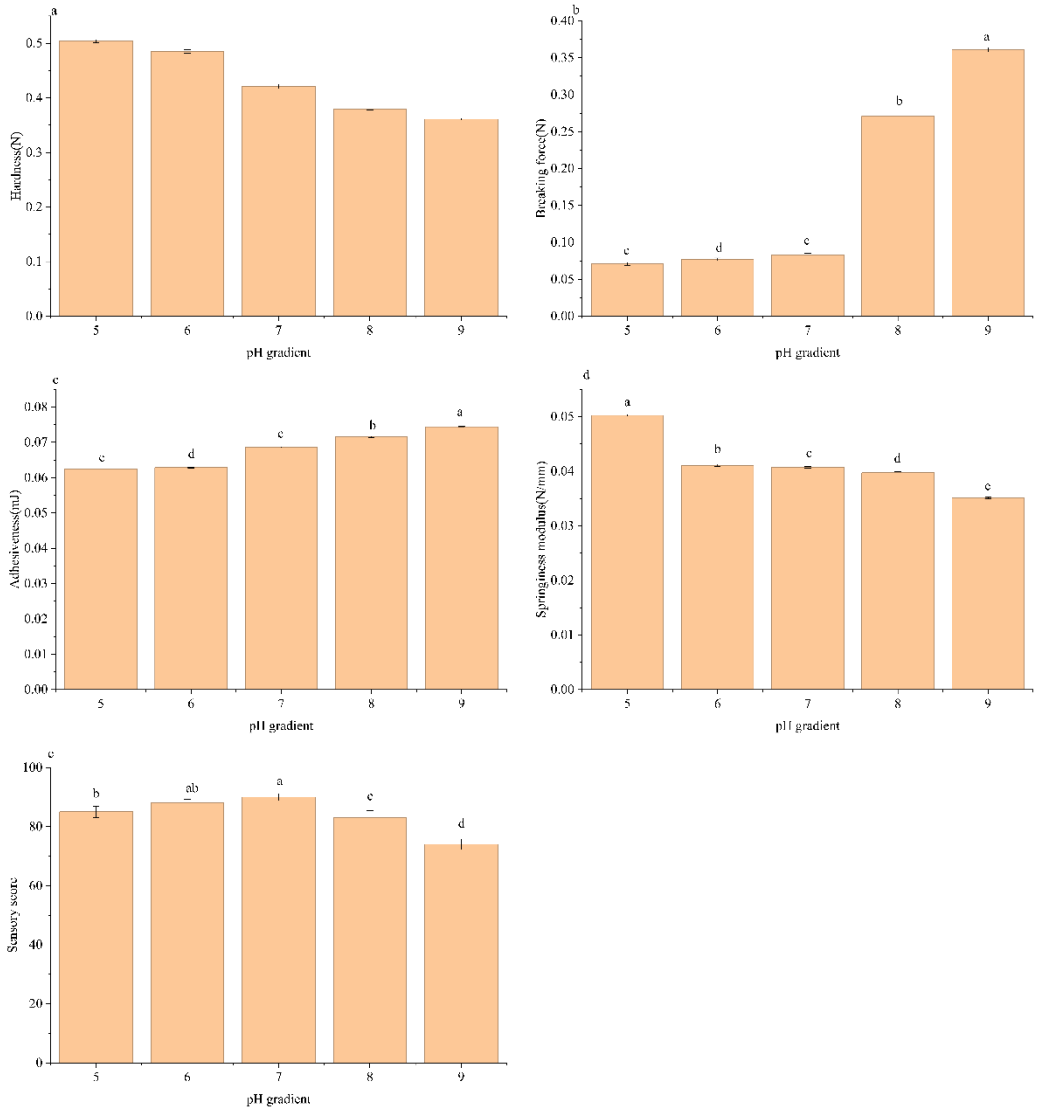

Fig. 1 Textural properties(a-e), including hardness, breaking force, adhesiveness, springiness modulus, and sensory score of FPP-EWP composite gels at different pH gradient

3.1.2 Freeze-thaw stability:

As the pH increased from 5 to 7, the freeze-thaw water-holding capacity of

the FPP–EWP complex system continuously improved (Fig. 2 f): the water-holding capacity was lowest at pH 5 (33.24%), and highest at pH 7 (40.01%). When the pH further increased to 8–9, the water-holding capacity decreased slightly, but remained higher than that under acidic conditions.

