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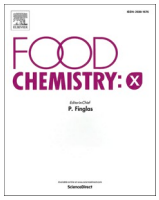

Development of emulsion gels as animal fat analogs: The impact of soybean and coconut oil concentration on rheological and microstructural properties

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ABSTRACT

This study investigates the effect of oil type and concentration on the rheological and microstructural properties of plant-based emulsion gels, comparing them to animal fat tissue. Emulsion gels were formulated with soybean or coconut oil, isolated soy protein, agar, and alginic acid at varying oil concentrations (0–30 %). The structural integrity of animal fat is attributed to a fibrous network of adipocytes and collagen. In contrast, oil concentration significantly affected the gel network density, with coconut oil-based gels maintaining stable viscoelasticity, while soybean oil-based gels exhibited more fluid-like behavior. The thermal behavior of the gels was significantly influenced by the fatty acid composition of the oils, with a distinct endothermic peak observed around 20 °C for coconut oil-based gels, while no peak appeared for soybean oil-based gels. These findings highlight the potential to optimize plant-based fat analogs by controlling oil type and concentration to replicate animal fats in plant-based food products.

1. Introduction

Solidified emulsion gels possess textural properties that closely mimic those of solid fats, providing a creamy and rich mouthfeel while maintaining the health benefits of plant-based oils. These properties have attracted considerable attention, particularly as novel fat substitutes in the food industry, in response to the growing demand for sustainable alternatives to animal fat (Guo et al., 2023). The structural, textural, and rheological characteristics of emulsion gels arise from the complex interactions between oils, emulsifiers, gelling agents, and processing methods. For instance, the choice and concentration of gelling agents can significantly affect the rigidity and stability of the gel network, whereas emulsifiers influence the particle size distribution and interfacial stability (Abdullah et al., 2022).

The volume fraction of oil incorporated into the gel matrix along with its physical state (liquid or solid) plays a crucial role in shaping the nutritional profile and texture of the gel. The oil volume fraction directly affects the viscoelastic behavior of the gel, and it is known that a higher fraction can promote a denser network of oil droplets, which can enhance the stiffness of the gel (Oliver et al., 2015). When the physical state of the oil (liquid or solid) is changed, the properties of the gel containing the oil are affected. Changing the physical state of oil by substituting liquid oils with solid fats results in the formation of a lipid crystal network, which increases the elastic modulus of the gel and yields a firmer texture (Lu et al., 2019). In addition, in emulsion gel systems, oil acts as a crucial filler that can either strengthen or soften the gel structure, depending on its interaction with the matrix. Active fillers, which strongly interact with the matrix, enhance the mechanical strength and stability, while inactive fillers contribute to a softer texture (Farjami & Madadlou, 2019). Given the significant role that oil plays in influencing the structural, textural, and rheological properties of emulsion gels, it is imperative to conduct systematic studies to explore how

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both oil type and concentration affect these properties.

Fat in meat is primarily stored as adipose tissue, comprising adipocytes embedded in a connective matrix of collagen proteins (Hocquette et al., 2010). This matrix provides rigidity, while adipocytes contribute not only to the mechanical properties of the tissue, such as rigidity, but also to its lubricity, oiliness, and melting characteristics (Roy & Bruce, 2024). These attributes are crucial for the sensory qualities of meat products, underscoring the need for a comprehensive approach that simulates the complex composition of adipose tissue, including both fat cells and connective matrix, in fat replacement applications.

In this study, we aimed to simulate adipose tissue by controlling the type and concentration of oil in the emulsion gel systems. We hypothesized that the influence of oil on the properties of the emulsion gel, including texture and rheology, has the potential to emulate the mechanical and functional attributes of adipose tissue, depending on the type and fraction of oil used (Liao et al., 2022). A deeper understanding of these factors will be key to optimizing emulsion gel formulations for specific applications, particularly in developing effective fat substitutes with desirable sensory and functional properties. To explore this, we selected two vegetable oils with contrasting properties: soybean oil, a liquid at room temperature rich in polyunsaturated fatty acids, and coconut oil, which is solid at room temperature and contains predominantly saturated medium-chain triglycerides. Emulsion gels were prepared with varying oil concentrations (0–30 %), and the effects of the oil composition and content on the behavior of the gel were examined and compared with the characteristics of animal adipose tissue. This study not only advances our understanding of the role of oil type and concentration in emulsion gels, but also provides valuable insights into the development of healthier and more sustainable alternatives to traditional animal fats.

2. Materials and methods

2.1. Materials

Soy protein isolate (SPI, crude protein >91 %) was purchased from Vixxol Co., Ltd. (Gunpo, Republic of Korea). Soybean oil and coconut oil were purchased from Ottogi Co. (Anyang, Republic of Korea) and Etssi International Co., Ltd. (Seoul, Republic of Korea), respectively. The fatty acid composition of experimental oils was shows in Table S1. Agar powder was purchased from Woori-ga Co. (Yangju, Republic of Korea). Sodium alginate (EP, purity>99 %) and calcium chloride dehydrate (EP, purity>99 %) were purchased from Ducksan (Incheon, Republic of Korea). Fluorescein sodium salt (FSS) was obtained from Sigma-Aldrich (St. Louis, MO, USA). Nile Red was obtained from Tokyo Chemical Industry (Tokyo, Japan). Animal fat samples were used as controls by carefully cutting the fat tissue attached to the loins of fresh beef purchased from a local butcher.

2.2. Preparation of emulsion gels

The emulsion gels were prepared according to the method described by Choi et al. (2023). The agar stock solution 5 % (*w*/w), alginate stock solution 5 % (w/w), and SPI stock solution 10 % (w/w) were dispersed in distilled water and stirred overnight to ensure dissolution. All stock solutions were mixed with soybean oil or coconut oil to form a series of dispersions with different oil volume fractions (0–30 %, w/w) and fixed concentrations of SPI (2 % w/w), agar (2 % w/w), and alginate (0.5 % w/w). The gel sample formulations are presented in Table 1. The mixtures were allowed to reach 90 °C in a water bath with constant stirring and then blended using an Ultra-Turrax T25D high-speed blender at 12,000 rpm for 2 min. The resulting samples were cooled to room temperature for 1 h, stirred in a 1 % (*w*/w) calcium chloride solution, and equilibrated for at least 30 min to complete cross-linking. The samples containing soybean oil are denoted as EG-S10, EG-S20, and EG-S30, respectively, and those containing coconut oil are denoted as EG-C10, EG-C20, and EG-C30, respectively. The samples without oil were denoted as HG.

Table 1
Formulation (%) of the gel samples.

Sample type	Concentration (%, *w*/w)				
	Soybean oil	Coconut oil	Soy protein isolate	Agar	Sodium alginate
HG	–	–	2	2	0.5
EG-S10	10	–	2	2	0.5
EG-S20	20	–	2	2	0.5
EG-S30	30	–	2	2	0.5
EG-C10	–	10	2	2	0.5
EG-C20	–	20	2	2	0.5
EG-C30	–	30	2	2	0.5

2.3. Color measurement

The L*a*b* color space is often used to describe color in food research. Based on the intermediate system CIE XYZ, L* represents luminance or lightness, whereas a* and b* correspond to the green-red and blue-yellow axes of the color, respectively (Mendoza et al., 2006). Before analysis, the colorimeter was calibrated using a white standard plate (Minolta Calibration Plate No. 15133143; Y = 86.5, x = 0.3176, y = 0.3339). The total color difference (ΔE) was determined using the following equation:

$$\Delta E = \sqrt{\left(L^*_{control} - L^*_{treatment}\right)^2 + \left(a^*_{control} - a^*_{treatment}\right)^2 + \left(b^*_{control} - b^*_{treatment}\right)^2}$$

The control refers to beef fat and the treatment refers to the gel sample.

2.4. Confocal laser scanning microscopy (CLSM)

Microstructural analyses of the samples were conducted using a confocal laser scanning microscope (SP8 X Confocal Microscope, Leica Microsystems, Mannheim, Germany). FSS and Nile Red were used as fluorescent dyes to selectively stain the protein and oil phases, respectively. Each dye was prepared as a stock solution at a concentration of 1 % (*w*/w) and subsequently diluted to achieve a final concentration of approximately 0.1 % (w/w). For imaging, Nile Red was excited at a wavelength of 550 nm with an emission range of 600–670 nm, whereas FSS was excited at 488 nm and emitted light in the range of 500–561 nm. Under these conditions, the protein phases labeled with FSS were visualized green, and the oil phases labeled with Nile Red were visualized as red.

