Food Science of Animal Products

Research Article

High-internal-phase emulsions stabilized by red ginseng and white ginseng as a fat substitute in meat sausages: effects on texture, flavour, and digestive properties

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Abstract: This study investigated the effects of red ginseng (RG) and white ginseng (WG) on complex coacervate high-internal-phase emulsions (HIPEs) stabilized by ovalbumin (OVA) and chitosan (CS) and their application in sausage fat replacement. Texture profile and rheological analyses demonstrated that the incorporation of RG and WG promoted interprotein cross-linking, significantly enhancing the centrifugal stability, pseudoplastic behavior, and viscoelastic moduli of the HIPEs, with 1% WG notably maximizing emulsion hardness and resilience index. By replacing 43.75% of pork backfat, the HIPEs effectively mimicked lipid functionalities and improved sausage texture. Furthermore, the RG and WG groups showed increased relative contents of alcohols and terpenoids, which corresponded with the reduced bitterness scores and enhanced flavor intensity. Notably, the 1.5%-RG group exhibited 2.21 times higher maximum digestibility, with 1,1-diphenyl-2-picrylhydrazyl radical and 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) cation radical scavenging capacities increasing by 1.21 and 1.15 times, respectively. This study provided a novel strategy for low-fat sausage development, expanded the application of OVA-CS composite coacervates in HIPEs, and highlighted the dual roles of RG and WG in HIPE stabilization and sausage flavor enhancement, which is of great significance for promoting the development and production of low-fat foods.

Keywords: high-internal-phase emulsions; complex coacervate; fat substitute

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1 Introduction

Gel-type meat products constitute a significant source of high-quality protein, providing the human body with essential amino acids that promote muscle growth and repair, whilst being rich in various vitamins and minerals[1]. In gel-type meat products, fat not only stabilises the gel structure through interactions with proteins but also significantly influences the product's texture, juiciness, mouthfeel and flavour[2]. Traditional sausages rely on pork backfat to enhance texture and juiciness, containing up to 30%. However, excessive consumption of pork back fat increases cardiovascular risks, contributes to obesity, and triggers metabolic disorders[3]. The development of low-fat foods aligns with consumers' health requirements, making it imperative to reduce the fat content in sausages. However, due to the characteristics of fat in sausages, simply reducing it may result in poor texture and negatively impact water retention, emulsion stability, and sensory qualities[2]. Traditional fat-reduction strategies often fail to replicate the sensory and nutritional qualities of animal fat. Therefore, it is necessary to identify a method that combines gel stability with flavour simulation capabilities to achieve fat replacement.

Traditional emulsions, due to their heavy reliance on emulsifiers or synthetic surfactants, exhibit significant drawbacks including safety concerns, poor stability, deterioration in sensory qualities, and environmental unfriendliness[4–5]. Novel fat alternatives such as oil gels, hydrogels, water-in-oil emulsions, and high-internal-phase emulsions (HIPEs) have emerged as promising solutions[6]. Among them, HIPEs requires fewer stabilisers, exhibits higher stability, and has a semi-solid, high-viscosity texture, demonstrating research and application potential in the food industry. Compared to traditional emulsions, HIPEs possess a highly concentrated internal phase (volume fraction exceeding 0.74) and a tightly packed interfacial network[4]. This unique structural advantage effectively prevents lipid coalescence and phase separation during the rigorous thermal processing of complex meat matrices, making HIPEs vastly superior for meat applications[7–8]. These properties make HIPE a strong candidate for fat replacement applications. However, HIPE is prone to lipid oxidation, posing a significant challenge to its stability. To mitigate this limitation, antioxidants such as red ginseng (RG) and white ginseng (WG) can be added to reduce lipid oxidation and enhance the performance of HIPE in fat replacement systems[9].

Currently, HIPE prepared from protein-polysaccharide mixtures has attracted widespread attention from researchers. Among them, composite-coacervated HIPEs formulated with ovalbumin (OVA)

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and chitosan (CS) exhibit distinct advantages. OVA, possessing an amphiphilic structure with a hydrophobic amino acid core and a hydrophilic amino acid shell, forms a dense adsorption layer at the oil-water interface, rendering it an excellent natural protein emulsifier[10]. As a functional polysaccharide, CS exhibits outstanding biocompatibility, antimicrobial activity, and high biodegradability[11]. Mechanistically, the complex coacervation between OVA and CS is primarily driven by spontaneous electrostatic attraction between the deprotonated carboxyl groups ($-COO^-$) of OVA and the protonated amino groups ($-NH_3^+$) of CS within a specific pH window. This cooperative pairing establishes a highly ordered, viscoelastic interfacial network around the oil droplets, providing robust steric hindrance that effectively suppresses droplet flocculation[12]. Previous studies demonstrated that OVA-CS stabilized HIPEs could effectively substitute animal fat in meat products, successfully maintaining their fundamental structure and texture[13]. However, the HIPE matrix contains abundant lipids, making it highly susceptible to lipid oxidation during processing. To overcome this limitation and endow the sausages with further health benefits, introducing natural antioxidants served as an ideal strategy. Ginseng is a distinctive agricultural product of Northeast China, particularly Jilin Province, renowned for its abundant resources and widespread popularity, earning it the esteemed title of 'King of Herbs'. Containing diverse bioactive compounds such as ginsenosides, ginseng polysaccharides, fatty acids, flavonoids, vitamins, and minerals, ginseng exhibits potent effects including anti-cancer, anti-aging, antioxidant, hypoglycaemic, and immune-modulating properties[14]. Common types of ginseng include RG and WG. RG is steamed, generating rare ginsenosides and antioxidant-rich Maillard reaction products, which specifically contribute to robust lipid oxidation inhibition and prominent flavor enhancement. Conversely, WG is naturally dried, retaining native high-molecular-weight polysaccharides that primarily provide superior structural reinforcement to the emulsion network and exhibit a unique capacity for bitterness regulation and masking. Both RG and WG contain bioactive compounds with strong antioxidant properties and flavor-improving capabilities. Consequently, incorporating ginseng as a natural antioxidant into sausages presents an ideal solution. However, existing research reports on employing ginseng alongside OVA-CS-stabilised HIPE technology for producing low-fat sausages remain relatively scarce.

This study aims to explore an innovative fat replacement strategy by preparing composite cohesive HIPEs stabilised with varying concentrations of RG and WG, investigating its texture, rheological properties, and other characteristics, and applying it to sausages. The study analysed the effects of RG and WG on the texture, colour, sensory characteristics, volatile compounds (VOCs), *in vitro* digestive behaviour, and oxidative stability of sausages. The findings of this study are expected to provide the gel-type meat products with a novel fat replacement solution that combines nutritional and functional benefits, driving the development of low-fat, high-nutrient meat products, while also offering theoretical and practical references for the development of other functional foods.

2 Materials and methods

2.1 Materials and reagents

OVA (A5253) was provided by Sigma Chemical Co. (St. Louis, MO, USA). CS (R051552, M_w = 300 000 Da, deacetylation ~85%) was procured from Shanghai Yien Chemical Technology Co., Ltd. (Shanghai, China). First-grade soybean oil (Fulinmen), seasoning, lean pork, and pork backfat were both procured from Eurasian supermarkets (Changchun, China). RG and WG were procured from Changbai Mountain (Baishan, China). All other chemicals used in this paper were supplied by Sinopharm Chemical Reagent Co., Ltd. (Shanghai, China). All food-grade ingredients were provided by Hebei Jiante Biotechnology Co., Ltd. (Hebei, China).

2.2 Preparation of OVA-CS complex coacervation solution

OVA powder was weighed and wholly dissolved in pure water to get the OVA solution (3 g/100 mL). CS powder was dissolved in acetic acid solution (1 g/100 mL) and stirred (8 000 r/min) at room temperature to obtain CS solution (1 g/100 mL). The two solutions were mixed according to the volume ratio of 3:1 and continued to be stirred thoroughly (8 000 r/min), then citric acid (1 mol/L) and sodium bicarbonate solutions (1 mol/L) were used to adjust the pH of the mixed solution system from 3.5 to 6.5. After the system's pH was stabilized, RG and WG were added to the system at mass fractions of 0.5%, 1% and 1.5%, respectively, thoroughly mixed and stirred for 1 h.

2.3 Preparation of HIPEs

Under pH 6.0, 10 mL of OVA-CS composite coagulation solution of different concentrations of RG and WG were mixed with 30 mL soybean oil. Subsequently, the mixture was homogenized at 12 000 r/min for 3 min using a high-speed homogenizer (T25 digital Ultra-Turrax, IKA, Germany) to produce HIPEs[13].

2.4 Dynamic light scattering and zeta potential measurements

The average particle size, polydispersity index (PDI) and zeta potential of HIPEs were characterized at ambient temperature via a Zetasizer Nano ZS90 (Malvern Instruments, Worcestershire, UK). Samples were equilibrated for 120 s prior to detection, with a minimum of 11 scanning cycles per measurement. Each measurement was conducted at 25 °C and performed in triplicate[15].