The effect of pH on freeze-thaw stability stems from its regulation of network structure uniformity: under neutral conditions, the electrostatic interactions between proteins and polysaccharides are in dynamic equilibrium, forming a continuous and uniform three-dimensional network with the strongest binding capacity for free water and weakly bound water; under acidic and weakly alkaline conditions, protein conformational changes and intermolecular interactions become unbalanced, network uniformity decreases, water migration increases, and water-holding capacity decreases.

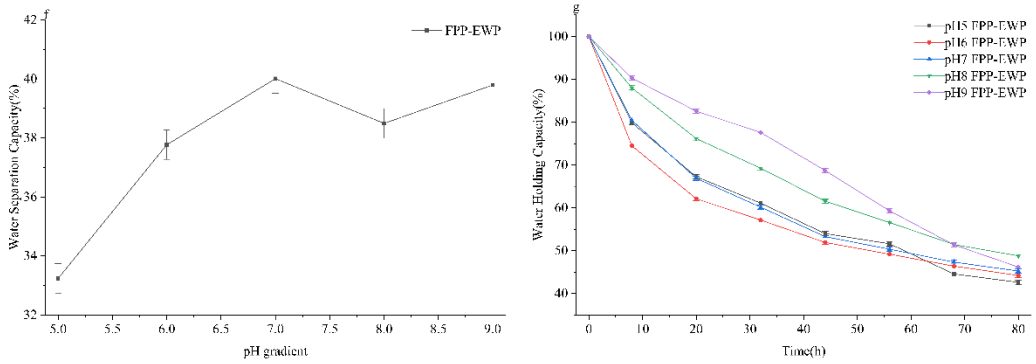

Fig. 2 Water separation capacity and water holding capacity during 80h storage of FPP-EWP composite gels at different pH gradient are shown in (f) and (g)

3.1.3 Sedimentation Properties

During storage of 0–80 h, the water-holding capacity of the gels in

each pH treatment group showed a continuous decreasing trend ($p < 0.05$) (Fig. 2 g). In the early stage of storage (0–56 h), the weakly alkaline system had a higher water-holding capacity, ranked as follows: pH 9 > pH 8 > pH 7 > pH 5 > pH 6, indicating that a weakly alkaline environment is beneficial for maintaining the initial water binding capacity. With the extension of storage time, the changes in water-holding capacity of each group became differentiated: the pH 9 group showed an accelerated decrease after 56 h, with the most significant structural degradation; the pH 7 and pH 8 groups showed a relatively gentle decreasing trend, exhibiting better long-term structural stability; under acidic conditions (pH 5, pH 6), the water-holding capacity of the system remained at a low level, and the gel network stability was poor. At the end of 80 h, the final ranking of water-holding capacity of each group was: pH 8 > pH 7 > pH 6 > pH 9 > pH 5. Slightly alkaline conditions are beneficial for maintaining the long-term storage stability of the FPP–EWP compound system; excessively alkaline conditions will accelerate network rearrangement and moisture migration, and the stability will decrease in the later stage; acidic conditions significantly enhance the tendency of precipitation, but the systems tend to reach a certain degree of structural equilibrium at the end of long-term storage.

3.1.4 X-ray diffraction (XRD)

XRD results of the FPP–EWP complex system under different pH conditions (Fig. 3. h) and key peak parameters are shown in Table 1.