2.5. Cryo-scanning electron microscopy (Cryo-SEM)

Cryo-field emission scanning electron microscopy (Cryo-FESEM, Crossbeam 550, Carl Zeiss, Oberkochen, Germany) was performed to investigate the microstructures of the samples. The samples were mounted on aluminum sample holders and rapidly frozen by immersion in a liquid nitrogen slush at −210 °C. Subsequently, the frozen samples were transferred to a cryo-preparation chamber, where they were fractured at −140 °C. The fractured surfaces underwent etching at −90 °C for 5 min. The samples were then coated with a platinum layer at a current of 10 mA for 60 s. Imaging was performed at a magnification of 80,000× and an accelerating voltage of 10 kV.

2.6. Rheological properties

The rheological properties of the samples were determined using a dynamic shear rheometer (AR, 1500e1500x, TA Instruments, New Castle, DE, USA). Samples (2 g) were loaded between parallel-plate geometries with a diameter of 40 mm, and the gap between the Peltier

and geometric plates was set to 1 mm. Samples were conditioned on Peltier plates for 10 min at the initial measurement temperature. The viscoelastic parameters were measured by performing frequency sweeps (0.1–10 Hz, stress = 1 Pa under linear viscoelastic region). Flow-sweep tests were conducted at a frequency of 1 Hz and shear rates ranging from 0.01 to 120 s^{-1}. All measurements were performed at 25 °C. Temperature-dependent changes in the samples were investigated in the linear viscoelastic range according to the following temperature profile (0.1 % strain and 1 Hz) using a slight modification of a previously established method (Wijarnprecha, Fuhrmann, et al., 2022). The temperature was increased from 20 °C to 90 °C at a rate of 5 °C/min, maintained isothermally for 10 min and then decreased from 90 °C to 20 °C at a rate of 5 °C/min.

2.7. Texture profile analysis

Texture profile analysis (TPA) of the samples was performed using TA. XT Plus texture analyzer (Stable Micro Systems, Godalming, Surrey, UK). The samples were cut into cubes measuring 1 cm on each side and then conditioned at 25 °C for 1 h prior to testing. The TPA was performed under the same temperature conditions using a P/100 probe with a diameter of 100 mm. During the analysis, a 40 % strain was applied to the samples at a crosshead speed of 2 mm/s.

2.8. Differential scanning calorimetry

The thermal properties of the samples were assessed using differential scanning calorimetry (DSC 4000, PerkinElmer, Waltham, MA, USA). An empty sealed pan served as a reference during the measurements. Each sample was placed in a sealed stainless-steel pan and allowed to equilibrate at room temperature for 1 h. Following equilibration, the pan was subjected to a temperature scan ranging from −40 °C to 100 °C at a heating rate of 5 °C/min. The results are presented as a heat flow (W/g) versus temperature curve.

2.9. Cooking properties

The samples were molded into a uniform cubic shape with length × width × height of 2 cm and cooked at 180 °C in a convection oven (MA324BGS, LGE, Korea). A thermometer (Traceable Thermometer 4052, Control Company, Scottsdale, AZ, USA) was installed at the center of the sample and the sample was cooked until the core temperature reached 75 °C. Following the cooking process, the sample was cooled to room temperature, the excess juice on the surface was removed, and the weight was measured. Cooking loss was determined by calculating the percentage change in weight before and after cooking using the following equation (Zhou et al., 2022): conducted at least in triplicate to obtain results.

$$\text{Cooking loss } (\%) = \frac{W_b - W_a}{W_b} \times 100$$

where W_b is the weight before cooking (g), and W_a is the weight after cooking (g).

2.10. Statistical analysis

Each experiment was performed with at least three biological replicates, and the results are reported as mean ± standard deviation. One-way analysis of variance (ANOVA) was used to assess statistical significance. Significant differences between groups were further analyzed using Tukey's honestly significant difference multiple range test, with the significance level set at $p < 0.05$. All statistical analyses were conducted using the SPSS software (version 25.0, SPSS, Inc., Chicago, IL, USA).

3. Results and discussion

3.1. Visual appearance

Visual appearance contributes to consumers' taste perception and product acceptance; therefore, meat analogs should strive to achieve an appearance similar to real meat (He et al., 2020). As shown in Fig. 1, visual assessment confirmed that all the gels formed solid structures with a white appearance, likely owing to the dispersion of oil droplets or proteins (Li et al., 2020). HG exhibited the highest level of transparency, whereas the emulsion gels containing soybean and coconut oils exhibited nearly identical visual characteristics. Some residual protein tissue was observed in beef fat, which likely influenced the Lab color values, particularly resulting in a higher red value compared to the emulsion gels due to the presence of myoglobin. The color of the gels was affected more by the oil content than by the oil type (Table 2). The lightness of the HG was the lowest at 68.89, and the lightness of the emulsion gels increased with increasing oil content, regardless of the oil type. In general, the higher the oil content and the smaller the oil droplets, the lighter the scattering, which can result in a high L* value (Teng & Campanella, 2023). Beef fat exhibited positive a* values owing to residual myoglobin pigment, whereas all emulsion gels showed negative a* values, indicating the absence of a red tint. In addition, HG exhibited the lowest b value. The total color difference (ΔE) was larger for emulsion gels than for HGs. The larger ΔE values for emulsion gels suggest more noticeable color differences compared to real meat, which may affect consumer acceptance. Addressing this issue with colorant additives may be crucial for improving the appearance and achieving the desired qualities of the fat analogs.

3.2. Rheological properties

Analysis of the rheological properties of emulsion gels for the development of plant-based fat analogs can provide critical insights into their ability to replicate the thermomechanical behavior of beef fat. The rheological behavior of gels is significantly influenced by their complex internal structures and interactions with their components (Dickinson, 2012).

3.2.1. Apparent viscosity

A flow sweep test was conducted to evaluate the apparent viscosity of the emulsion gel samples. All tested emulsion gel samples exhibited shear-thinning behavior, with a gradual decrease in viscosity with increasing shear rate (Su et al., 2022). In the case of EG-S, the viscosity increased consistently across all the tested shear rates as the oil content increased (Fig. 2a). This behavior can be attributed to the more densely packed oil droplets, which enhanced the overall viscosity and structure of the emulsion gel matrix. Conversely, EG-C displayed a more complex rheological response. While viscosity also increased at low shear rates with increasing oil content, the EG-C30 sample showed a higher degree of shear-thinning properties in viscosity at high shear rates (Fig. 2b). This disparity in rheological behavior between soybean and coconut oil emulsion gels is likely a result of their distinct fatty acid compositions.

The relatively weaker intermolecular forces between polyunsaturated fatty acids within soybean oil allow the droplets to remain fluid and dynamic even at higher oil contents, forming a more stable network under shear stress (Moakes et al., 2015). In contrast, coconut oil, rich in medium-chain fatty acids, tends to form smaller oil droplets, promoting the formation of a compact network (Lu et al., 2019). In addition, the melting peak temperature of coconut oil is known to be approximately 25–26.5 °C, with the melting endpoint at around 30 °C (Srivastava et al., 2017). Given that the sweep test was conducted at 25 °C, it is plausible that coconut oil underwent partial crystallization during the test, which could significantly alter the gel structure. In particular, the sharp drop in viscosity at high shear rates pronounced in the EG-C30 sample is likely due to the high saturated fatty acid content