2.5 Texture profile analysis (TPA) of HIPEs

To evaluate the texture characteristics of HIPEs, hardness, resilience index, chewiness, cohesiveness, and gumminess of HIPEs were measured at room temperature (25 °C) using a texture analyzer (CT3-4500g, Brookfield, USA). The gel was compressed twice with a cylindrical probe of 10 mm diameter (p/0.5) at 40% compression[16]. All measurements were performed in triplicate with new samples.

2.6 Rheological measurements

A rheometer (AR-1000, TA, USA) fitted with 40 mm steel parallel plates was employed to monitor variations in the rheological properties of the samples. Freshly prepared HIPEs (2 mL) were added to the plates, and the gap was set at 1 000 μm. To prevent evaporation during measurements, the exposed sample edge was covered with a thin layer of dimethyl silicone oil. The samples were allowed to equilibrate at 25 °C for 10 min and then performed the test. The apparent viscosity of the HIPEs was tested by setting a shear rate range of 0.01–100 s^{-1}, with one data point acquired per second over a total test duration of 60 s. In a similar manner, freshly

prepared HIPEs (2 mL) was repositioned, and the sample was left on the instrument platform for a 30-min interval for frequency scan testing. The specific parameters included a strain of 1%, and the storage modulus (G') and loss modulus (G'') were measured at 25 °C across a frequency range of 0.1–500 Hz in order to ascertain their frequency-dependent variations.

2.7 Centrifugal stability measurement

The centrifugal stability of each HIPE sample was assessed by calculating the change in mass before and after centrifugation at 12 000 × *g* and 4 °C for 15 min according to Eq. (1)[17]:

$$\text{Centrifugal stability}\,(\%) = \frac{m_2}{m_1} \times 100 \quad (1)$$

Where m_1 and m_2 represent the mass of HIPEs before and after centrifugation (g), respectively.

2.8 Meat sausage preparation

The preparation of meat sausage was slightly modified with reference to the previously described method[13], and the sausage recipe was detailed in Table 1. Each group was added with an equal amount of 1.5% (*m*/*m*) sodium salt, 1% garlic powder, 1% pepper, 1% sugar, 2% soybean isolate protein, 5% starch, and 0.005% sodium tripolyphosphate mixed and chopped for 30 min to make the materials mix well. Finally, the multifunctional smoker (DBXZ50, Hebei Xiaojin Machinery Manufacturing Inc., Shijiazhuang, China) was applied for meat sausage drying, steaming, and smoking. Each set of meat sausage was made in triplicate.

Table 1 Components and addition amounts (g) of sausage.

Group	Lean pork	Pure water	Pork backfat	HIPES	RG	WG
Control	240	80	80	0	0	0
0.5%-RG	240	80	45	35	2.01	0
1%-RG	240	80	45	35	4.04	0
1.5%-RG	240	80	45	35	7.06	0
0.5%-WG	240	80	45	35	0	2.01
1%-WG	240	80	45	35	0	4.04
1.5%-WG	240	80	45	35	0	7.06

2.9 TPA determination of meat sausage

For the TPA test, the meat sausages were equilibrated at room temperature for at least 1 h and then trimmed into cylindrical samples (2 cm in both height and diameter) according to the previously described method[18]. The samples were compressed twice using a cylindrical probe with a diameter of 10 mm (P/0.5). Each sample underwent two consecutive compressions to 50% of its original height using a pre-test speed of 5.0 mm/s, a test speed of 2.0 mm/s, and a post-test speed of 5.0 mm/s, with a 5-s interval between compressions and a trigger force of 5.0 g.

2.10 Color determination of meat sausage

The sausage samples were sliced into 1 cm thick sections and their color was measured using a colorimeter (CR-400, Konia Minolta, Tokyo, Japan). L^*, a^* and b^* were determined to indicate lightness, redness and yellowness values, respectively. The color difference (ΔE) was calculated according to Eq. (2):

$$\Delta E = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \quad (2)$$

Where ΔL^*, Δa^* and Δb^* are the differences between the control and each of the experimental samples.

2.11 Flavour analysis

2.11.1 Sensory evaluation

Fifteen members from the Nutrition and Functionality Laboratory of Food Science and Engineering of Jilin University with experience in sensory evaluation were selected to conduct sensory evaluation. The products were randomly numbered before measurement and scored according to the criteria of the given scale. The panelists were asked to evaluate the overall taste, acceptability, bitterness, astringency, and aroma[19]. They were asked to rate each attribute on a scale from 1 to 10, the score criteria of the meat sausages was shown in Table S1.

2.11.2 E-tongue analysis

E-tongue analysis was performed according to a previous method[20] with some modifications. Briefly, 25 g of the minced meat sausage was mixed with 125.0 mL of distilled water to extract the taste substances. After the mixed solution was centrifuged 8 000 × *g* for 10 min at 4 °C, and the supernatant filtrate was filtered and analyzed using an E-tongue (Model SA402B, Intelligent Sensor Technology, Inc., Atsugi-shi, Japan).

2.11.3 E-nose analysis

The odor characteristics of the sausages were analyzed using an electronic nose analysis system (PEN3, Airsense Inc., Schwerin, Germany), following the methodology previously reported[21]. The PEN3 electronic nose system consisted of ten different metal oxide semiconductor sensors (W1C, W5S, W3C, W6S, W5C, W1S, W1W, W2S, W2W, and W3S) to provide selectivity for VOC categories. The performance of each sensor is summarized in Table S2. Sausage mince (5.0 g) was weighed and placed in a 20.0 mL injection bottle, which was covered with a cap. The injection bottle was heated in a water bath at 60 °C for 40 min, then left to equilibrate at room temperature for detection using an electronic nose. The specific conditions were as follows: a sampling interval of 1 s, cleaning time of 120 s, zeroing time of 10 s, sample preparation time of 5 s, and measurement time of 120 s. The carrier gas and sample flow rates were 300 mL/min. The signal acquisition time was 93–95 s.

2.11.4 Gas chromatography-mass spectrometry (GC-MS) analysis

Blend all sausages for 10, 20, 30, and 40 s to simulate chewing the sausages for different lengths of time. These specific time points were designed based on the study by Aguayo-Mendoza et al.[22]. Their research revealed that the typical consumption time for sausages in the general population ranges from approximately 16.8–29.5 s, whereas this duration can extend to nearly 40 s for slow chewers. VOCs were extracted from the samples and analyzed using a GC-MS system (7890A-5975C, Agilent, USA). Transfer 2 mL of the sample into a 15 mL extraction vial. Add 10 μL of internal standard (4-methyl-2-pentanol, concentration 100 μg/mL, resulting in an internal standard concentration of 0.5 μg/mL in the sample). Place the sample vial on the solid-phase microextraction (SPME) device and set the temperature to 60 °C; preheat the sample vial on the extraction device for 15 min; insert

the SPME extraction head through the vial cap into the headspace of the sample, extend the fibre head, ensuring the extraction head is approximately 1.0 cm above the sample surface, and perform headspace extraction for 40 min; retract the fibre head and remove the extraction head from the sample vial; reinsert the extraction head into the GC-MS injection port, extend the fibre head, and desorb at 250 °C for 5 min for injection and analysis.

The following experimental conditions were applied using the DB-Heavy Wax column (30 m × 250 μm, 0.25 μm): the column temperature was held at 40 °C for 5 min, then increased to 120 °C at a rate of 5 °C/min and increased to 230 °C at a rate of 10 °C/min. Finally, the temperature was maintained at 230 °C for 8 min with 1.0 mL/min of the flow rate, 99.99% of the helium as the carrier gas. The gasification chamber temperature is 250 °C; the transmission line temperature is 240 °C.

The relative content of the VOC (C_i) was calculated using Eq. (3):

$$C_i\,(\%) = \frac{A_i}{A_1 + A_2 \cdots + A_i \cdots + A_n} \times 100 \tag{3}$$

Where A_i is the peak area corresponding to a certain identified component; n represents the total number of identified components.

2.12 Antioxidant activity analysis

2.12.1 2,2′-Azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) cation radical scavenging activity

The determination of ABTS cation radical scavenging activity was performed according to previously reported methods[23]. The mother liquor of ABTS was obtained by mixing 200 mg of ABTS with 34 mg of potassium persulfate and 50 mL of distilled water, shaking well, and leaving overnight at room temperature away from light. The ABTS solution, with an absorbance of 0.70 ± 0.02 at 734 nm, was prepared by diluting the ABTS mother solution to a certain multiple with 95% ethanol solution. The 2 g of minced meat sausage was transferred into 10 mL distilled water and homogenized for 3 min, then shaken in a water bath for 1 h at 30 °C. The homogeneous substance was filtered with a 0.45 μm syringe filter. The 50 μL of the filtrate was mixed with 2 mL of ABTS working solution, and the absorbance at 734 nm was measured after reacting at room temperature for 6 min. Here, 50 μL of distilled water and 2 mL of ABTS solution were used as the blank group. The ABTS cation radical scavenging rate of the meat sausage was calculated according to Eq. (4):

$$\text{ABTS cation radical scavenging rate}\,(\%) = \frac{A_{\text{blank}} - A_{\text{sample}}}{A_{\text{blank}}} \times 100 \tag{4}$$

Where A_{sample} is the absorbance of the experimental group at 734 nm, and A_{blank} is the absorbance of the blank group at 734 nm.