Significant differences were observed in the FWHM values among the groups, ordered as pH 5 < pH 7 < pH 9 < pH 8 < pH 6. The diffraction peak in the pH 5 group shifted to higher angles, indicating that the acidic environment promoted the orderly aggregation of FPP and EWP molecules, enhancing short-range order. Intermolecular ordering weakened under pH 6 and pH 8 conditions, resulting in a relatively increased degree of disorder in the system. The complex system at pH 7 and pH 9 exhibited relatively stable structures. Peak position changes reflected alterations in interlayer spacing and intermolecular forces: the peak positions at pH 5 and pH 9 were significantly higher than those at pH 6, 7, and 8, indicating that extreme acid-base conditions altered the hydrogen bonds and electrostatic interactions between FPP–EWP, causing changes in interlayer spacing. Peak area reflects the content of ordered regions in the system. The peak area is largest at pH 9 and smallest at pH 7. Combined with FWHM value analysis, the total amount of ordered regions in the pH 9 group is relatively large, but the regularity of their arrangement is generally low, while the total amount of ordered regions in the pH 7 group is relatively small and the regularity of their arrangement is low.

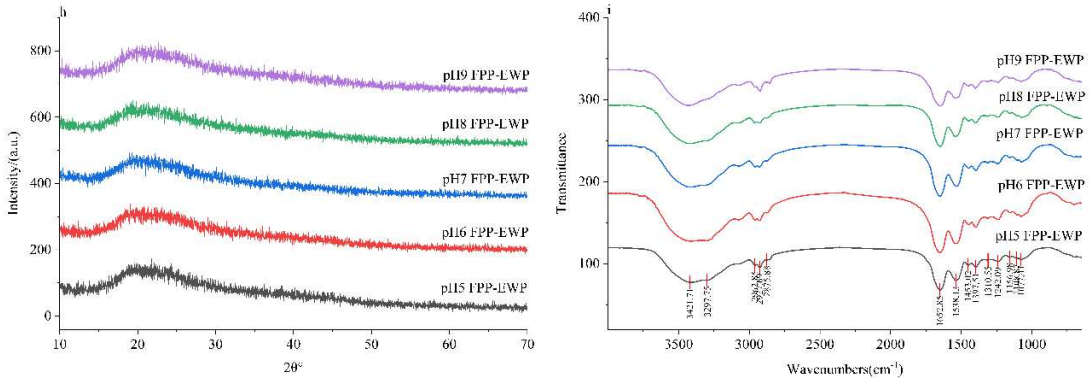

Fig. 3 Structural characteristics of FPP-EWP composite gels at different pH gradient are presented in (h) and (i)

Tab.1 XRD Peak Analysis Data Table

pH	Max Height	X at Max Height	Area	FWHM
5	98.43098	21.81	240.7	10.5243
6	81.66705	19.03	428.32	13.77932
7	79.54244	19.27	103.74	13.32788
8	77.54187	19.35	117.18	13.70564
9	108.1629	22.71	1260.64	13.44823

3.1.5 Fourier Transform Infrared Spectroscopy (FTIR)

FITR was used to characterize the lyophilized FPP–EWP compound gel powder under different pH conditions (Fig. 3. i). The results showed that the peaks of each group were basically consistent under different pH conditions, with no new covalent bonds formed, and the chemical structure of the system was stable in the pH range of 5–9 (Fig. 1 g). The main absorption peaks were assigned as follows: a broad peak at 3600–3000

cm^{-1} (O–H/N–H stretching vibration), 2925.53 cm^{-1} (C–H stretching vibration), 1648.87 cm^{-1} and 1537.01 cm^{-1} (Amide I band C=O stretching and Amide II band N–H bending vibration), 1398.16 cm^{-1} (pectin COO- symmetric stretching), and 1200–1000 cm^{-1} (polysaccharide C–O–C glycosidic bond vibration). The pH 6 group showed the highest absorption intensity in the O–H/N–H, amide I/II bands and C–O–C vibrational regions, indicating that hydrogen bonding and non-covalent interactions were most significant under near-neutral conditions, resulting in the best gel network density.