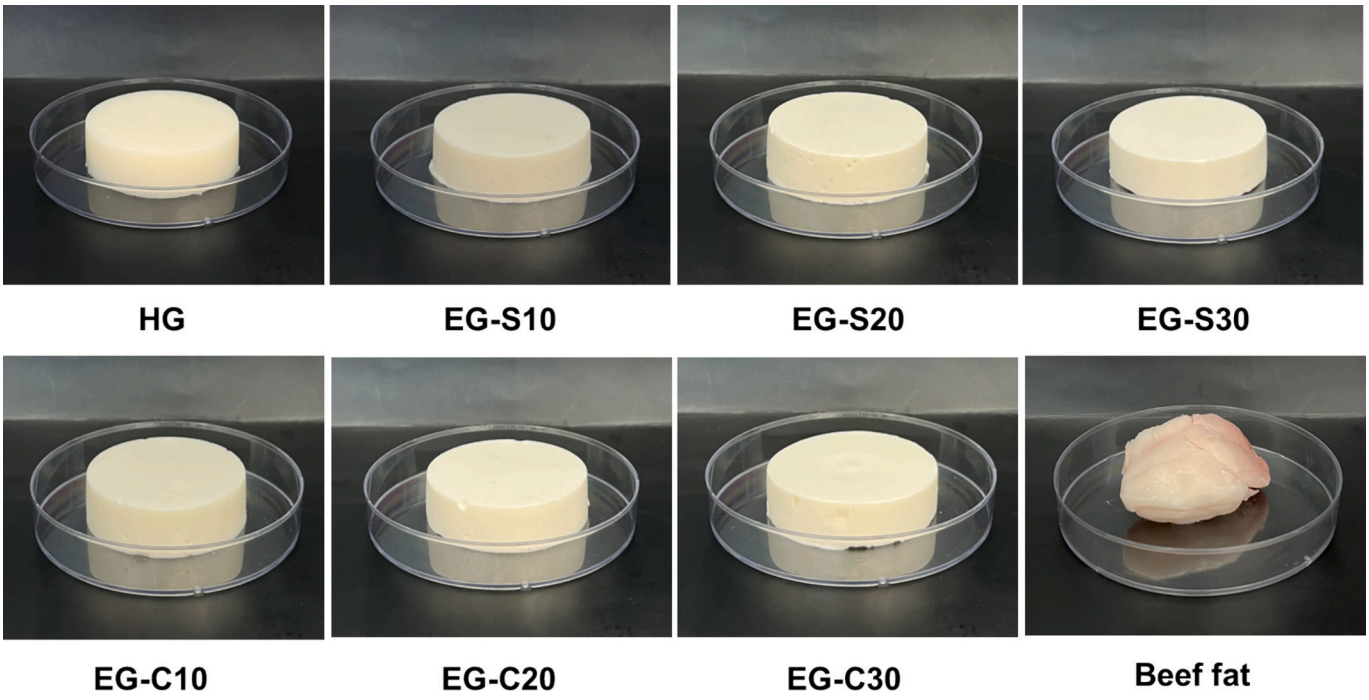

Fig. 1. Visual appearance of beef fat and gels with different oil types and concentrations. HG represents hydrogel, and the emulsion gels containing 10 % soybean oil and coconut oil were labeled as "EG-S10" and "EG-C10," and the rest of the samples were labeled following the same format. HG, hydrogel; EG-S, emulsion gel containing soybean oil; EG-C, emulsion gel containing coconut oil.

Table 2
Colorimetric analysis of beef fat and gels.

Sample type	L*	a*	b*	ΔE
Beef fat	72.50 ± 1.05^{b}	3.64 ± 0.36^{c}	6.53 ± 0.34^{b}	–
HG	68.89 ± 0.11^{a}	-1.56 ± 0.01^{a}	4.91 ± 0.05^{a}	6.53 ± 0.04^{a}
EG-S10	86.40 ± 0.64^{cd}	-0.43 ± 0.07^{b}	7.30 ± 0.19^{c}	14.51 ± 0.49^{bc}
EG-S20	87.29 ± 0.33^{d}	-0.36 ± 0.02^{b}	6.88 ± 0.35^{bc}	15.32 ± 0.26^{c}
EG-S30	89.56 ± 0.65^{e}	-0.33 ± 0.03^{b}	6.44 ± 0.16^{b}	17.52 ± 0.51^{d}
EG-C10	85.55 ± 0.11^{c}	-0.39 ± 0.01^{b}	6.89 ± 0.04^{bc}	13.66 ± 0.08^{b}
EG-C20	87.18 ± 0.17^{d}	-0.26 ± 0.04^{b}	6.43 ± 0.07^{b}	15.19 ± 0.13^{c}
EG-C30	90.57 ± 0.07^{e}	-0.22 ± 0.07^{b}	7.21 ± 0.19^{c}	18.49 ± 0.07^{d}

Hydrogel (HG); lightness (L*); red/green value (a*); blue/yellow value (b*); total color difference (ΔE). The emulsion gels containing 10 % soybean oil and coconut oil were labeled as "EG-S10" and "EG-C10," and the rest of the samples were labeled following the same format. All data represent the mean of triplicates. Different letters in the same column represent significant differences ($p < 0.05$).

of coconut oil and the partial crystallization process, which could weaken the viscoelastic network. Crystallized fat regions may lead to an uneven distribution within the continuous phase, reducing the uniformity of the gel matrix and increasing its susceptibility to structural failure under shear stress (Fredrick et al., 2010; Giermanska-Kahn et al., 2005). Additionally, the destabilization of oil droplets at high shear rates could further contribute to the breakdown of the network structure. Under normal conditions, emulsion gels rely on stable oil-protein and oil-polysaccharide interactions to maintain their structural stability. However, at high shear rates, the physical forces exerted on the system can disrupt these interactions, leading to oil droplet coalescence or phase separation. This disruption weakens the gel's structural framework, making it more prone to mechanical failure and contributing to the rapid decrease in viscosity observed in EG-C30.

In conclusion, both the oil content and fatty acid composition play pivotal roles in modulating the rheological properties of emulsion gels. Specifically, coconut oil-based gels at higher concentrations exhibit greater susceptibility to structural failure under shear due to a combination of fat crystallization, non-uniform oil distribution, and the disruption of stabilizing molecular interactions. These findings have important implications for the development of plant-based fat analogs, as optimizing oil composition and processing conditions could enhance structural stability and functional performance in food applications.

3.2.2. *Frequency sweep test*

The frequency-dependent test results for the gels and beef fat are shown in Fig. 2c, d. Across the entire tested frequency range, all samples exhibited higher storage moduli (G') than loss moduli (G"), indicating their predominantly solid-like behavior. Notably, beef fat demonstrated the highest G' value, consistent with its high saturated fat content and the presence of a robust elastic network formed by collagen and protein bundles within the adipose tissue (Hausman et al., 2018). For the emulsion gel samples, both EG-S and EG-C showed a similar trend, in which the G' values increased with increasing oil content. This behavior is attributed to the compact packing of oil droplets within the gel network with increasing oil content, which likely enhances the elastic properties of the emulsion gels. This structural aspect likely supports the emulsions gel with higher oil content to maintain higher G' values than those with lower oil content (Park et al., 2020; W. Xu, Yin, et al., 2024).

In terms of frequency-specific behavior, G' remained relatively stable across the frequency range, suggesting that the internal gel network retains its structural integrity under dynamic conditions. G" also exhibited minimal fluctuations, further reinforcing the solid-like characteristics of these systems. Additionally, while no significant deviations were observed in the overall frequency-dependent behavior of the gels, slight variations in the G' and G" values between the different oil types and concentrations suggest that the two oils respond differently to frequency-induced strains. For example, at higher oil contents, the EG-S