2.12.2 1,1-Diphenyl-2-picrylhydrazyl (DPPH) radical scavenging activity

DPPH radical scavenging capacity was carried out via a previous method[24] with slight modifications. Briefly, 2 g minced meat sausage was transferred into 10 mL distilled water and homogenized for 3 min, then shaken in a water bath for 1 h at 30 °C. The homogeneous substance was filtered with a 0.45 μm syringe filter. Filtrate (0.2 mL) was mixed with 1 mL of DPPH solution (0.1 mmol/L, diluted with anhydrous ethanol). After 30 min of light-avoidance reaction at room temperature, the absorbance at 517 nm was measured as the experimental group. Also, 0.2 mL of distilled water and 1 mL of DPPH solution were used as the control group, and 0.2 mL of filtrate and 1 mL of anhydrous ethanol were used as the blank group. The DPPH radical scavenging rate of the meat sausage was calculated according to Eq. (5):

$$\text{DPPH radical scavenging rate}\,(\%) = \frac{A_1 - A_2 - A_3}{A_1} \times 100 \tag{5}$$

Where A_1 is the absorbance at 517 nm of the control group, A_2 is the absorbance at 517 nm of the experimental group, and A_3 is the absorbance at 517 nm of the blank group.

2.13 *In vitro* digestion simulation

The *in vitro* digestion was undertaken using the procedure reported by previous methods[25] with minor modifications. Sausage mince (2 g) was added to 20 mL of phosphate-buffered saline (pH 7.0), and the pH was adjusted to 2.0 using 1 mol/L HCl. Pepsin (final enzyme activity 2 000 U/g) was added to initiate gastric digestion. The reaction mixture was incubated at 37 °C at 150 r/min in a shaking incubator for 2 h and terminated by adjusting the pH to 7.5 with 6 mol/L NaOH.

2.14 Gastric digestive kinetic peptide determination

The method for determining peptide concentrations following gastric digestion of sausages was carried out with minor modifications to previously reported procedures[15]. Briefly, trichloroacetic acid was added to the digestion products at a final concentration of 10% (*m*/*m*) and reacted at 4 °C for 120 min, then centrifuged at 10 000 × *g* for 10 min at 4 °C. The peptide content of the supernatant was determined using a BCA assay kit (P0012, Beyotime Biotechnology, Shanghai, China), with bovine serum albumin as the protein standard. Sample data obtained at different digestion time points (0, 5, 10, 15, 20, 30, 40, 50, 60, 80, 100, and 120 min) were fitted to a first-order kinetic equation using Eq. (6):

$$\rho(t) = \rho_{\max}\,(1 - \exp(-Kt)) \tag{6}$$

Where $\rho(t)$ is the peptide concentration (mg/mL) at digestion time t; t is the gastric digestion time (min); K is the first-order rate constant (min^{-1}), which is calculated using Eq. (7):

$$K = \frac{\ln 2}{t_{1/2}} \tag{7}$$

The digestion rate ($\mathrm{d}\rho(t)/\mathrm{d}t$, mg/(mL·min)) is calculated according to Eq. (8):

$$\mathrm{d}\rho(t)/\mathrm{d}t = \rho_{\max} \times K \times \exp(-Kt) \tag{8}$$

Parameters can be derived from Eqs. (6) and (7): maximum peptide concentration ($\rho_{\max}$, mg/mL); half-life time ($t_{1/2}$, min); maximal rate of digestion (mg/(mL·min)); and the initial slope ($\mathrm{d}\rho(t)/\mathrm{d}t$, mg/(mL·min)), which was calculated as the mean value over the first 15 min for the pepsin digestion phases.

2.15 Statistical analysis

Statistical analysis was calculated using SPSS statistical software 21.0 (SPSS Inc., Chicago, USA). Data were expressed as mean ± standard error. Statistical analysis was performed using Duncan's mean comparison test and regression analysis. Data processing and linear fitting of samples treated by different methods were

performed utilizing Origin 2025b (Origin Lab Co., Northampton, MA) to analyze similarities and differences between groups. The significant differences were analyzed at the 0.05 level of significance.

3 Results and discussion

3.1 Particle size, PDI, and zeta potential of HIPEs

As illustrated in Figure 1, incorporating RG and WG powders significantly decreased the PDI of the HIPEs, yielding highly uniform droplet distributions. This structural refinement is attributed to non-covalent interactions (e.g., hydrogen bonding) between the OVA-CS complexes and active compounds (polyphenols and polysaccharides) released from the powders. These interactions facilitated rapid interfacial adsorption, forming a densely packed viscoelastic film[26].

Concurrently, the zeta potential decreased precipitously from 20.4 (control) to 5.72 (1.5%-RG) and 2.38 mV (1.5%-WG). This reduction was driven by electrostatic neutralization, as the negatively charged functional groups from the powders bound to the positively charged CS at the interface[27].

Although low absolute zeta potentials typically indicate insufficient electrostatic repulsion[28], the weakened electrostatic forces in these HIPEs were effectively compensated by the thickened viscoelastic film. This robust physical barrier provided formidable steric hindrance, significantly suppressing droplet aggregation. These micro-scale enhancements—refined droplet size, uniform distribution, and dominant steric stabilization—constitute a crucial structural foundation, mechanistically explaining the superior macroscopic rheological behaviors and centrifugation stability discussed subsequently.

3.2 TPA of HIPEs

The textural parameters of HIPEs obtained via TPA were shown in Figure 2. The incorporation of RG and WG significantly affected the textural properties of the emulsion. Specifically, the hardness and elasticity of the emulsion initially increased and then decreased as the addition of RG and WG increased. Rather than definitive

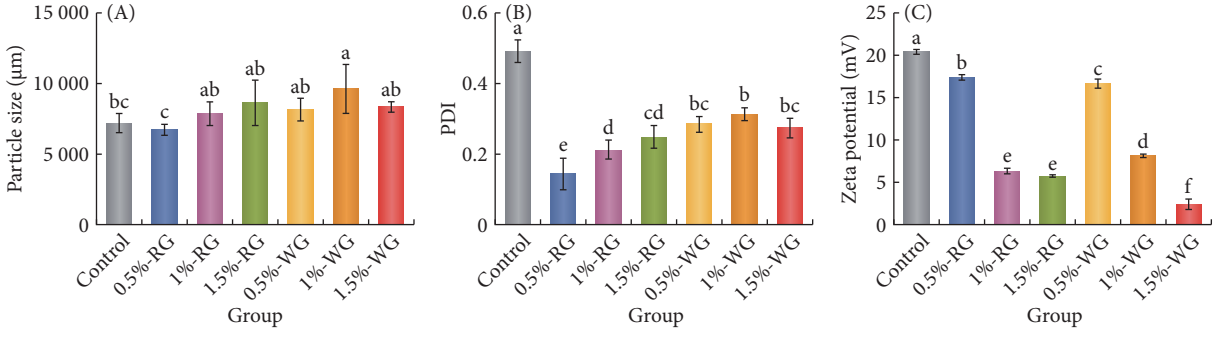


Figure 1 (A) Average particle size, (B) PDI, and (C) zeta potential of HIPEs with different concentrations of RG and WG. Different lowercase letters represent significant differences ($P < 0.05$).

