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The effects of different vegetable oils and gelation techniques (hot vs. cold) on pea protein emulsion gel properties as fat replacers

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PAPER

Abstract

A fat replacer mimics the properties of fat in foods, offering a healthier option that reduces calories and fat while maintaining good texture and flavor. This work aimed to produce pea protein emulsion gel (PPEG) using pea protein isolate with different oils (olive oil, sunflower oil, or canola oil) and gelation techniques (hot or cold), with beef fat (BF) as the control. The nutritional, physicochemical, and microstructural properties of the PPEG were evaluated. The type of oil and gelation technique did not affect the proximate composition, color, or water-holding capacity of PPEG ($p>0.05$). None of the PPEGs showed differences in oil-binding capacity compared to BF. Hot-prepared PPEG has a lower pH and smaller particle size, resulting in significantly higher hardness and gel strength ($p<0.05$). The use of sunflower oil enhances the springiness, chewiness, and cohesiveness of PPEG significantly ($p<0.05$). The cold gelation technique may preserve more polyunsaturated fatty acids than the hot gelation technique. Principal component analysis (PCA) results indicate that PPEG prepared from sunflower oil using the hot gelation technique has properties closest to those of BF, particularly in terms of high values of springiness, cohesiveness, and chewiness. Its hardness and gel strength are significantly lower than those of BF; however, it possesses the strongest gel network among all PPEGs. In conclusion, the use of sunflower oil and the hot gelation technique can produce an emulsion gel with the best properties for use as a fat replacer.

Keywords: Fat substitute; Gelling properties; Meat product; Oil type; Protein-based fat replacer

Introduction

Meat products with animal fat as an ingredient are highly favored because they provide flavor, texture, and mouthfeel. However, consuming a high amount of saturated fatty acids (SFAs) from animal fat is strongly linked to the risk of several chronic diseases. The development of fat replacers is a strategic approach to address this issue by reducing the health risks associated with meat product consumption while maintaining product quality (Nourmohammadi *et al*., 2023). There are several types of fat replacers available, including powders, pastes, emulsion gels, and oleogels. The application of emulsion gel is considered the most practical form of fat replacers, as it can mimic the effects of fat on hardness and water-holding capacity (WHC). In addition, they possess solid-like properties and provide a healthy lipid profile (Asyrul-Izhar *et al*., 2023b; Lin *et al*., 2020). Protein-based fat replacers have gained increasing attention as they can enhance the protein content. The use of protein-based fat replacers enables the replacement of a maximum percentage of fat in meat products (Yashini *et al*., 2019). Several studies have reported the successful development of protein-based emulsion gel from various sources, such as PSE-like chicken protein isolate (Li *et al*., 2024a), egg and soybean protein isolates (Zhang *et al*., 2020), whey protein isolate (Liang *et al*., 2020; Seddiek *et al*., 2025), and chia flour (Pintado *et al*., 2015) without their application on meat matrix.

Pea protein is a promising alternative to soybean protein due to its low allergenicity, high nutritional value, and good emulsification property (Lu *et al*., 2019), but it has poor gelling capacity. On the other hand, gel formation is crucial for the development of emulsion gels, as it imparts the products' texture. Basically, the texture of emulsion gel is significantly influenced by the types of raw materials and the gelation techniques used. As one of the main materials in the emulsion gel, lipid plays an important role in the texture of the emulsion gel, as the oil droplets interact with the surrounding gel matrix (Li *et al*., 2022). Gel formation can be done with or without heating. Gelation by heating typically occurs at 80–95°C for 20–30 min at high protein concentration (more than 10%) to induce the denaturation of protein subunit by polypeptide chains unfolding, which then exposes the reactive groups, including hydrophobic groups, and results in protein aggregation and crosslinking (Chao and Aluko, 2018; Nourmohammadi *et al*., 2023). The incorporation of a heated emulsion gel results in sausages with improved microstructure, reduced purge loss, and enhanced sensory properties. Another method of gelation, which does not involve heating, called cold gelation, could preserve PUFA and some heat-sensitive ingredients (Li *et al*., 2024b; Öztürk-Kerimoğlu *et al*., 2021). Thus, the type of oil and the gelation technique significantly contribute to the properties of the emulsion gel.