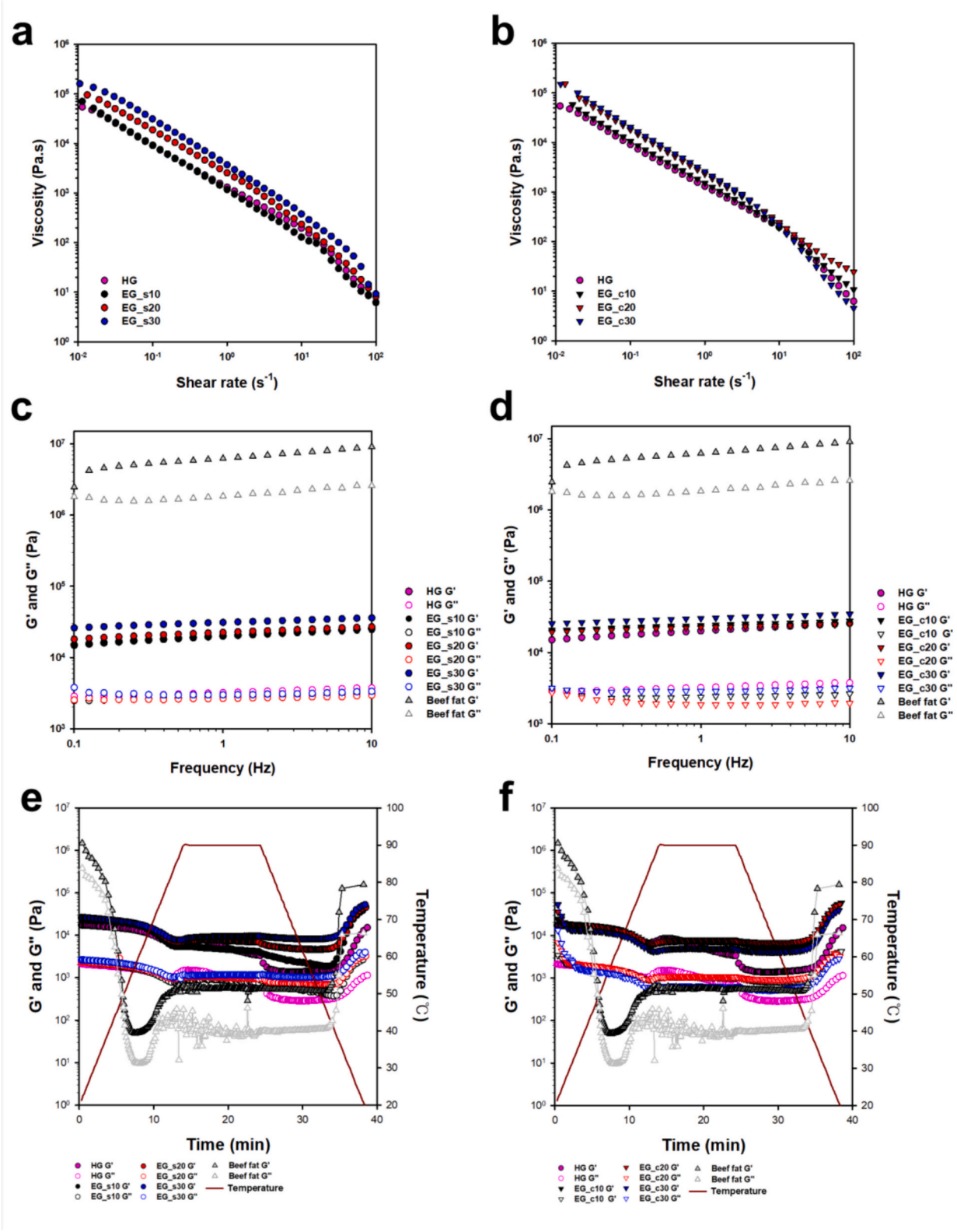

Fig. 2. Effects of different oil types and concentrations on the rheological properties of gels and comparison with beef fat. Apparent viscosities of the gels containing different concentrations of (a) soybean oil (EG-S) and (b) coconut oil (EG-C), with shear rates of 0 to 10 s^{-1}. Frequency sweep curves of the gels containing different concentrations of (c) soybean oil (EG-S) and (d) coconut oil (EG-C) compared to beef fat. Temperature sweep curves of the gels containing different concentrations of (e) soybean oil (EG-S) and (f) coconut oil (EG-C) compared to beef fat with heating and cooling from 20 to 90 °C at 3 °C/min. HG represents hydrogel, and the emulsion gels containing 10 % soybean oil and coconut oil were labeled as "EG-S10" and "EG-C10," and the rest of the samples were labeled following the same format.

samples exhibited slightly higher moduli than the EG-C samples, possibly because of the more flexible polyunsaturated fatty acids in soybean oil, which allow for a more adaptive gel structure under stress. Overall, the frequency sweep test results confirmed that increasing the oil content enhanced the mechanical strength of the emulsion gels, with G' values indicative of a stronger and more resilient network.

3.2.3. Temperature sweep test

To elucidate the thermomechanical behavior of the beef fat and emulsion gel samples, we conducted a detailed analysis of their deformation responses during controlled heating and cooling cycles from 20 °C to 90 °C (Fig. 2e, f). For beef fat, G′ considerably reduced between 20 °C and 50 °C, which is consistent with the melting of solid fats in beef tallow, a phenomenon commonly observed around its melting point of approximately 40 °C (Zeng et al., 2024). As the temperature increased beyond 50 °C up to 90 °C, both G′ and G″ started increasing, which can be attributed to protein denaturation and partial swelling of adipocytes, which may contribute to the tightening of the network and an improvement in the viscoelastic properties (Wijarnprecha, Gregson, et al., 2022). During the cooling process from 90 °C to 20 °C, beef fat solidifies rapidly once the temperature drops below 40 °C, which corresponds to the re-crystallization of fat, leading to an increase in G′. This behavior reflects the typical phase transitions of animal fat.

In the case of EG, the presence of oil resulted in a significantly higher modulus during the cooling phase compared with that of HG, which did not contain oil. This highlights the critical role of the oil droplets in reinforcing the gel structure and enhancing its mechanical strength. The soybean oil-based emulsion gel (EG-S) gradually softened during heating up to 90 °C and exhibited a concentration-dependent response in viscoelastic properties during cooling from 90 °C to 50 °C. Interestingly, the tendency for viscoelasticity to decrease was less pronounced as the oil content increased from 10 % to 30 %. In other words, gels with higher oil content (20 % and 30 %) maintained greater viscoelastic stability compared to those with lower oil content (10 %). This behavior may be attributed to the higher concentration of soybean oil promoting a more uniform distribution of oil droplets within the gel matrix, thereby enhancing the stability of the gel structure. In contrast, the coconut oil-based emulsion gel (EG-C) exhibited relatively stable viscoelastic properties across all tested oil concentrations (10 %, 20 %, and 30 %) during cooling from 90 °C to 50 °C. This thermal behavior is likely due to the high content of saturated fatty acids in coconut oil. The straight chains of saturated fatty acids may form a more rigid interfacial network than unsaturated fatty acids, contributing to a stable gel matrix (Watanabe et al., 2017). During further cooling to 20 °C, all emulsion gels, regardless of oil type or concentration, showed a gradual increase in viscoelasticity, reflecting a uniform solidification process throughout the samples.

These results highlight the combined influence of oil concentration and fatty acid composition on the thermal behavior of emulsion gels. While soybean oil exhibits a more dynamic thermal response, increasing its concentration improves viscoelastic stability during cooling. Conversely, coconut oil promotes consistent structural integrity across a wide range of concentrations. Temperature sweep tests confirm that both oil type and concentration are critical factors in modulating the viscoelastic properties of emulsion gels. Understanding these interactions is essential for designing plant-based fat analogs that closely mimic the phase transitions and textural properties of animal fats.

3.3. Textural properties

The textural characteristics of animal fats and their substitutes are important quality attributes that affect appearance, handling, and overall consumer acceptance of a product. Table 3 lists the textural characteristics of the samples. Beef fat exhibited a softer texture than all the gels, except for those containing 30 % oil (EG-S30 and EG-C30). The textural characteristics of beef fat are influenced by adipocytes and the complex fibrous network formed by collagen, which contribute significantly to its structural properties (Comley & Fleck, 2010). All types of EG with 10 % and 20 % oil contents showed increased hardness and chewiness compared to HG, most likely because the oil in this concentration range acts as an active filler within the gel matrix. Oils acting as active fillers can interact with the continuous phase of the gel, thereby improving the mechanical strength (Torres et al., 2017; Xi et al., 2019).

However, EG-S30 exhibited the lowest hardness value among all the samples. In the case of EG-C, the hardness and chewiness values remained relatively consistent at oil contents of 10–20 %, but EG-C30 exhibited a notable decrease in both hardness and chewiness, similar to that observed for EG-S30. While oil can reinforce the gel network by acting as an active filler, it may also function as an inactive filler, potentially weakening the network and negatively impacting the rheological properties. The observed decrease in gel stiffness when the oil content increases from 20 % to 30 % may be attributed to the volume fraction approaching the particle packing limit, disrupting the continuity of the gel matrix (Langendörfer et al., 2024).

When comparing by oil type, EG-S exhibited higher hardness and chewiness than EG-C at 10 % and 20 % oil content. However, this trend reversed at 30 % oil, with EG-C demonstrating greater textural strength. This suggests that the influence of oil content on texture is closely related to the type of oil. In soybean oil, which is rich in long-chain unsaturated fatty acids, the presence of double bonds introduces kinks in the hydrocarbon chains, reducing the overall packing density compared to coconut oil, which contains a high proportion of medium-chain saturated fatty acids with straight hydrocarbon chains. This structural difference likely affects the gel's network integrity by altering the arrangement of oil droplets and polymer interactions, which in turn influences the maximum particle packing volume fraction and the resulting textural properties of the gel (Pal, 2002). These findings reflect the complex interplay between oil content, fatty acid composition, filler behavior, and the structural dynamics of the gel network. While further analysis is required to fully understand these interactions, the current findings underscore the importance of optimizing the oil concentration to achieve precise textural control. At optimal concentrations, oil can act

Table 3
Texture analysis profile (40 % deformation) of beef fat and gels.