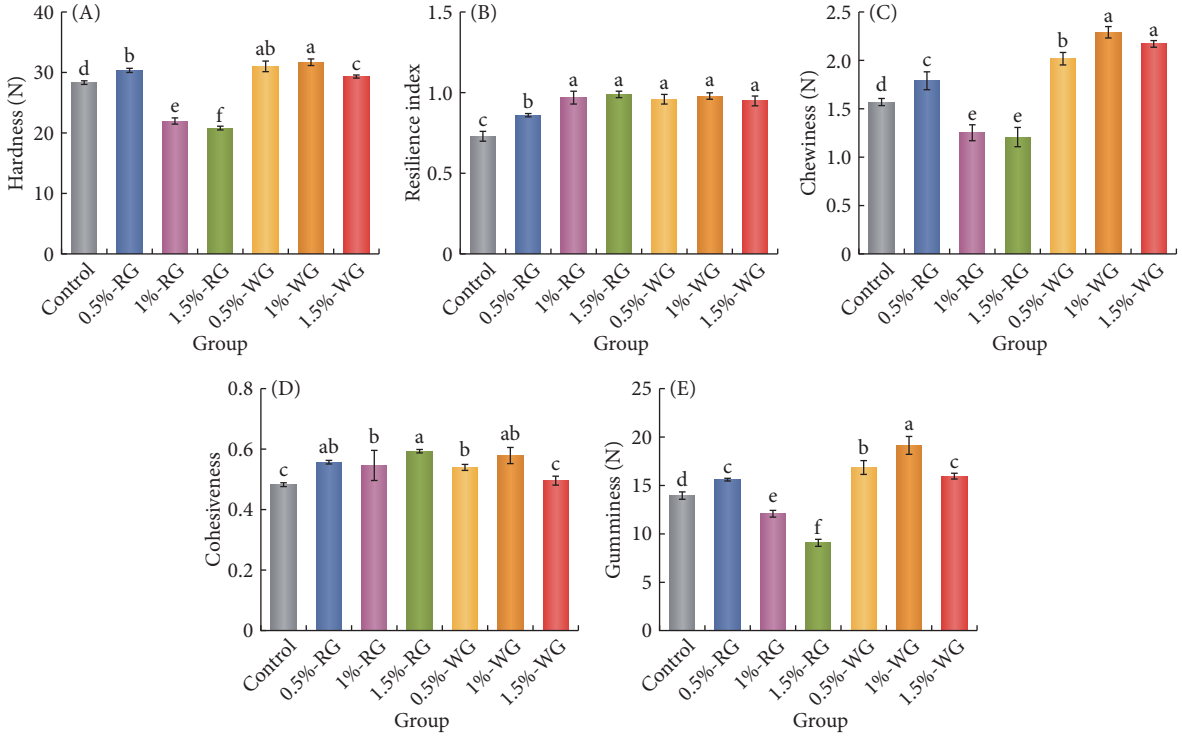


Figure 2 The (A) hardness, (B) resilience index, (C) chewiness, (D) cohesiveness, and (E) gumminess of the HIPEs stabilized by OVA-CS complex coacervation as a function of different RG and WG concentrations. Different lowercase letters represent significant differences ($P < 0.05$).

electrostatic repulsion, we hypothesize that excessive RG may disrupt the optimal OVA-CS interfacial interactions, thereby hindering the formation of a rigid emulsion network structure. Interestingly, while the group with 1.5% RG addition exhibited better cohesiveness, its overall structural integrity was weakened. Without direct microstructural characterization, it is speculated that excessive RG might interfere with protein-protein cross-linking, leading to a softer, more sticky matrix rather than a firm gel. This rheological softening directly explains the impaired hardness and chewiness. The 1.5%-RG group exhibited a hardness reduction of approximately 26.5% compared with the control, indicating that high RG concentrations soften the emulsion structure. Conversely, when 1%-WG was added, hardness and resilience index reached their maximum values. The insoluble dietary fibre in ginseng possesses lipophilic adsorption properties[29], which likely facilitates the formation of a more robust network structure, consistent with the enhanced textural results obtained after adding WG.

3.3 Rheological properties of HIPEs

The rheological properties of complex coacervation HIPE solutions with different ginseng concentrations were measured via dynamic rheology. As shown in Figure 3A, the apparent viscosity of different emulsions decreased significantly with increasing shear rate, indicating pseudoplastic behavior and shear thinning. The 0.5%-WG group exhibited higher viscosity, whilst increased RG (particularly the 1.5%-RG group) resulted in a significant decrease in apparent viscosity. Crucially, this rheological behavior perfectly correlates with the corresponding decrease in hardness observed in the TPA results. The centrifugal stability of HIPEs is shown in Figure 3B. The control group exhibited lower centrifugal stability, which improved upon the addition of RG and WG. Groups with higher cohesivity (e.g., the 1%-WG group) demonstrated superior centrifugal stability, which was likely attributed to the cohesive network suppressing phase separation. This finding was consistent with both the TPA and the rheological data. Frequency scanning reflected the viscoelastic behavior of the emulsions. As shown in Figures 3C and D, during frequency scanning, the G' was higher than the G'', indicating that elastic behavior dominated across all samples. Addressing previous inconsistencies, the rheological data clearly aligns with the TPA findings: the 1.5%-RG formulation exhibited the lowest G' and G''. This confirms that excessive RG weakens the internal viscoelastic structure, leading to a softer emulsion rather than elevating the modulus. In contrast, appropriate concentrations of WG (e.g., 0.5% and 1%) likely promoted the formation of complex structures and enhanced interprotein cross-linking, which successfully elevated the modulus values and stabilized the internal structure.

3.4 Quality characteristics of sausages

Figures 4A–E display the TPA test results of emulsified sausages, values for most items were improved except for resilience index. This was attributed to the amphiphilic structure of ginsenosides in RG and WG, which could adsorb onto the surface of fat particles in the sausages. We hypothesize that the adsorbed layer formed at the oil-water interface may exhibit a certain degree of rigidity. When external forces acted on the sausage, this potentially stabilized interfacial membrane required more energy to be disrupted, thereby increasing chewiness and hardness. The addition of RG and WG significantly improved the cohesiveness of the sausage, likely because RG and WG contained ginseng polysaccharides, which

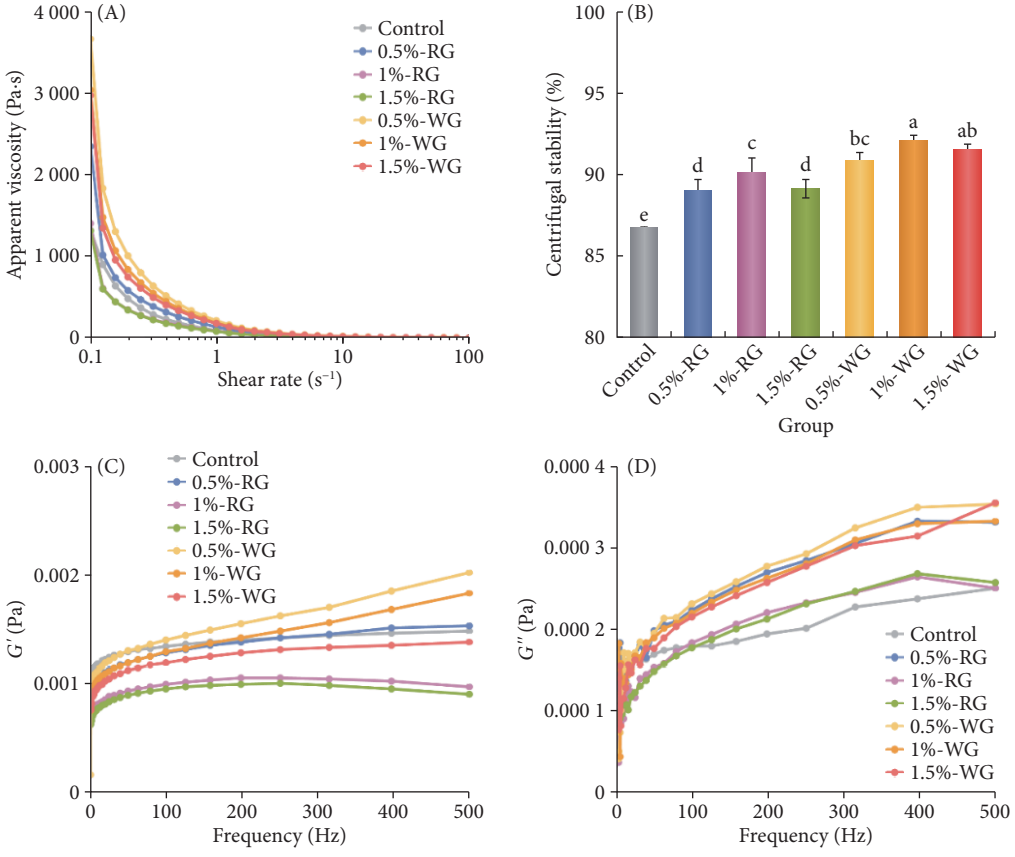


Figure 3 (A) Apparent viscosity, (B) centrifugal stability, and (C–D) frequency scan curves of the HIPEs stabilized by OVA-CS complex coacervation as a function of different RG and WG concentrations. Different lowercase letters represent significant differences ($P < 0.05$).