In recent years, the effect of oil type and gelation technique has been explored separately. Li *et al*. (2024a) studied the effect of vegetable oil on the properties of PSE-like chicken meat protein isolate–based emulsion gels. They found that using sunflower oil significantly increases the emulsion gel's gel strength. Furthermore, the emulsion gel with sunflower oil exhibits the lowest centrifugal loss compared to emulsions with peanut oil, corn oil, and soybean oil. This means that using sunflower oil can help the system retain water. Another study reported the effect of oil polarity on rheology properties of emulsion gel, including the ability of the system to resist structure breakdown (Zou *et al*., 2019). In addition, Zhang *et al*. (2020) indicated that different oil types affect the texture properties, water loss, and oil loss. A study compared the use of cold-set and hot-set emulsions as beef fat (BF) replacers in heat-treated fermented sausages. The results indicated that hot-set emulsion gel obtained sausages with lower purge loss and less rancid flavor than cold-set emulsion gel (Öztürk-Kerimoğlu *et al*., 2021). A pea protein emulsion gel (PPEG) with low pea protein concentration has been developed using a cold gelation technique (Li *et al*., 2024b).

Olive oil predominantly consists of around 55–83% monounsaturated fatty acid (MUFA), 3.5–21.0% polyunsaturated fatty acid (PUFA), and 9–25% SFA (Boskou *et al*., 2006). Canola oil contains about 60% MUFA, 30% PUFA, and 7% SFA. In comparison to other vegetable oils, canola oil has the lowest amount of SFA (Barthet, 2016). Sunflower oil is a vegetable oil with a high content of PUFA, which may reach around 88.39%, while only 11.61% is SFA (Devi and Khatkar, 2017). These oils are commonly used in the development of emulsion gels, but they differ in fatty acid composition and degree of saturation, leading to distinct behavior during emulsification, heating, and gelation. Few studies have been conducted to determine the optimal gelation technique for developing protein-based emulsion gels, as their behavior varies under different conditions. The best practice for selecting an oil type and a gelation technique for producing a PPEG has not yet been explored. Therefore, this study aimed to evaluate the effects of different vegetable oils, including olive oil, sunflower oil, and canola oil, as well as various gelation techniques, on the properties of PPEGs, which further compared to BF as control. The use of BF as the control was aimed to check the suitability of PPEG as a fat replacer by comparing their properties and finding the PPEG with the most-matched properties with BF (Totaro *et al*., 2025). This study could provide an insight for the industry in the utilization of pea protein and lay the foundation for processing PPEG, as pea protein is affordable and widely available in the market.

Materials and Methods

Materials

The pea protein isolate was purchased from CK Ingredient Sdn Bhd, Puchong, Selangor, Malaysia. Fish gelatine was purchased from Bake 123, Seri Kembangan, Selangor, Malaysia. Olive oil, canola oil, and sunflower oil were purchased from Lotus's Supermarket, IOI City Mall, Selangor, Malaysia. BF was purchased from Pasar Borong Selangor, Selangor, Malaysia, and stored at −20°C in the freezer before processing.

Preparation of PPEG

The procedure for the preparation of PPEG followed a previous study (Pintado and Cofrades, 2020). PPEG was prepared by mixing the pea protein isolate (10%) with water (isolate: water ratio, 1:4) for 45 s using a homogenizer at 10,000 rpm to emulsify the mixture and ensure uniformity and particle size. Gelatine (5%) was added and mixed for 15 s at 10,000 rpm. After that, a second mixing was performed for 3 min at 10,000 rpm, and the oil (sunflower, olive, or canola oil at 30%) was gradually added during homogenization. For the hot gelation technique, the emulsion gel was heated for 30 min at 90°C in a water bath. For the cold gelation technique, the emulsion gel was stored directly in the chiller without undergoing heating treatment. All PPEGs were chilled at 4°C ± 1°C for 20 h before further analysis. The samples in this study were labelled as follows: HO for hot gelation with olive oil, HS for hot gelation with sunflower oil, HC for hot gelation with canola oil, CO for cold gelation with olive oil, CS for cold gelation with sunflower oil, and CC for cold gelation with canola oil. BF is beef fat that was used as a control, as it was commonly used as fat in the meat product formulation. Each sample was produced in triplicate.

Analysis of PPEG properties

PPEG was evaluated for its proximate composition, pH, color, oil-binding capacity (OBC), WHC, particle size, texture profile (including hardness, springiness, cohesiveness, and chewiness), gel strength, fatty acid composition, microstructure, and melting profile. These properties were compared to those of BF.