3.2 Effect of FPP Concentration on Gel Properties of FPP-EWP Blended System

3.2.1 Texture Measurement and Sensory Evaluation

With increasing FPP concentration, the hardness of the blended gel showed a trend of first increasing and then decreasing: the 0.2% FPP group had the highest hardness (0.678 N), which was 50.2% and 157.8% higher than the 0.3% and 0.4% groups, respectively. The initial modulus showed a consistent trend with the hardness. The sensory evaluation score also decreased with increasing FPP concentration, indicating that the gel quality decreased with increasing FPP concentration (Fig. 4. j-n).

It is speculated that low concentrations of FPP (≤0.2%) form additional physical cross-linking points with EWP through intermolecular

hydrogen bonds, moderately increasing the rigidity of the gel network; high concentrations of FPP (>0.2%) induce thermodynamic phase separation, leading to increased network pore size, decreased continuity, and significantly reduced hardness and chewiness.

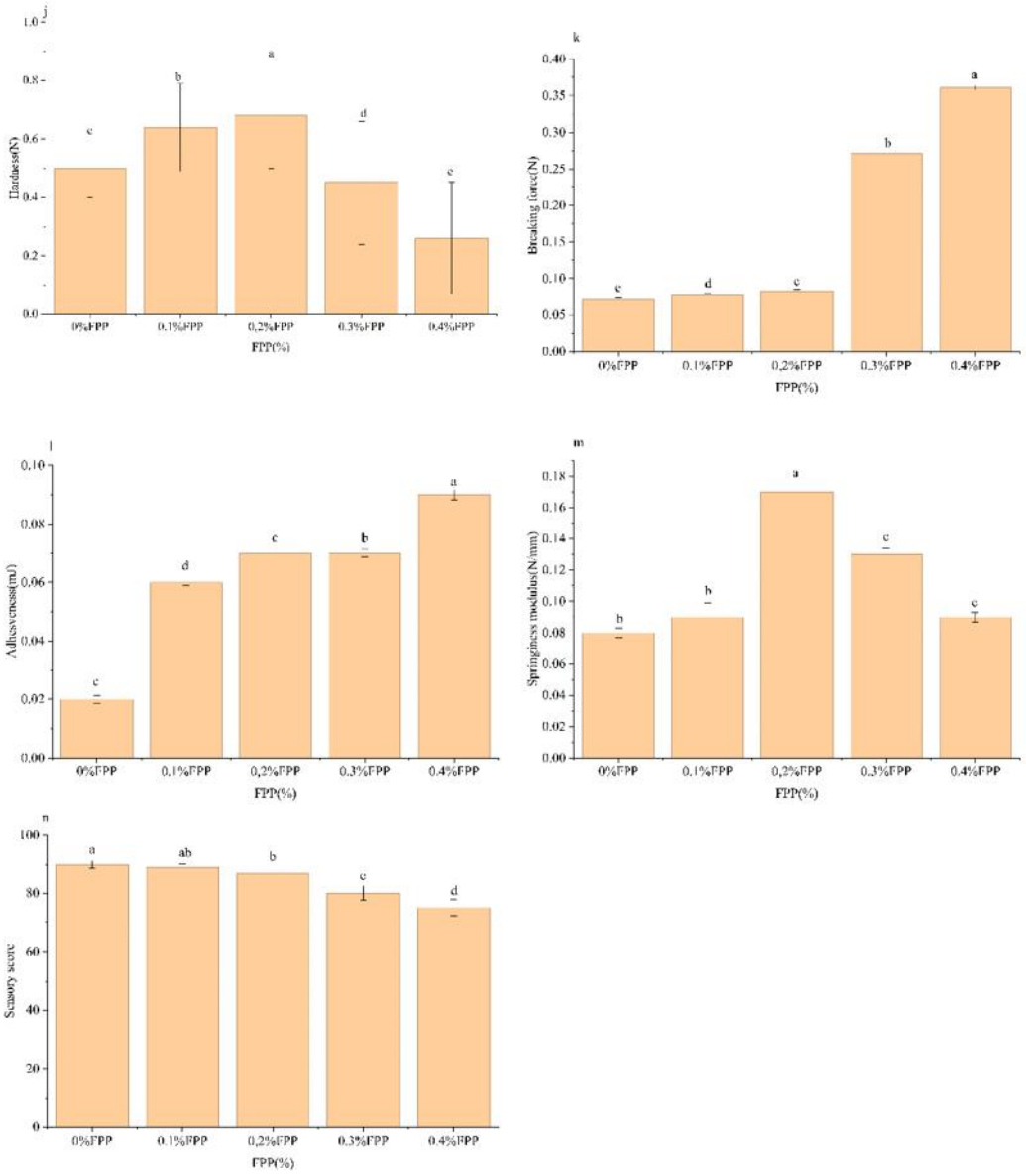

Fig. 4 Textural properties(j-n), including hardness, breaking force, adhesiveness, springiness modulus, and sensory score of FPP-EWP composite gels at different FPP concentrations

3.2.2 Freeze-thaw stability

With increasing FPP concentration, the freeze-thaw water separation rate