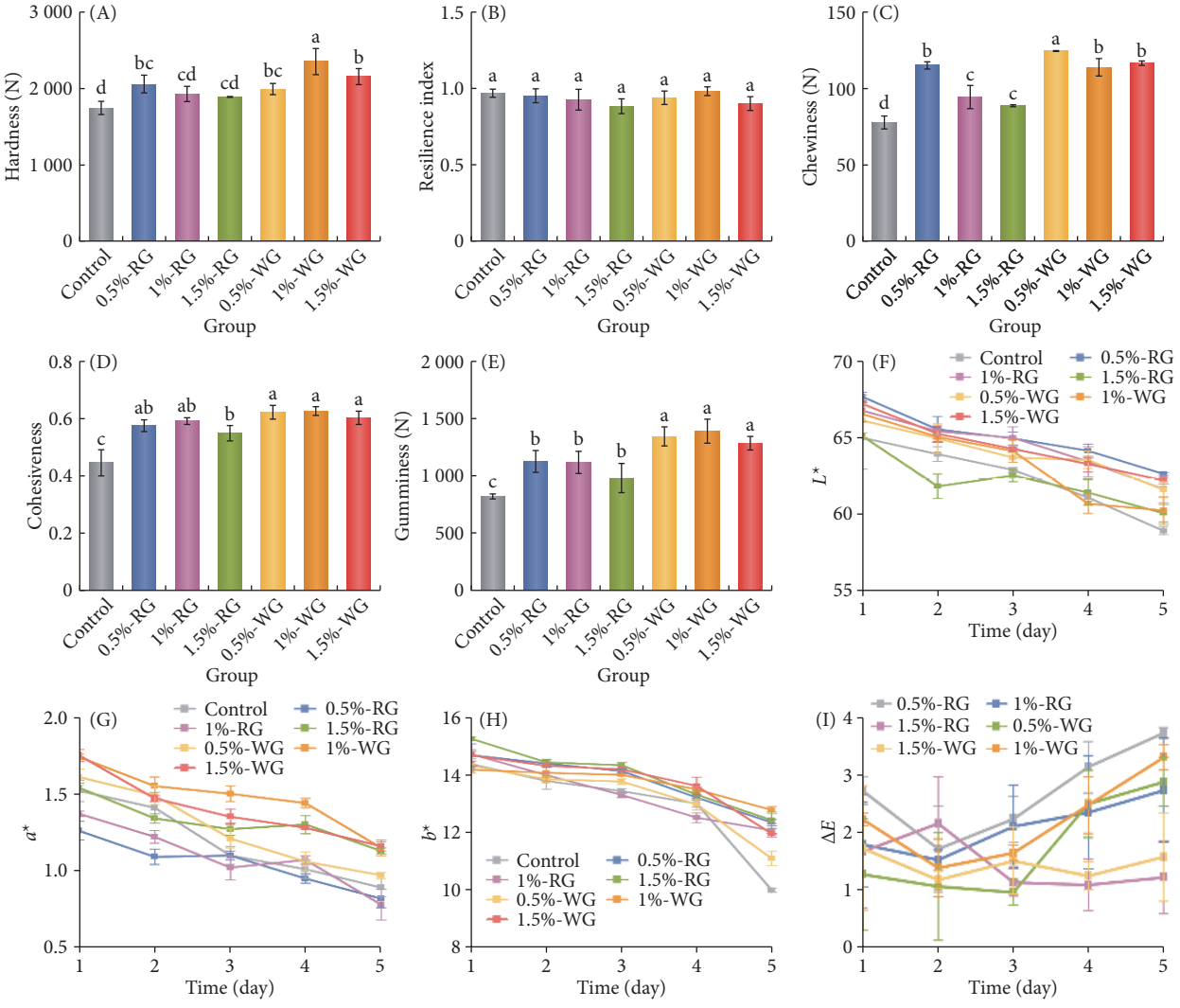


Figure 4 The (A) hardness, (B) resilience index, (C) chewiness, (D) cohesiveness, (E) gumminess, (F) L^*, (G) a^*, (H) b^* and (I) ΔE during storage of sausages after replacing pork backfat with HIPEs stabilized with different concentrations of RG and WG. Different lowercase letters represent significant differences ($P < 0.05$).

could theoretically form polysaccharide-protein composite gel networks with proteins in the sausage through hydrogen bonds and ionic bonds[30]. This theorized interaction likely made the sausage structure more compact and enhancing cohesiveness and gelatinousness, which was consistent with the results of HIPEs.

Figures 4F–I present the color parameters of all the sausages formulations during the 5-day storage period. Color is one of the most important factors determining consumer preference for meat products. When the L^* and a^* of sausages were high, the sausage product exhibited an attractive rose color. The addition of RG increased the a^*, b^*, and L^* of the sausage, improving its appearance. This improvement was attributed to the synergistic effect of pre-existing Maillard reaction products from the steaming process of RG and hemoglobin in enhancing the color of the sausage, imparting a deeper hue. To evaluate overall color variations, the ΔE relative to the control group was analyzed (Figure 4I), showing significant concentration- and time-dependent variations. For RG groups, higher concentrations superiorly suppressed color shifts, with the 1.5%-RG group maintaining the lowest and most stable ΔE (1.22 ± 0.63 on day 5). Conversely, 1%-WG offered the optimum color stability among WG groups (ΔE = 1.58 ± 0.77), whereas insufficient (0.5%) or excessive (1.5%) WG addition led to sharp ΔE increases during late storage (days 4–5). Notably, the final ΔE for both 1.5%-RG and 1%-WG groups remained below 2.0. In food colorimetry, ΔE < 2.0 represents a color difference imperceptible to the untrained human eye[31], demonstrating that these two formulations successfully mimicked and preserved the visual appearance of traditional sausages. During storage, L^* generally decreased. However, sausages containing RG and WG exhibited a smaller decreasing trend, which was speculated to be due to the antioxidant components (such as ginsenosides) inhibiting fat oxidation and protein degradation[32], or because the oil droplet diameter in sausages containing HIPE was smaller than that produced by animal fat, resulting in greater light reflection and scattering, thus maintaining higher L^*[33–34].

3.5 Flavour analysis of sausages

3.5.1 *Sensory evaluation and E-tongue analysis*

Sensory evaluation is one of the key indicators for assessing food flavour. As shown in Figure 5A, the sensory evaluation results of the 1.5%-WG group were inferior to those of the control group, while the 1%-RG group demonstrated particularly outstanding performance in sensory evaluation. Notably, the aroma score of the 0.5%-RG group was comparable to that of the 1%-RG group. As shown in Figure 5B, electronic tongue analysis revealed that the 0.5%-RG and 0.5%-WG groups outperformed the control group in umami and overall flavor intensity. The 1.5%-WG group exhibited

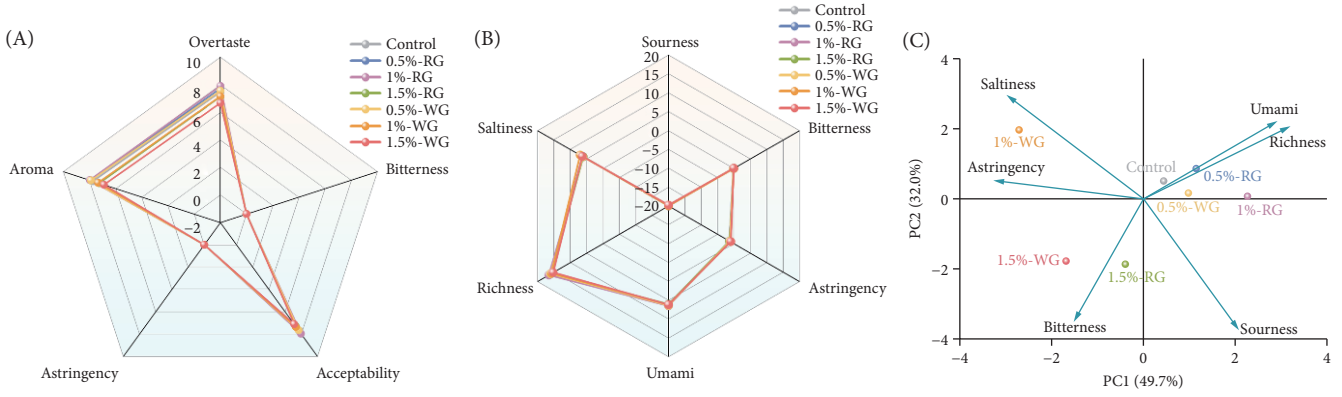


Figure 5 (A) Indicator scores of the sensory evaluation, (B) radar chart and (C) principal component analysis (PCA) plot of E-tongue data for sausages.

the lowest bitterness score, indicating that high concentrations of WG effectively adsorbed or masked bitter peptides. As illustrated in Figure 5C, the cumulative explanatory power of PC1 and PC2 reached 81.7%, demonstrating their effectiveness in representing the overall characteristic information of all samples. The 0.5%-RG group was significantly separated from the control group along the positive axis of PC1 (umami, richness direction), with high loadings for umami and richness. The 1.5%-WG group diverged distinctly from other groups along the negative axis of PC2 (bitterness, astringency direction). In summary, low-concentration RG emphasized mild flavour activation, while high-concentration WG highlighted bitterness regulation, with both showing differentiated advantages in sensory, flavour, and aroma dimensions.

3.5.2 *E-nose analysis*

The electronic nose, as an electronic system simulating the structure of the human nose, exhibited selective recognition characteristics for various molecules. As shown in Figure 6A, the high response values of sensors W1W, W2S, and W1S indicated that sulfides/terpenes, alcohols, and methyl compounds, respectively, were the primary VOCs contributing to the overall flavor profile of the sausages. Additionally, the slight response of sensor W5S indicated the presence of nitrogen oxides. The cumulative contribution of PC1 and PC2 reached 91.3% (Figure 6B), indicating that the two PCs encompassed the primary characteristic information of VOCs in the sausages. The 0.5%-RG groups were significantly separated from the control group along the negative axis of PC1 (W1C and W2S sensor directions), suggesting that low concentrations of RG introduced terpenoid compounds, altering the original aromatic characteristics. Notably, the 1.5%-WG groups were significantly separated from other WG groups along the positive axis of PC2 (primarily associated with the W3C and W5C sensor directions), suggesting that high concentrations of WG trigger unique aroma-generating pathways (such as the Maillard reaction), leading to changes in aroma components. Intermediate-dose groups (1%-RG and 1%-WG) were subjected to sensory, E-tongue and E-nose tests in this study. Since these groups did not yield distinctive observations that could provide additional mechanistic insights, only 0.5%-RG/WG and 1.5%-RG/WG were selected for subsequent analyses to focus on comparing low- and high-dose effects.