Proximate composition

The AOAC standard methods were used to perform the proximate analysis (AOAC, 2005). The moisture content was determined using the gravimetric method by measuring the weight difference of the sample before and after drying at 105°C for 5 h. The samples (5 g each) were weighed and placed in crucibles before drying. The dried samples were placed in the desiccator until they reached constant weight. Ash contents were assessed by measuring the weight difference of the samples before and after incineration using a furnace (Carbolite GERO AAF 1100, United Kingdom) at 550°C for 2 h.

The micro-Kjeldahl method was used to quantify total protein content. Acidic digestion with sulfuric acid and protein determination were conducted in triplicate using a digestor followed by an automatic Kjeldahl protein-determining Kjeltec 8400 system (Foss, Hillerod, Denmark). The Soxhlet-Henkel method was used to analyze the fat content of the emulsion gel. The dried samples were refluxed continuously for 6 h with petroleum ether as the solvent, then evaporated using a rotary evaporator to purify the fat.

pH

The pH analysis was done by weighing 1 g of the sample and homogenizing it with distilled water (1:10 w/v). The sample was analyzed using a pH meter (Wahab *et al*., 2024).

Color

The samples were placed in a round plastic container and then analyzed using a colorimeter. The instrument was calibrated with white paper. The objective color CIE-LAB tristimulus values, L∗ (lightness), a∗ (red/green axis), and b∗ (yellow/blue axis) parameters were recorded (Huang *et al*., 2022).

Oil-binding capacity (OBC)

OBC was measured using a method suggested by Asyrul-Izhar *et al.* (2023a). Emulsion gels (15 g) were centrifuged at 9170 g for 15 min at 20°C to expose the emulsion gel to centrifugal force and separate from unbound oil. The tubes were inverted to drain any oil for 5 min. The %OBC was calculated as the ratio of the oil mass after drainage to the initial oil mass.

WHC

For measuring WHC, a method suggested by Li *et al.* (2022) with slight modification was used. Emulsion gels (5 g) were weighed as Wt and placed in a centrifuge tube (50 mL), then centrifuged for 15 min at room temperature

at 8000 rpm to expose the emulsion gel to centrifugal force and separate it from free water. The separated water was removed by filter paper, and the emulsion gel was weighed again. The mass of gels after centrifugation and water drainage was recorded as W1. The WHC was calculated using the following formula (%):

$$\frac{Wt - W1}{Wt} \times 100\%$$

Particle size

The particle size of the emulsion gel was analyzed using Malvern Zetasizer Nano ZS (Malvern Instruments Ltd., Malvern, UK) (Zeng *et al*., 2023). The samples were diluted at a 1:200 ratio with distilled water, and each sample was measured three times.

Texture profile and gel strength

The procedure for texture profile and gel strength analysis followed a method previously described by Asyrul-Izhar *et al*. (2023a) with slight modifications. The texture profile and gel strength of the emulsion gel were analyzed using a texture analyzer (TAXT2, Stable Microsystem System Ltd., Godalming, UK) aided by the software "Texture Expert." Emulsion gels were cut into cylinders measuring 2 cm in diameter and 2 cm in height. The texture profile of the emulsion gels was measured using a stainless steel 36 mm cylindrical probe, with the following settings: pretest speed, 1 mm/s; test speed, 3 mm/s; posttest speed, 10 mm/s; distance, 10 mm; and force, 5 g. The gel strength of emulsion gels was measured using a spherical probe of 0.25 mm p/5S (pretest speed, 1.0 mm/s; test speed, 1.1 mm/s; posttest speed, 20.00mm/s; force 10 g; and sample distance 15 mm).

Fatty acid composition

The fatty acid composition of emulsion gels and BF was examined by following the AOAC 20th edition, 996.06/GC-FID (Gök *et al*., 2011). The fatty acid methyl esters (FAMEs) were prepared and analyzed by gas chromatography with a flame ionization detector (FID). The major fatty acids were determined by comparing the retention times of the peaks with those of the standards used.

Differential Scanning Calorimetry (DSC)

A DSC (DSC822, Mettler Toledo, Columbus, OH, USA) was used to analyze the thermal properties of the samples in the temperature range of 0–100°C at a rate of 10°C/min (Asyrul-Izhar *et al*., 2023a). The samples were weighed at approximately 15–30 mg and placed in an aluminum pan, which was then hermetically sealed. An empty pan was used as a reference.