first decreased and then increased: the water separation rate of the blank group (0% FPP) was 11.43%; the water separation rate of the 0.1%–0.2% FPP group decreased to about 7.49%; and the water separation rate of the 0.3%–0.4% FPP group increased significantly (Fig. 5. o). The intermolecular hydrogen bonds introduced by low-concentration FPP make the three-dimensional network structure more compact, effectively encapsulating water and inhibiting ice crystal migration during freeze-thaw, thus improving freeze-thaw stability; high-concentration FPP causes phase separation due to thermodynamic incompatibility, resulting in a looser network and decreased water holding capacity.

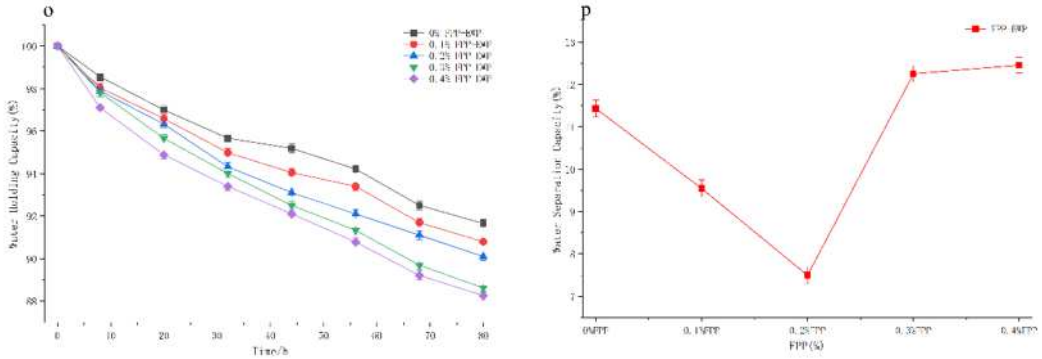

Fig. 5 Water separation capacity and water holding capacity during 80h storage of FPP-EWP composite gels at different FPP concentrations are shown in (o) and (p)

3.2.3 Sedimentation Properties

During storage (0–80 h), the water-holding capacity of gels at all FPP concentrations continuously decreased ($p < 0.05$) (Fig. 5. p). Within the same storage time, the water-holding capacity decreased with increasing FPP concentration, indicating that high FPP concentration exacerbated the

phase separation tendency during refrigerated storage. The mechanism is as follows: with increasing FPP concentration, network order decreases, peptide chain flexibility increases, and the network structure is more prone to relaxation and rearrangement during long-term refrigeration; the increased thermodynamic incompatibility between FPP and EWP further promotes phase separation, causing a continuous decrease in the water-holding capacity of the gel network, continuous precipitation of the supernatant, and a continuous decrease in sedimentation with increasing FPP concentration.