3.5.3 *GC-MS*

In order to better explore the flavour of the sausage and establish physiological relevance, VOCs were detected after simulating different chewing times (10, 20, 30, and 40 s). These specific temporal intervals were strategically selected to mimic the dynamic phases of human oral processing—ranging from initial mechanical breakdown (10 s) to the progressive formation of a cohesive saliva-bolus prior to swallowing (40 s)—thereby accurately reflecting the temporal release dynamics of flavor compounds in the oral cavity. A total of 88 VOCs were detected in the sausages and they were listed in Figure 7 and Table S3–S7, including 9 benzenoids, 23 alcohols, 3 aldehydes, 8 acids, 31 terpenes, 7 ketones, 2 alkanes and 5 esters. The relative content, types, and quantities of VOCs detected in sausages under different chewing times were shown in Figure 8 and Table S8.

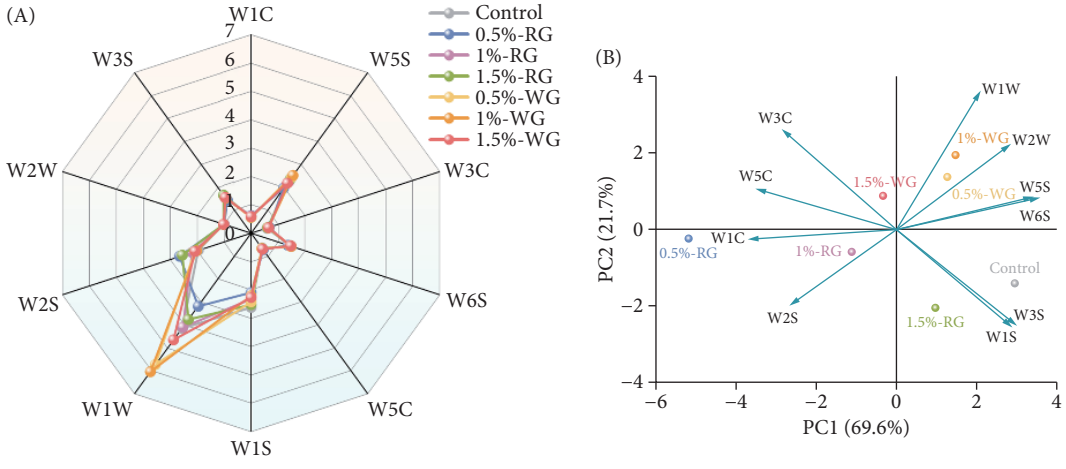


Figure 6 (A) Radar chart and (B) PCA plot of E-nose data for sausages.

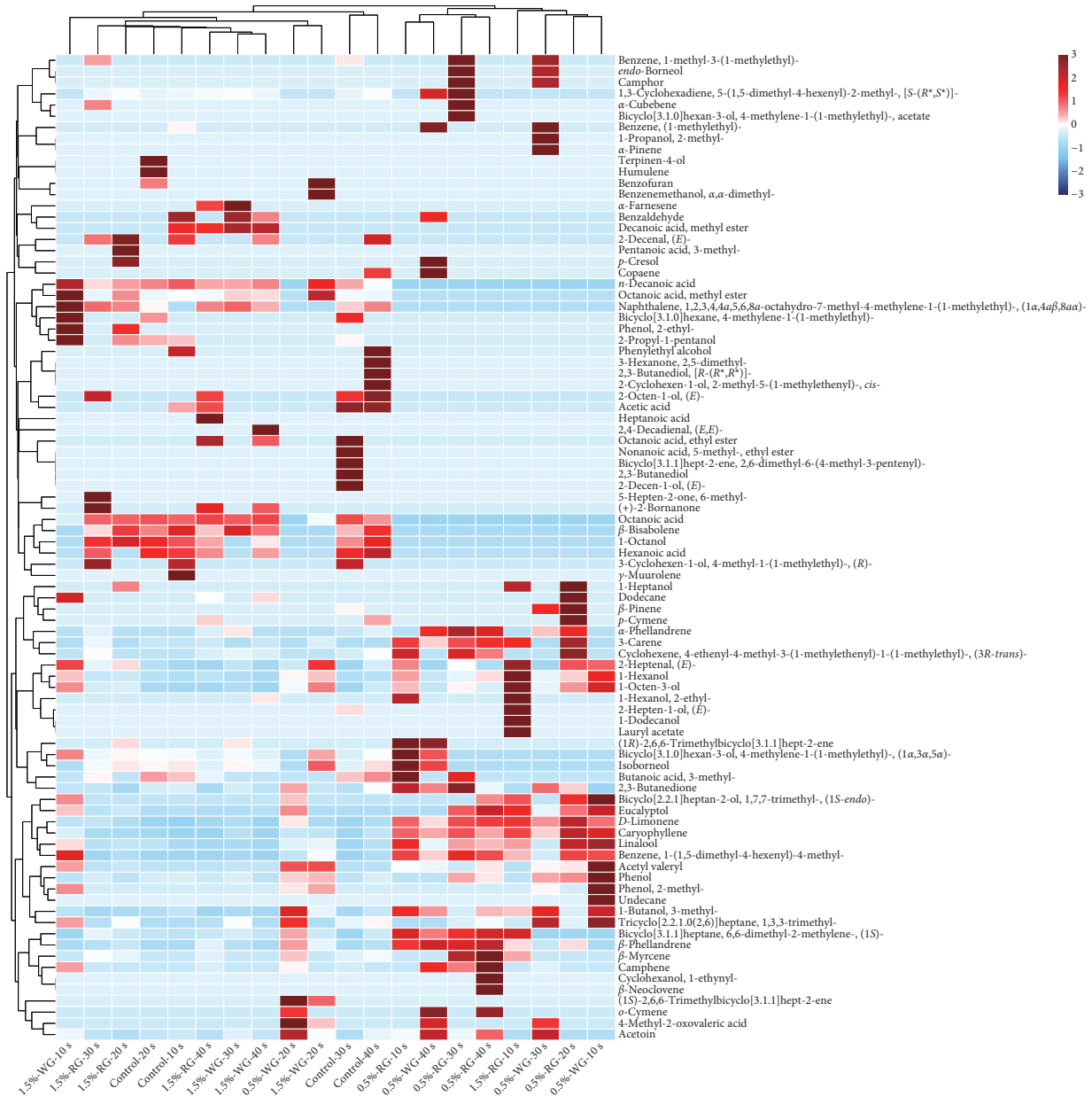


Figure 7 The effect of replacing pork back fat with HIPEs containing different concentrations of RG and WG on volatile flavour compounds in sausages.

A total of 23 alcohol compounds were identified across all sausage samples, with the RG groups exhibiting significantly higher relative contents. Alcohols are secondary by-products generated from the further degradation of aldehydes during the oxidation of unsaturated fatty acids[35]. The 0.5%-RG and 1.5%-RG groups exhibited higher alcohol relative content at 10 s (25.52% and 46.68%, respectively), which subsequently declined gradually. This initial enrichment was attributed to RG's high content of ginsenosides and polysaccharides. During sausage processing, ginsenosides interacted with meat proteins and carbohydrates, promoting the Maillard reaction—a key source of alcohol precursors. Importantly, this rapid initial enrichment of volatile alcohols perfectly aligns with the E-nose results (Section 3.5.2), where the 0.5%-RG group separated significantly along the negative axis of PC1, driven by sensors highly sensitive to these exact compounds. As mastication time increased, alcohol relative content decreased. It was hypothesised that this occured because naturally occurring lipases in the meat matrix bound to saponins in RG (such as Rb1), inhibiting lipid hydrolysis and thereby preventing the generation of further alcohol precursors. In this study, 1-butanol, 3-methyl-1-butanol, 1-octen-3-ol, and linalool were identified in all sausages. The relative contents of 3-methyl-1-butanol, and 1-octen-3-ol in RG/WG sausages were higher than those in the control group. 3-Methyl-1-butanol had a strong malt and grain aroma with a hint of fruitiness, and at low concentrations, it enhanced the complexity of the flavour. 1-Octen-3-ol had a mushroom-like aroma, providing a fresh, herbal scent and a slight oily taste, with a unique and distinctive aroma[36]. Linalool had floral and fruity aromas, enhancing the aromatic layers of the sausage[37]. Crucially, the prominent presence of these specific flavour-enhancing alcohols corroborates the E-tongue findings (Section 3.5.1), which identified the 0.5%-RG group as possessing the highest umami and richness. These compounds significantly contributed to the aromatic profile of ginseng sausage.