Microstructure

The microstructure of emulsion gels was recorded using scanning electron microscopy (SEM). The sample preparation method was as suggested by Asyrul-Izhar *et al*. (2023a) with slight modifications. The emulsion gels were freeze-dried for 72 h and then cut into approximately 3 × 3 × 1 mm pieces. The cut samples were put in the carbon tint. The images were obtained at 100× magnification, and the most representative micrographs were selected to determine microstructural properties.

Statistical analysis

All experiments were repeated three times. Data were expressed as the standard deviation (SD) ± mean. All the data obtained were analyzed using MiniTab Statistical Software 22. A one-way ANOVA test was conducted to evaluate the effect of oil type and gelation technique on the characteristics of PPEG. Post hoc Tukey was performed to identify significant differences ($p<0.05$) between all samples (PPEG and natural BF). Principal component analysis (PCA) was conducted to evaluate the relationship between oil type and gelation technique on the characteristics of PPEG.

Results and Discussion

Proximate composition and pH of PPEG

The proximate composition of PPEG is presented in Table 1. The type of oil and gelation technique did not significantly affect the moisture, ash, fat, and protein content of PPEG ($p>0.05$). However, PPEG has a significantly different composition compared to BF ($p<0.05$). The moisture content of PPEGs was considerably high (53.51–54.77%) due to the high water content in the formulation (55%) and was significantly higher than that of BF at 7.48% ($p<0.05$). The moisture content of PPEG is strongly influenced by the materials used and their percentages in the formulation (Asyrul-Izhar *et al*., 2023a; Pintado *et al*., 2015). PPEG had a significantly higher ash content (0.35–0.43%) than BF (0.09%) ($p<0.05$). Regardless of the protein extraction method used, commercial pea protein isolates also contain a certain amount of ash (ranging from 2.79 to 5.90%) (Schumacher *et al*., 2025), which contributes to the ash content in the PPEG.

Table 1. Proximate composition and pH values of beef fat and pea protein emulsion gel (PPEG) prepared from different oil types (olive oil, sunflower oil, and canola oil) using different gelation techniques (hot and cold gelation techniques).

Sample	Moisture (%)	Ash (%)	Fat (%)	Protein (%)	pH
HO	53.80 ± 1.66^{a}	0.43 ± 0.07^{a}	25.18 ± 2.02^{b}	26.89 ± 1.89^{a}	7.00 ± 0.00^{ab}
HS	54.24 ± 0.89^{a}	0.43 ± 0.09^{a}	24.46 ± 2.46^{b}	26.41 ± 0.72^{a}	6.97 ± 0.06^{ab}
HC	54.77 ± 0.87^{a}	0.35 ± 0.03^{a}	25.65 ± 0.88^{b}	27.57 ± 0.61^{a}	7.00 ± 0.00^{ab}
CO	53.98 ± 0.54^{a}	0.37 ± 0.07^{a}	29.06 ± 3.21^{b}	27.50 ± 0.93^{a}	6.97 ± 0.06^{ab}
CS	54.69 ± 0.26^{a}	0.36 ± 0.06^{a}	23.09 ± 3.06^{b}	28.21 ± 0.63^{a}	7.10 ± 0.00^{a}
CC	53.51 ± 1.66^{a}	0.36 ± 0.07^{a}	26.78 ± 3.65^{b}	28.89 ± 0.20^{a}	7.07 ± 0.06^{a}
BF	7.48 ± 0.95^{b}	0.09 ± 0.01^{b}	90.72 ± 1.91^{a}	1.67 ± 0.03^{b}	6.87 ± 0.15^{b}

HO: hot gelation-olive oil; HS: hot gelation-sunflower oil; HC: hot gelation-canola oil; CO: cold gelation-olive oil; CS: cold gelation-sunflower oil; CC: cold gelation-canola oil; BF: beef fat. ^{a,b}Different letters in the same column indicate a significant difference ($p<0.05$). Data were presented as the mean ± standard deviation.

The fat content of PPEGs ranges from 23.09 to 29.06%, which is initially achieved by using 30% olive oil, sunflower oil, or canola oil in the formulation. The fat content can be diminished during processing, especially for heat-treated PPEG (HO, HS, and HC) (Öztürk-Kerimoğlu *et al*., 2021). The protein content of the emulsion gels is approximately 26.41–28.89%, which is higher than that reported in previous study, due to the use of pea protein isolates and fish gelatine in the formulation (Asyrul-Izhar *et al*., 2023a).