Sample type	Hardness (g.force)	Adhesiveness (g·seconds [g ·s])	Springiness (mm)	Cohesiveness	Chewiness
Beef fat	945.73 ± 30.76^{b}	−135.22 ± 33.38^{a}	0.64 ± 0.14 ^{a}	0.25 ± 0.02^{a}	156.12 ± 49.96^{a}
HG	1121.92 ± 16.01^{d}	−1.87 ± 0.09^{b}	0.78 ± 0.02^{ab}	0.62 ± 0.01^{c}	543.76 ± 11.84^{d}
EG-S10	1350.98 ± 3.36^{f}	−2.51 ± 0.42^{b}	0.78 ± 0.01^{ab}	0.60 ± 0.01^{c}	641.56 ± 14.64^{e}
EG-S20	1315.01 ± 8.80^{f}	−2.21 ± 0.40^{b}	0.81 ± 0.01^{b}	0.61 ± 0.01^{c}	654.67 ± 12.80^{e}
EG-S30	780.40 ± 12.06^{a}	−1.95 ± 0.20^{b}	0.80 ± 0.03^{b}	0.48 ± 0.03^{c}	304.64 ± 31.87^{b}
EG-C10	1246.01 ± 5.81^{e}	−2.22 ± 0.21^{b}	0.76 ± 0.02^{ab}	0.60 ± 0.01^{c}	579.65 ± 17.32^{de}
EG-C20	1240.78 ± 11.99^{e}	−2.78 ± 0.32^{b}	0.77 ± 0.02^{ab}	0.60 ± 0.01^{c}	577.14 ± 29.73^{de}
EG-C30	990.69 ± 10.79^{c}	−2.25 ± 0.11^{b}	0.76 ± 0.03^{ab}	0.58 ± 0.12^{b}	444.36 ± 45.98^{c}

The emulsion gels containing 10 % soybean oil and coconut oil were labeled as "EG-S10" and "EG-C10," and the rest of the samples were labeled following the same format. All data represent the mean of triplicates. Different letters in the same column represent significant differences ($p < 0.05$).

as an active filler, reinforcing the gel matrix and enhancing texture. These insights are essential for developing fat substitutes with textural properties similar to those of beef fat, thereby improving the sensory quality and consumer acceptance of plant-based or alternative fat products.

3.4. Microstructure

CLSM and cryo-SEM were performed to characterize the microstructure of the gel and beef fat (Figs. 3 and 4). In the CLSM images, the oil phase is shown in red, and the water phase contains proteins and polysaccharides in green. In beef fat, adipocytes with a diameter of 50–100 μm were present, separated, and surrounded by a thin membrane network composed of proteins. The diameter of beef adipocytes is 50–200 μm and the membrane wall thickness is approximately 2 μm (Hood & Allen, 1973). The gel samples containing oil exhibited the typical characteristics of oil-in-water emulsions, with spherical oil droplets uniformly dispersed within the continuous aqueous phase Both EG-S and EG-C samples, an increase in oil content resulted in a higher number of oil droplets, leading to a denser packing arrangement. However, no evidence of droplet coalescence or aggregation was observed for any of the tested samples. In this system, soy protein likely played a crucial role in stabilizing the emulsion droplets at the oil-water interface because of its amphiphilic properties, facilitating the formation of a stable interfacial layer (Nishinari et al., 2014). Additionally, agar and alginate can contribute to emulsion stability not only by forming a gel network, but also by increasing the viscosity of the aqueous phase, which restricts droplet mobility and minimizes the likelihood of aggregation (W. Xu, Yin, et al., 2024). The absence of coalescence or aggregation, even at the highest tested oil concentrations (30 % soybean oil and coconut oil), suggests that the continuous phase matrix, comprising proteins and polysaccharides, provides a robust mechanical barrier that effectively prevents droplet coalescence (Wei et al., 2020). Furthermore, the densely packed oil droplets formed an interconnected network within the gel matrix, which likely enhanced the mechanical properties of the gel by increasing the contact points and reinforcing its structural integrity (Chen et al., 2024).

Cryo-SEM images of beef fat showed a foam-like structural organization filled with a high internal phase, similar to the results of a previous study of pork back fat (Wijarnprecha, Gregson, et al., 2022). For the gel samples, a polymer mesh network composed of agar and alginate was confirmed (Mao et al., 2016). All oil-containing gel samples exhibited a denser network structure with smaller pore sizes than the HG sample without oil. This structural change may be attributed to the presence of dispersed oil droplets, which may promote closer packing and enhanced interactions among the polymer chains within the gel matrix (Zhao et al., 2022). Both the EG-S and EG-C samples exhibited a progressively denser gel network with smaller pore sizes as the oil content increased. A denser gel network is typically associated with improved structural integrity, aligning with our texture analysis results that the gel strength increased as the oil content increased to 20 % (Zhao et al., 2023).

3.5. Thermal behavior

DSC analysis of fat analogs is essential for optimizing their thermal properties and accurately replicating the texture and mouthfeel characteristics of animal fats with unique structures and melting behaviors (McClements et al., 2021). The thermal behavior of all samples was measured by heating from −40 to 100 °C (Fig. 5). The beef fat melted up to approximately 50 °C, which is consistent with previously published results (Wijarnprecha, Fuhrmann, et al., 2022). A comparison of HG, beef fat, and an emulsion gel containing soybean oil is shown in Fig. 5a. All gel samples, except beef fat, showed a large endothermic peak near 0 °C when heated, and HG, which had the highest proportion of water phase, showed the largest peak. A smaller peak was observed as the fraction of the water phase in the emulsion gel decreased. This may be the result of the melting of the ice crystals formed during the cooling of the gel (Hu et al., 2022). No peaks related to the melting of fat crystals were observed because soybean oil is rich in unsaturated fatty acids,