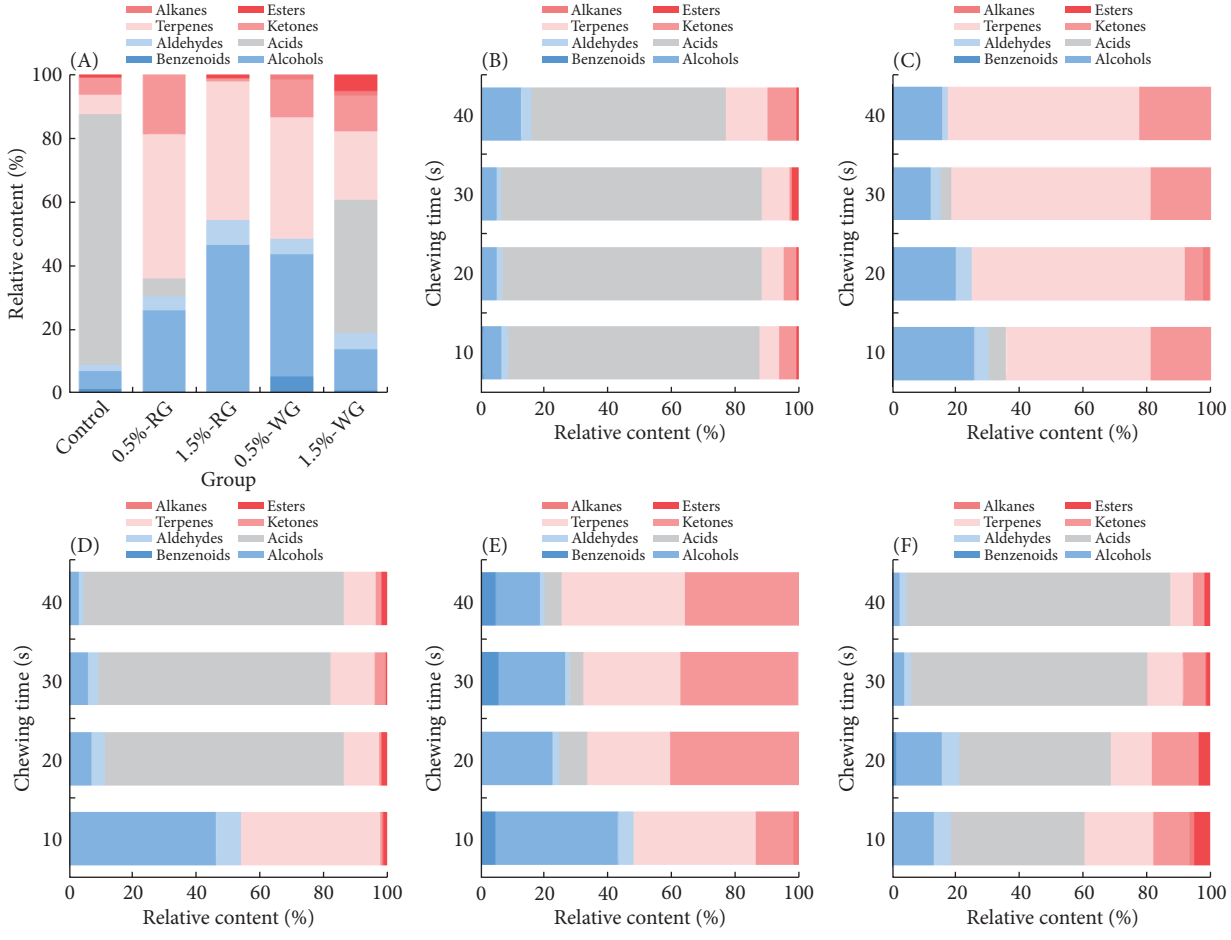


Figure 8 The relative content of VOCs in sausages after replacing pork back fat with HIPEs containing different concentrations of RG and WG. (A) Relative content at 10 s; (B) control group; (C) 0.5%-RG group; (D) 1.5%-RG group; (E) 0.5%-WG group; (F) 1.5%-WG group.

Three types of aldehydes were identified. Aldehyde compounds mainly originated from the oxidation of lipids and the metabolism of amino acids[38–39]. The 0.5%-RG group exhibited an initial increase followed by a decrease in aldehyde relative content, while the 1.5%-RG group showed a sustained reduction. This was attributed to the antioxidant components within RG, such as ginsenosides, inhibiting oxidation. Due to their low threshold characteristics, they had a significant impact on the flavour of sausages. (*E*)-2-Heptenal had the highest relative content. It was an aromatic compound produced by the oxidative degradation of oleic acid/linolenic acid, possessing an aroma similar to roasted meat. It could synergistically interact with other flavour components (such as aldehydes, ketones, and esters) to form a complex flavour profile[40].

Acids mainly come from the hydrolysis of triglycerides and phospholipids or lipid oxidation reactions[41]. Substantial amounts of octanoic acid and *n*-decanoic acid were detected in the control group, the 1.5%-RG group, and the 1.5%-WG group. Notably, the control group maintained the highest relative total acid content during the early stage of mastication, whereas both the 1.5%-RG and 1.5%-WG groups surpassed the control group at 40 s. This phenomenon originated from the lack of exogenous antioxidants in the control. Without the potent radical-scavenging ginsenosides and phenolic compounds provided by RG or WG, the control sausage matrix underwent largely unchecked lipid oxidation and continuous triglyceride hydrolysis during processing and mastication. This excessive accumulation of acids, lacking the harmonious flavour modulation provided by ginseng components, directly correlates with the E-tongue results (Section 3.5.1), where the control group exhibited significantly lower umami and richness scores compared to the supplemented groups. Despite this, at appropriate levels, these acids serve as substrates for esters and have a positive impact on the flavour development of sausages[42]. The acid relative content in the 1.5%-RG group was 0% at 10 s, subsequently rising sharply (reaching 80.93% at 40 s). High concentrations of RG significantly promoted acid production over time, potentially due to RG-enhanced lipid hydrolysis. Short-chain fatty acids (C < 6) have a strong odour and a low threshold, significantly influencing flavour[43], such as 3-methylbutanoic acid. Additionally, acetic acid has been proven to be the most abundant organic acid in dry-cured sausages, but it was not detected in our sausages, possibly due to chemical conversion, consistent with the findings of a previous study[44].

Ketones were primarily produced by the Maillard reaction and the oxidative degradation of unsaturated fatty acids and amino acids. Seven ketones were detected in all sausages, with 2,3-butanedione and acetoin being the primary ketones. These two key aromatic compounds enhanced post-nasal olfaction[45]. The 0.5%-RG group exhibited higher ketone compound relative content at 10 s (18.65%), which subsequently continued to rise (reaching 22.28% at 40 s). RG promoted ketone body formation throughout the entire chewing process, potentially by enhancing alcohol oxidation and Maillard reactions. Furthermore, the ketone compound content in the 1.5%-WG group exhibited a trend of initial increase followed by decrease. This early ketone surge correlates directly with the E-nose results (Section 3.5.2), where the 1.5%-WG group was distinctly separated along the positive axis of

PC2, indicating that high-concentration WG triggered unique, WG-specific aroma-generating pathways during processing. Although high-concentration WG triggered initial ketone enrichment, subsequent degradation occurred, possibly attributable to reactions with excessive acids. Rather than merely reacting with excess acids, these highly reactive transient ketones likely underwent further oxidation or participated in Schiff base formations with meat proteins during extended mastication in the saliva-bolus matrix. Interestingly, this intense WG-induced protein interaction effectively adsorbed or outcompeted the precursors required for bitter peptide generation, which perfectly elucidates the E-tongue data (Section 3.5.1) showing that the 1.5%-WG group exhibited the lowest bitterness score. Acetoin was a product of carbohydrate metabolism and imparts a fruity aroma. Acetoin could further oxidise into 2,3-butanedione, which had a distinctive buttery and sweet aroma with a very low threshold, playing a crucial role in the aroma of sausages[46].

A total of 31 terpenes were identified in this study. Terpenoids are typically derived from added flavourings[37], but the terpenoid relative content of sausages containing RG and WG was significantly increased, possibly because RG and WG itself were natural source of terpenoids and their components could reduce terpenoid loss during processing through antioxidant and stabilizing effects. The 0.5%-RG group exhibited higher relative content at 10 s (45.14%), increased to a peak value of 66.52% at 20 s, and then gradually decreased to 62.26% at 30 s and 59.80% at 40 s. RG introduced substantial precursors of terpenoid compounds (e.g., ginsenosides/thiols), which were gradually released during chewing, enhancing the sausage's flavour profile. The rapid increase from 10 to 20 s indicated a fast release of terpenoid-related precursors at the early chewing stage, while the subsequent mild decline suggested that 0.5% RG addition could effectively retard excessive terpenoid degradation during later mastication. The 1.5%-RG group exhibited higher relative content at 10 s (43.59%), subsequently declining (to 10.26% at 40 s). High RG concentrations caused initial terpenoid enrichment, but rapid loss during later chewing, potentially due to reactions with acids/alcohols. In addition, some researchers[47–48] found that these substances, such as 3-pinene, *D*-limonene, or *β*-pinene could be detected in products without added spices, inferring that the presence of these VOCs might be related to the animals' diet.