3.2.4 X-ray diffraction (XRD)

XRD showed broad diffuse scattering peaks at $2\theta \approx 20°$ for all FPP concentration groups and the control group, with no sharp crystalline diffraction peaks. This indicates that the composite gel system has an amorphous (non-crystalline) structure, and no new crystalline complex has formed between FPP and EWP. Their interaction is mainly non-covalent (Fig. 6. q). With increasing FPP concentration, the intensity gradient of the diffuse peak at $2\theta \approx 20°$ increased and gradually shifted to higher angles, indicating a decrease in molecular packing distance. The introduction of FPP altered the aggregated arrangement of protein molecules, enhancing the non-covalent interactions (especially intermolecular hydrogen bonds) between FPP and EWP, which to some extent improved the rigidity of the gel network. However, the macromolecular thermodynamic

incompatibility effect induced by high FPP concentration partially offset the effect of hydrogen bond enhancement.

Key parameters of the XRD diffraction peaks for the composite system at each FPP concentration are shown in Table 2. The 0.2% FPP group had the smallest FWHM (21.62°) and the highest peak intensity, indicating that the composite gel at this concentration had the best molecular order and the largest grain size.

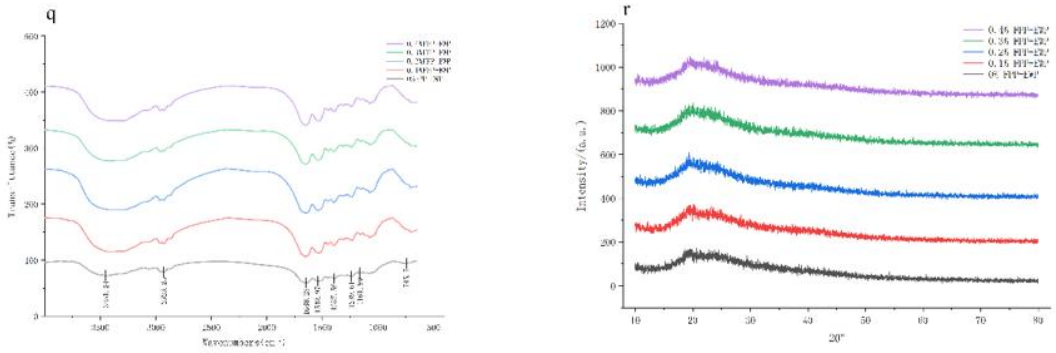

Fig. 6 Structural characteristics of FPP-EWP composite gels at different FPP concentrations are presented in (h) and (i)

Tab.2 XRD Peak Parameters of FPP-EWP composite Gels at Different Concentrations

FPP%	**Max Height**	**X at Max Height**	**Area**
0%	170	20.63	31.62
0.1%	194	19.99	27.78069
0.2%	229	19.37	21.62225
0.3%	218	20.07	24.56118
0.4%	203	19.45	25.30179

3.2.5 Fourier Transform Infrared (FTIR) spectroscopy

The FTIR spectra of FPP–EWP composite gels at various concentrations all exhibited consistent characteristic protein absorption peaks (Fig. 6. r): approximately 3300 cm^{-1} was the amide A band (contributed by the superposition of N–H and O–H stretching vibrations); the weak peak at approximately 2925 cm^{-1} was due to C–H stretching vibrations; the amide I band was near 1640 cm^{-1} (C=O stretching vibrations); and the amide II band was approximately 1530 cm^{-1} (contributed by the superposition of N–H bending and C–N stretching vibrations). After the addition of FPP, the overall shape of the FTIR spectrum remained unchanged, but the amide A band showed a significant blue shift, indicating that the introduction of FPP enhanced the hydrogen bonding interactions in the system[9,18].