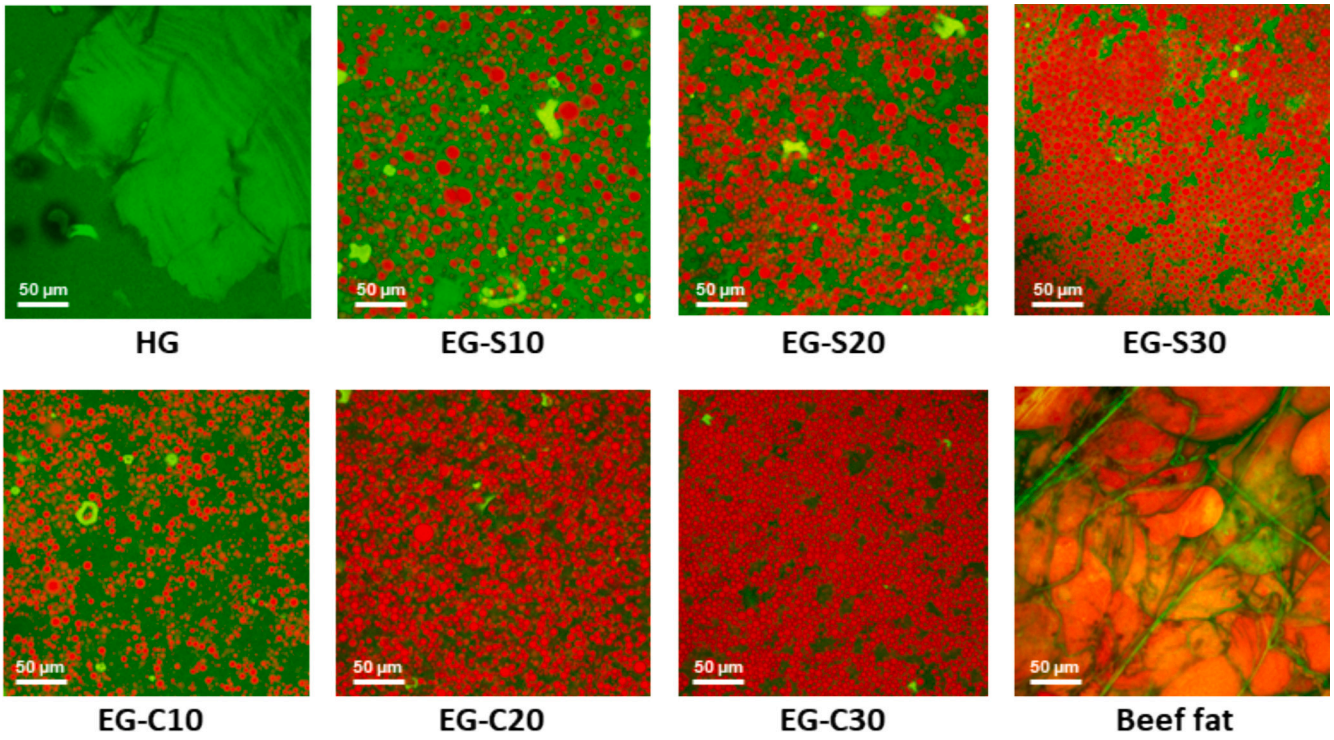

Fig. 3. Confocal microscopy of beef fat and gels with different oil types and concentrations. HG represents hydrogel, and the emulsion gels containing 10 % soybean oil and coconut oil were labeled as "EG-S10" and "EG-C10," and the rest of the samples were labeled following the same format.

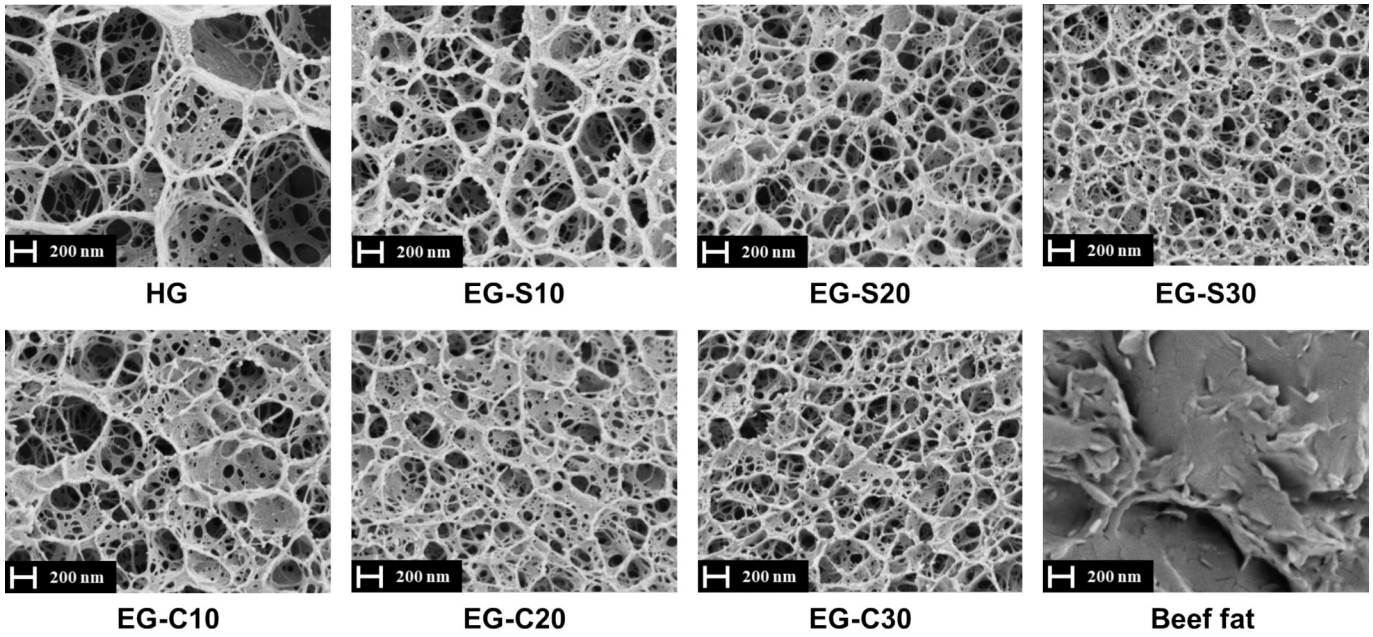

Fig. 4. Cryo-field emission scanning electron microscopy of gel with different oil types and concentrations. HG represents hydrogel, and the emulsion gels containing 10 % soybean oil and coconut oil were labeled as "EG-S10" and "EG-C10," and the rest of the samples were labeled following the same format.

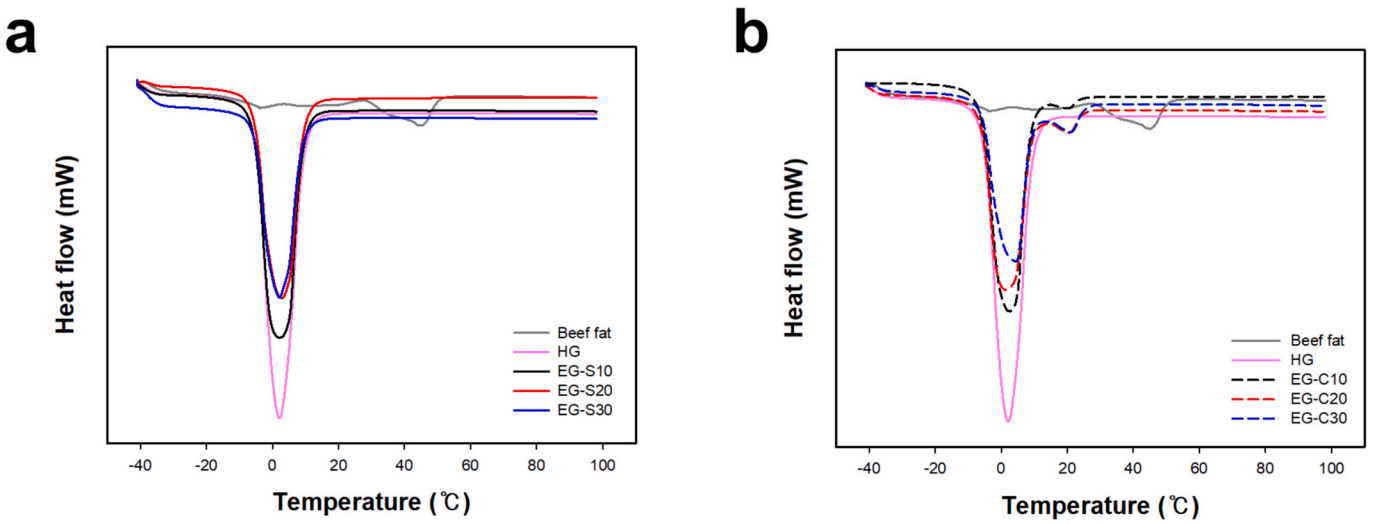

Fig. 5. Differential scanning calorimetry thermograms of beef fat and gels containing (a) EG-S and (b) EG-C. HG represents hydrogel, and the emulsion gels containing 10 % soybean oil and coconut oil were labeled as "EG-S10" and "EG-C10," and the rest of the samples were labeled following the same format.

including linoleic acid (C18:2) and oleic acid (C18:1), which have low melting points (Zambiazi et al., 2007). However, in the case of coconut oil-based emulsion gels, an endothermic peak was observed at approximately 20 °C (Fig. 5b). The observed difference in the melting behavior, particularly the peak in the coconut oil-based emulsion gel, can be attributed to the varying saturated/unsaturated fatty acid ratios, with higher saturation significantly influencing the enthalpy and melting point of the fat (Faridah et al., 2023). These data suggest that the thermal behavior of the emulsion gels is significantly influenced by the fatty acid composition of the incorporated oils. The absence of a pronounced melting peak in the soybean-oil-based gels confirms the impact of the high unsaturated fatty acid content, resulting in low melting points and no observed melting of fat crystals within the tested temperature range. In contrast, the distinct endothermic peak observed in coconut oil-based gels at around 20 °C underscores the role of saturated fatty acids, particularly medium-chain fatty acids such as lauric acid, in contributing to the thermal transitions (Jayadas & Nair, 2006). This highlights the importance of selecting the appropriate fat sources based on their fatty acid profiles to tailor the melting behavior and structural characteristics of fat analogs in meat-like products.