3.6 Antioxidant activity analysis of sausages

The determination of ABTS cation radical and DPPH radical scavenging capacities was frequently used to evaluate the antioxidant activity of substances. As shown in Figures 9A and B, the ABTS cation radical and DPPH radical scavenging capacities of

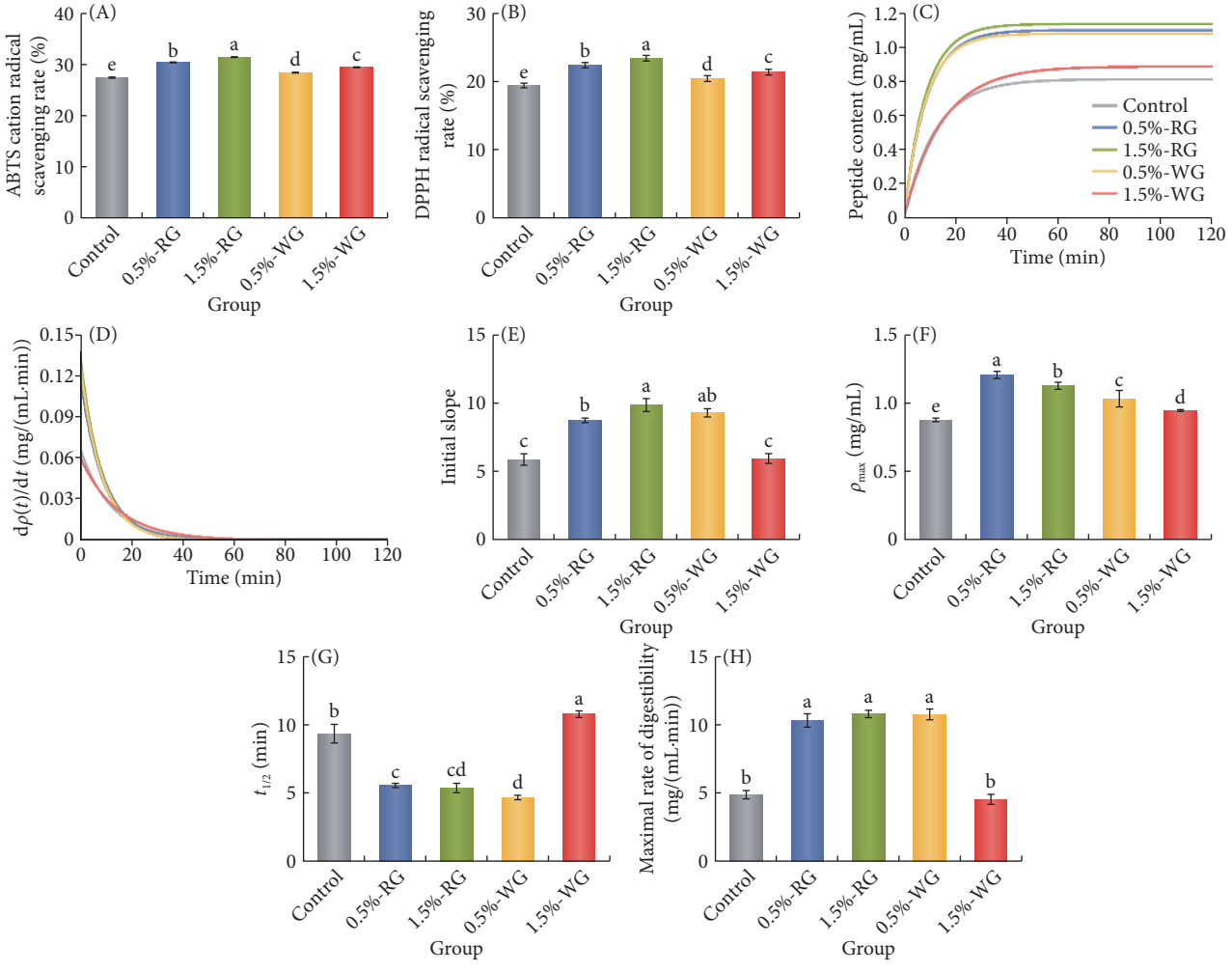


Figure 9 The (A) ABTS cation radical and (B) DPPH radical scavenging abilities; (C) fitted values of pepsin digestion curves, and (D) the correspondingly derivative of the curves; (E) initial slope; (F) ρ_{max}; (G) $t_{1/2}$ and (H) maximal rate of digestion of sausages after replacing pork back fat with HIPEs containing different concentrations of RG and WG. Different lowercase letters represent significant differences ($P < 0.05$).

the sausages containing HIPE were significantly greater than those of the control group ($P < 0.05$), which was related to the strong radical scavenging capacity of the RG and WG in HIPEs. Among them, the 1.5%-RG group exhibited 1.15 times higher ABTS cation radical and 1.21 times higher DPPH radical scavenging capacity, respectively. Ginsenosides and ginseng polyphenols in RG and WG had multiple phenolic hydroxyl structures. When encountering free radicals, the hydrogen atoms on these phenolic hydroxyl groups could rapidly transfer and bind with free radicals, thereby quenching them and exerting an antioxidant effect on sausages[23]. As the concentration of RG and WG increased, the antioxidant capacity of the sausage significantly increased. Previous research examining cream soups containing varying concentrations of ginseng powder reached identical conclusions[14]. Notably, the 1.5%-RG group exhibited a significantly higher antioxidant capacity compared to the WG groups. This superior antioxidant performance is fundamentally driven by the physicochemical transformations that occur during the specific thermal processing of RG. Unlike WG, which is naturally dried, RG undergoes high-temperature steaming. Extensive research has established that this specific steaming process triggers robust Maillard reactions, generating potent endogenous antioxidant products such as melanoidins and maltol, which significantly enhance the overall electron-donating capacity[49]. Furthermore, during the RG production process, the high-temperature steaming induces the structural conversion of primary natural ginsenosides (e.g., Rg1, Rb1, Rc, Rb2, and Rd) into converted rare ginsenosides (e.g., Rg3 and Rh1)[50]. As demonstrated by previous studies, these heat-induced structural changes and the resulting converted ginsenosides exhibit significantly stronger free radical-scavenging abilities than the native precursors found in WG[51]. Consequently, thermally processed RG effectively scavenged free radicals and suppressed lipid peroxidation in sausage matrices.

3.7 Gastric digestive kinetics of sausages

As shown in Figures 9C–H, peptide contents across all meat sausage groups exhibited a gradual increase over extended digestion periods before stabilising. The 1.5%-RG group demonstrated relatively higher peptide contents, rates of change in peptide content, initial slope, ρ_{max}, and maximum digestion rate, whereas the 1.5%-WG group performed less favourably. Notably, the 1.5%-RG group exhibited 2.21 times higher maximum digestibility. This disparity is hypothesized to stem from compositional differences between RG and WG. RG underwent chemical transformation during steaming, yielding unique constituents such as rare ginsenosides Rg3 and Rh2, oligosaccharides, phenolic compounds, and Maillard reaction products. Rather than directly modulating enzyme activity, it is speculated that these substances may interact with the meat protein matrix, potentially altering its spatial conformation to increase the accessibility of enzymatic cleavage sites[52]. This structural facilitation was reflected in the faster rise in peptide concentration and higher maximum digestion rate observed in the 1.5%-RG group. In contrast, sun-dried WG retained more original constituents, including ginsenosides Rb1 and Rg1, alongside proteins and abundant native high-molecular-weight polysaccharides. At a higher content (1.5%), these polysaccharide components might increase the localized viscosity of the chyme or form a physical steric barrier around the protein substrates. This theoretical steric hindrance would likely restrict the diffusion of digestive enzymes and delay enzyme-substrate interactions, manifested as the observed slower peptide concentration increases[53].

4 Conclusion

This study highlights the substantial application value of RG and WG, synergistically formulated with OVA-CS complex coacervates to produce HIPEs, as a functional fat substitute in sausages. The results demonstrated that HIPEs containing RG and WG exhibited superior texture and rheological properties. Compared to the control group, the RG and WG sausages showed significantly increased hardness and chewiness, improved color profiles, and excellent sensory characteristics. Notably, low concentrations of RG effectively enhanced overall flavor intensity, while high concentrations of WG robustly regulated and masked bitterness. Furthermore, the 1.5%-RG formulation significantly improved the *in vitro* gastric digestibility of the sausages and demonstrated exceptional antioxidant capacity, effectively retarding lipid oxidation within the meat matrix. While this study elucidates the initial gastric breakdown of the sausages, future research incorporating a complete gastrointestinal model is necessary to fully evaluate the intestinal bioaccessibility and metabolic fate of the functional components. In conclusion, this study provided a novel, effective strategy for developing low-fat meat sausages using RG and WG, and held significant commercial implications for advancing the production of premium functional meat products.

Conflict of interest

The authors declare no competing financial interest.

Acknowledgments

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Author contributions

Xinyuan Wei: Writing-original draft; formal analysis. Meng Sun: Writing-original draft; formal analysis. Duo Bai: Methodology; investigation; validation. Fei Meng: Writing-review & editing; validation. Jiaqi Lin: Writing-review & editing; validation. Dongyan Chen: Writing-review & editing; validation. Jingbo Liu: Supervision; project administration. Ting Zhang: Supervision; project administration. Xuanting Liu: Funding acquisition; conceptualization; writing-review & editing.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at https://doi.org/10.26599/FSAP.2026.9240183.

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