3.2.6 SEM

SEM observation showed that the 0% FPP–EWP gel exhibited a continuous, dense, and uniform three-dimensional network structure with small and concentrated pores, smooth and uniformly thick network walls, and good connectivity, which is typical of EWP thermally induced gels. With increasing FPP concentration, the gel network pore size gradually increased, and the structure became more porous; the 0.3% and 0.4% FPP groups showed significantly reduced network continuity, larger pores, and a more porous structure (Fig. 7. s).

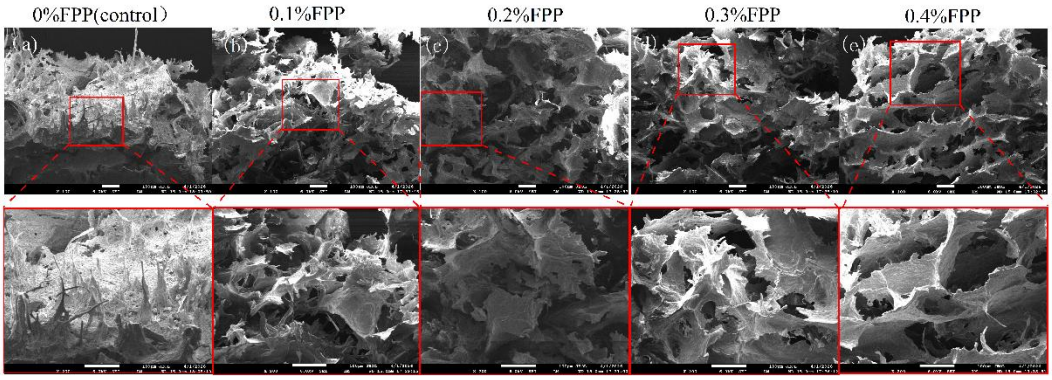

Fig. 7 SEM micropttuctures of FPP-EWP composite gels at different FPP concentrations are shown in (s),upper row: 100x, scale bar =100 um; lower row: 200x, scale bar = 50 pm.

4. Discussion

4.1 Synergistic Effect Mechanism of pH on Complex Gel Systems

pH influences intermolecular electrostatic interactions and spatial conformation by altering the ionization degree of protein surface groups, making it a key environmental factor regulating the structure of protein-polysaccharide complex systems[4,14]. In the FPP-EWP system, the regulation of the EWP charge state and its interaction mode with FPP by pH directly determines the macroscopic mechanical properties and water-holding capacity of the gel.

When the system pH approaches the isoelectric point of the protein, the net surface charge of the EWP decreases, intermolecular electrostatic repulsion weakens, and local protein aggregation and the formation of a dense structure are promoted. However, this structure exhibits poor uniformity and low network continuity, consistent with the reports of

Tolstoguzov (1997) and McClements (2015) on the thermodynamic behavior of biomacromolecule gels[2,19]. Under neutral conditions, the surface charge distribution of proteins is balanced, electrostatic interactions are in a dynamic stable state, and protein-polysaccharide interactions tend to be balanced, forming a continuous and uniform three-dimensional network. This results in optimal overall gel performance, consistent with the conclusions of Schmitt et al. (1998)[18] and Turgeon et al. (2007)[13] regarding the formation mechanism of the protein-polysaccharide complex system. When the pH deviates from neutral, gel performance declines: under acidic conditions, local aggregation is enhanced, but network heterogeneity leads to decreased gel elasticity and brittle fracture[1,20]; under alkaline conditions, the density of negative charges on molecular surfaces increases, electrostatic repulsion is enhanced, the gel network becomes loose, and both strength and water-holding capacity decrease[21]. This multiscale correlation between molecules, networks, and macroscopic properties is consistent with the multiscale colloidal structure stability theory described by McClements (2015)[19], and has also been widely reported in whey protein-polysaccharide systems[5,12].