3.6. Cooking properties

The physicochemical properties of fat substitutes change during cooking and processing due to phenomena such as water evaporation and fat crystal melting, making cooking loss a key parameter affecting the properties of meat products (Zhou et al., 2022). Fig. 6 shows a graph comparing the cooking losses of beef fat and gel samples. Beef fat showed the highest cooking loss among all the gel samples, which was thought to be due to its high fat content and low melting point. Beef fat tissue melts from approximately 40 °C, and a large amount of fat is released due to the denaturation of connective tissue containing fat

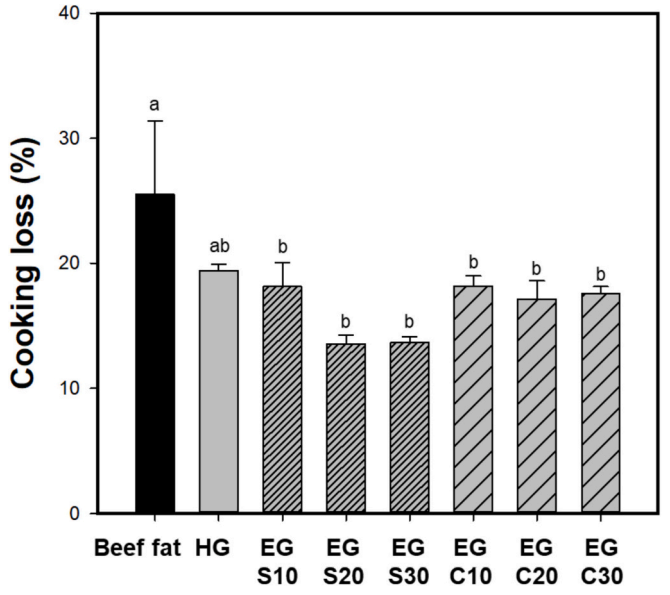

Fig. 6. Cooking loss of beef fat and gels. HG represents hydrogel, and the emulsion gels containing 10 % soybean oil and coconut oil were labeled as "EG-S10" and "EG-C10," and the rest of the samples were labeled following the same format.

during heating, which can lead to weight loss. The HG showed a higher cooking loss than all types of emulsion gels, which may be due to differences in the structural and molecular interactions depending on the existence of oil in the gel matrix (Su et al., 2024) In addition, cooking loss is closely related to the gel network structure that holds moisture or oil and can be greatly affected by the density of the gel network (Liang et al., 2020). Cryo-SEM images revealed that the hydrogel (HG) sample exhibited the largest pore size, which likely contributed to its significantly higher cooking loss compared to other gel samples. In contrast, all emulsion gels displayed a dense gel structure with small, uniform pore sizes of less than 600 nm. This dense network accounts for the lower cooking losses observed across all emulsion gels, rather than beef fat and hydrogel. The cooking temperature which effect on gel network also played a critical role in the results. To replicate conditions suitable for cooking and consuming meat, the samples were cooked until a core temperature of 75 °C. Since alginate is thermally stable within the range of 100–120 °C (Ching et al., 2017), the gel network composed of agar and alginate likely retained its structural integrity through the cooking process.

While no statistically significant differences were observed among the emulsion gels, certain trends were evident based on oil content and type (Table S2). Specifically, as the oil content increased, the cooking loss for the soybean oil-based emulsion gels decreased from 18.14 % (10 % oil content) to 13.53 % and 13.64 % (20 % and 30 % oil content, respectively). Similarly, for the coconut oil-based emulsion gels, the cooking loss decreased from 18.17 % (10 % oil content) to 17.13 % and 17.59 % (20 % and 30 % oil content, respectively). Notably, the reduction in cooking loss was more pronounced in the soybean oil-based emulsion gels compared to those made with coconut oil. This suggests that differences in fatty acid composition, oil concentration and oil-gel interactions may have influenced water retention and structural stability during cooking. While cooking loss measurements alone do not fully explain these effects, further investigation into the mechanisms underlying these variations would be valuable for optimizing the formulation of plant-based fat analogues.

4. Conclusion

This study provides key insights into how oil content and type influence the rheological, textural, and thermal properties of emulsion gels as fat substitutes. The findings demonstrated that increasing oil content enhanced the mechanical properties of emulsion gels, including hardness and chewiness, up to a certain threshold, with this trend varying based on oil type. This suggests the potential that optimizing oil concentration and selection can fine-tune gel formulations to replicate the texture of beef fat. The thermal behavior of the gels was strongly dependent on oil type; coconut oil-based gels, rich in saturated fats, exhibited phase transitions similar to those of beef fat, making them promising candidates for replicating the thermal properties of animal fats in meat applications. The differences in properties depending on the oil content and type of gels result from the complex interplay between oil acting as a filler and the structural dynamics of the gel network, and these mechanisms warrant further investigation. Overall, these results underscore the need to optimize oil type and concentration to develop emulsion gels with desirable fat-mimicking properties. Expanding research to a broader range of oils and formulations could further enhance the sensory and functional qualities of plant-based fat analogues, supporting their application in diverse food products.

CRediT authorship contribution statement

Minji Choi: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Hyun Woo Choi:** Writing – review & editing, Visualization, Methodology, Conceptualization. **Yaeji Choe:** Validation, Investigation, Formal analysis. **Jungwoo Hahn:** Writing – review & editing, Methodology, Conceptualization. **Young Jin Choi:** Writing – review & editing, Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fochx.2025.102439.

Data availability

The authors are unable or have chosen not to specify which data has been used.

References

Abdullah, Liu, L., Javed, H. U., & Xiao, J. (2022). Engineering emulsion gels as functional colloids emphasizing food applications: A review. *Frontiers in Nutrition, 9*, Article 890188.

Chen, J., Shen, S., Chen, X., Tang, Z., Yang, J., Jiang, X., Fang, Y., & Ding, J. (2024). Fabrication of strong and elastic HIPPEs gel by rigid-flexible double network structure as a novel adipose tissue substitutes. *Food Hydrocolloids, 156*, Article 110367.

Ching, S. H., Bansal, N., & Bhandari, B. (2017). Alginate gel particles–A review of production techniques and physical properties. *Critical Reviews in Food Science and Nutrition, 57*, 1133–1152.

Choi, M., Choi, H. W., Kim, H. E., Hahn, J., & Choi, Y. J. (2023). Mimicking animal adipose tissue using a hybrid network-based solid-emulsion gel with soy protein isolate, agar, and alginate. *Food Hydrocolloids, 145*, Article 109043.

Comley, K., & Fleck, N. A. (2010). A micromechanical model for the young's modulus of adipose tissue. *International Journal of Solids and Structures, 47*, 2982–2990.

Dickinson, E. (2012). Emulsion gels: The structuring of soft solids with protein-stabilized oil droplets. *Food Hydrocolloids, 28*(1), 224–241.
Faridah, M. R., Yusoff, M. M., Rozzamri, A., Ibadullah, W. Z. W., Hairi, A. N. A., Daud, N. H. A., … Ismail-Fitry, M. R. (2023). Effect of palm-based shortenings of various melting ranges as animal fat replacers on the physicochemical properties and emulsion stability of chicken meat emulsion. *Foods, 12*, 597.
Farjami, T., & Madadlou, A. (2019). An overview on preparation of emulsion-filled gels and emulsion particulate gels. *Trends in Food Science & Technology, 86*, 85–94.
Fredrick, E., Walstra, P., & Dewettinck, K. (2010). Factors governing partial coalescence in oil-in-water emulsions. *Advances in Colloid and Interface Science, 153*, 30–42.
Giermanska-Kahn, J., Laine, V., Arditty, S., Schmitt, V., & Leal-Calderon, F. (2005). Particle-stabilized emulsions comprised of solid droplets. *Langmuir, 21*, 4316–4323.
Guo, J., Cui, L., & Meng, Z. (2023). Oleogels/emulsion gels as novel saturated fat replacers in meat products: A review. *Food Hydrocolloids, 137*, Article 108313.
Hausman, G. J., Bergen, W. G., Etherton, T. D., & Smith, S. B. (2018). The history of adipocyte and adipose tissue research in meat animals. *Journal of Animal Science, 96*, 473–486.
He, J., Evans, N. M., Liu, H., & Shao, S. (2020). A review of research on plant-based meat alternatives: Driving forces, history, manufacturing, and consumer attitudes. *Comprehensive Reviews in Food Science and Food Safety, 19*, 2639–2656.
Hocquette, J., Gondret, F., Baéza, E., Médale, F., Jurie, C., & Pethick, D. (2010). Intramuscular fat content in meat-producing animals: Development, genetic and nutritional control, and identification of putative markers. *Animal, 4*, 303–319.
Hood, R. L., & Allen, C. E. (1973). Cellularity of bovine adipose tissue. *Journal of Lipid Research, 14*, 605–610.
Hu, X., Zhou, H., & McClements, D. J. (2022). Utilization of emulsion technology to create plant-based adipose tissue analogs: Soy-based high internal phase emulsions. *Food Structure, 33*, Article 100290.
Jayadas, N. H., & Nair, K. P. (2006). Coconut oil as base oil for industrial lubricants—Evaluation and modification of thermal, oxidative and low temperature properties. *Tribology International, 39*, 873–878.
Langendörfer, L. J., Guseva, E., Bauermann, P., Schubert, A., Hensel, O., & Diakité, M. (2024). The viscoelastic behavior of legume protein emulsion gels—The effect of heating temperature and oil content on viscoelasticity, the degree of networking, and the microstructure. *Foods, 13*, 3875.
Li, M., Wu, J., Chen, Z., & Wu, T. (2020). Improving the solubility of myofibrillar proteins (MPs) by mixing with sodium alginate: Effects of pH, mixing ratios and preheating of MPs. *Food Biophysics, 15*, 113–121.
Liang, X., Ma, C., Yan, X., Zeng, H., McClements, D. J., Liu, X., & Liu, F. (2020). Structure, rheology and functionality of whey protein emulsion gels: Effects of double cross-linking with transglutaminase and calcium ions. *Food Hydrocolloids, 102*, Article 105569.
Liao, Y., Sun, Y., Wang, Z., Zhong, M., Li, R., Yan, S., Qi, B., & Li, Y. (2022). Structure, rheology, and functionality of emulsion-filled gels: Effect of various oil body concentrations and interfacial compositions. *Food Chemistry: X, 16*, Article 100509.
Lu, Y., Mao, L., Cui, M., Yuan, F., & Gao, Y. (2019). Effect of the solid fat content on properties of emulsion gels and stability of β-carotene. *Journal of Agricultural and Food Chemistry, 67*, 6466–6475.
Mao, B., Divoux, T., & Snabre, P. (2016). Normal force controlled rheology applied to agar gelation. *Journal of Rheology, 60*, 473–489.
McClements, D. J., Weiss, J., Kinchla, A. J., Nolden, A. A., & Grossmann, L. (2021). Methods for testing the quality attributes of plant-based foods: Meat- and processed-meat analogs. *Foods, 10*, 260.
Mendoza, F., Dejmek, P., & Aguilera, J. M. (2006). Calibrated color measurements of agricultural foods using image analysis. *Postharvest Biology and Technology, 41*, 285–295.
Moakes, R. J. A., Sullo, A., & Norton, I. T. (2015). Preparation and rheological properties of whey protein emulsion fluid gels. *RSC Advances, 5*, 60786–60795.
Nishinari, K., Fang, Y., Guo, S., & Phillips, G. (2014). Soy proteins: A review on composition, aggregation and emulsification. *Food Hydrocolloids, 39*, 301–318.
Oliver, L., Berndsen, L., van Aken, G. A., & Scholten, E. (2015). Influence of droplet clustering on the rheological properties of emulsion-filled gels. *Food Hydrocolloids, 50*, 74–83.
Pal, R. (2002). Complex shear modulus of concentrated suspensions of solid spherical particles. *Journal of Colloid and Interface Science, 245*, 171–177.
Park, J. J., Olawuyi, I. F., & Lee, W. Y. (2020). Characteristics of low-fat mayonnaise using different modified arrowroot starches as fat replacer. *International Journal of Biological Macromolecules, 153*, 215–223.
Roy, B. C., & Bruce, H. L. (2024). Contribution of intramuscular connective tissue and its structural components on meat tenderness-revisited: A review. *Critical Reviews in Food Science and Nutrition, 64*, 9280–9310.
Srivastava, Y., Semwal, A. D., Sajeevkumar, V. A., & Sharma, G. (2017). Melting, crystallization and storage stability of virgin coconut oil and its blends by differential scanning calorimetry (DSC) and Fourier transform infrared spectroscopy (FTIR). *Journal of Food Science and Technology, 54*, 45–54.
Su, C., Li, Y., Zhu, J., Gao, Y., Li, Q., Du, S., & Yu, X. (2022). Effect of flaxseed gum on the brittleness of oleogels based on candelilla wax. *RSC Advances, 12*, 30734–30741.
Su, C. Y., Li, D., Wang, L. J., & Wang, Y. (2024). Development of corn starch-sodium alginate emulsion gels as animal fat substitute: Effect of oil concentration. *Food Hydrocolloids, 157*, Article 110439.
Teng, C., & Campanella, O. H. (2023). A plant-based animal fat analog produced by an emulsion gel of alginate and pea protein. *Gels, 9*(5), 393.
Torres, O., Tena, N. M., Murray, B., & Sarkar, A. (2017). Novel starch based emulsion gels and emulsion microgel particles: Design, structure and rheology. *Carbohydrate Polymers, 178*, 86–94.
Watanabe, T., Kawai, T., & Nonomura, Y. (2017). Effects of fatty acid addition to oil-in-water emulsions stabilized with sucrose fatty acid ester. *Journal of Oleo Science, 67*, 307–313.
Wei, Y., Xie, Y., Cai, Z., Guo, Y., Wu, M., Wang, P., Li, R., & Zhang, H. (2020). Interfacial and emulsion characterisation of chemically modified polysaccharides through a multiscale approach. *Journal of Colloid and Interface Science, 580*, 480–492.
Wijarnprecha, K., Fuhrmann, P., Gregson, C., Sillick, M., Sonwai, S., & Rousseau, D. (2022). Temperature-dependent properties of fat in adipose tissue from pork, beef and lamb. Part 2: Rheology and texture. *Food & Function, 13*, 7132–7143.
Wijarnprecha, K., Gregson, C., Sillick, M., Fuhrmann, P., Sonwai, S., & Rousseau, D. (2022). Temperature-dependent properties of fat in adipose tissue from pork, beef and lamb. Part 1: Microstructural, thermal, and spectroscopic characterisation. *Food & Function, 13*, 7112–7122.
Xi, Z., Liu, W., McClements, D. J., & Zou, L. (2019). Rheological, structural, and microstructural properties of ethanol induced cold-set whey protein emulsion gels: Effect of oil content. *Food Chemistry, 291*, 22–29.
Xu, W., Yin, Y., Cao, B., Sun, H., Zhu, X., Zang, J., … Luo, D. (2024). Fabrication and characterization of mayonnaise based on xanthan gum/lysozyme nanoparticles and konjac glucomannan as egg yolk substitutes under different temperature stresses. *LWT, 210*, Article 116832.
Zambiazi, R. C., Przybylski, R., Zambiazi, M. W., & Mendonca, C. B. (2007). Fatty acid composition of vegetable oils and fats. *B. Ceppa, Curitiba, 25*, 111–120.
Zeng, Z., Qin, X., Wang, H., Chen, Z., Huang, D., Xiang, D., & Liu, X. (2024). Effect of the chemical composition and structural properties of beef tallow from different adipose tissues on bread quality. *LWT, 192*, Article 115736.
Zhao, X., Li, D., Wang, L. J., & Wang, Y. (2022). Rheological properties and microstructure of a novel starch-based emulsion gel produced by one-step emulsion gelation: Effect of oil content. *Carbohydrate Polymers, 281*, Article 119061.
Zhao, X., Li, D., Wang, L. J., & Wang, Y. (2023). Role of gelation temperature in rheological behavior and microstructure of high elastic starch-based emulsion-filled gel. *Food Hydrocolloids, 135*, Article 108208.
Zhou, H., Vu, G., Gong, X., & McClements, D. J. (2022). Comparison of the cooking behaviors of meat and plant-based meat analogues: Appearance, texture, and fluid holding properties. *ACS Food Science & Technology, 2*(5), 844–851.

Glossary

FSS: Fluorescein sodium salt
HG: hydrogel
CLSM: Confocal laser scanning microscopy
Cryo-SEM: Cryo-scanning electron microscopy
TPA: Texture profile analysis
DSC: differential scanning calorimetry
ANOVA: One-way analysis of variance
HSD: honestly significant difference