4.2 Synergistic Effect Mechanism of FPP Concentration on Composite Gel Systems

The structural stability of the FPP–EWP composite system originates from the driving force of non-covalent interactions (hydrogen bonds and

electrostatic interactions) on gel network formation[13]. Low concentrations of FPP, uniformly dispersed in the protein network, enhance cross-linking density through hydrogen bonds and molecular chain entanglement, thereby improving gel strength and water-holding capacity, consistent with the general principle of the "structural enhancement effect" in protein-polysaccharide systems[4,9,10,14]. As FPP concentration increases, intermolecular interactions of polysaccharide molecules strengthen and gradually occupy protein binding sites, leading to increased thermodynamic incompatibility, microphase separation, decreased network continuity, and deterioration of gel properties. This aligns with the phase separation-driven mechanism of biomacromolecule systems [8,13,15,22]. High concentrations of FPP also restrict protein rearrangement by enhancing chain entanglement and local enrichment effects, resulting in a more heterogeneous system structure[7]. Overall, FPP exhibits a biphasic regulatory mechanism in complex systems: "low concentration enhances structure – high concentration disrupts phase separation"[13,19,22], consistent with typical biomacromolecule gel structure transitions and network evolution mechanisms.

5. Conclusion

This study constructed a compound gel system using FPP and EWP as raw materials. Through macroscopic characterization (texture analysis, freeze-thaw stability, sedimentation) and microscopic techniques (FTIR,

XRD, SEM), the synergistic regulatory mechanism of pH and FPP concentration on the structure and functional properties of the gel was systematically elucidated. The results showed that pH affects the gel network structure by regulating intermolecular electrostatic interactions. Under acidic conditions (pH 5), the gel exhibited the highest hardness and strongest short-range order, but poor freeze-thaw and long-term storage stability. Under neutral conditions (pH 7), the gel showed the best overall texture and freeze-thaw stability (water holding capacity 40.01%). Under weakly alkaline conditions (pH 8), the gel showed the best long-term refrigerated sedimentation stability. The regulation of EWP gel by FPP concentration exhibited a concentration-dependent biphasic effect. Low-concentration FPP (0.2%) enhances gel network rigidity through intermolecular hydrogen bonds, minimizing freeze-thaw water separation (7.49%) and achieving peak hardness (0.678 N). High-concentration FPP (>0.2%) induces phase separation due to thermodynamic incompatibility, leading to a comprehensive decrease in gel hardness, chewiness, and water retention.

This study reveals the multi-factor regulation of FPP–EWP composite gels, providing parameter guidance for formulation design in food systems: 0.2% FPP and a pH of 7 are recommended for high freeze-thaw stability requirements; a slightly alkaline pH of 8 is suitable for long-term cold storage. Furthermore, this system demonstrates its potential as a

biocompatible and processable natural composite material platform in food gels, edible film preparation, fruit and vegetable preservation coatings, and probiotic delivery and protection. Future research can further integrate membrane performance evaluation, active substance encapsulation, and food storage experiments to expand its practical applications in the field of functional food materials.

Data availability

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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Author contributions

W.J. Jia: Writing – original draft, Investigation, Formal analysis, Writing – review & editing, Methodology, Data curation

H.J. Geng：Investigation, Formal analysis, original draft

P.P. Wang: Investigation, Data curation

S.J. Ma: Methodology

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Declarations

Materials and Methods

All methods were carried out in accordance with relevant guidelines and regulations. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

The experimental protocol of the sensory evaluation was reviewed and approved by the Ethics Committee of the School of Life Science and Technology, Lingnan Normal University (Approval No. LSKY-2025-018).

Written informed consent was obtained from all individual participants included in the study.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to W.J. Jia and H.J. Geng