The pH values of PPEGs were not influenced by the type of oil and the gelation technique (Table 1). Compared with all PPEGs, BF exhibited the lowest pH of 6.87 ($p<0.05$) due to its different composition. The pH value of PPEG was higher compared to emulsion gels from some previous studies (Asyrul-Izhar *et al*., 2023a; Öztürk-Kerimoğlu *et al*., 2021). This might be due to the different ingredients used. The pH value of PPEGs is in the neutral pH range, 6.97–7.10, which is far from the isoelectric point of pea protein (pH 4.0-5.0) (Guldiken *et al*., 2023; Yang *et al*., 2021). Therefore, it could prevent the occurrence of droplet flocculation and lead to a good emulsification capacity (Guldiken *et al*., 2023).

Color

Color plays a significant role in consumers' purchasing decisions. To resemble animal fat, a light and less yellow fat replacer is strongly recommended for use in meat product processing (Utama *et al*., 2018). The color of emulsion gels is given in Table 2, while the picture of emulsion gels is presented in Figure 1. The L* value indicates the lightness of the product. The L* value was not affected by the different oil types and gelation techniques ($p>0.05$). Based on the color measurement, the lightness of PPEG ranged from 86.47 (HO) to 88.58 (CC). In comparison to BF (73.15), all PPEGs showed significantly brighter color ($p<0.05$). However, PPEGs had a darker color compared to other emulsion gels from other studies (90.79–91.61) due to the use of modified corn starch (Asyrul-Izhar *et al*., 2023a). Similarly to lightness, the redness (a*) and yellowness (b*) values of PPEGs were not affected by the different oil types and gelation techniques ($p>0.05$). However, BF showed a significantly higher yellowness value than PPEGs ($p<0.05$), indicating a more intense yellow color.

OBC

OBC refers to the ability of the emulsion gel system to bind oil. The OBC of PPEG is presented in Table 3. The higher OBC value indicated that the emulsion gel is suitable for application in food matrices (Asyrul-Izhar *et al*., 2023a). All PPEGs exhibited excellent oil retention, with retention rates ranging from 99.77% to 99.95%. These values were higher than those reported for emulsion gels in a previous study (Asyrul-Izhar *et al*., 2023a; Serdaroğlu *et al*., 2017). The excellent oil retention in the PPEGs is attributed to the presence of nonpolar amino acid groups from pea protein, which can bind to the oil's hydrophobic groups (Asyrul-Izhar *et al*., 2023a). The presence of hydrophobic regions formed by heating also contributes to the formation of a strong gel network that can retain the oil in the system. It was also supported by the neutral pH of PPEGs, which enhances their emulsifying ability, particularly in terms of oil binding (Lu *et al*., 2019). However, BF exhibited the highest OBC (99.97%) compared with all PPEGs ($p<0.05$).

WHC

WHC refers to the ability of an emulsion gel to retain water. The WHC of PPEG is given in Table 3. The WHC of PPEGs was high (98.36–99.85%) and as strong as BF (99.81%). Regardless of the gelation technique and oil type used, all PPEGs exhibited a high WHC of more than 90%, confirming that the gel is formed tightly and possesses excellent hydrophilicity, allowing them to bind water molecules tightly (Lu *et al*., 2019).

Table 2. Color of beef fat and pea protein emulsion gel (PPEG) prepared from different oil types (olive oil, sunflower oil, and canola oil) using different gelation techniques (hot and cold gelation techniques).

Sample	L*	a*	b*
HO	86.47 ± 0.47^{a}	1.68 ± 0.14^{b}	13.07 ± 0.27^{b}
HS	87.28 ± 0.78^{a}	2.06 ± 0.36^{b}	11.58 ± 0.51^{b}
HC	87.93 ± 0.36^{a}	1.73 ± 0.08^{b}	11.98 ± 0.51^{b}
CO	87.66 ± 1.44^{a}	1.30 ± 0.34^{b}	12.64 ± 1.45^{b}
CS	88.04 ± 0.74^{a}	1.60 ± 0.28^{b}	11.10 ± 0.78^{b}
CC	88.58 ± 2.44^{a}	1.75 ± 0.67^{b}	11.93 ± 1.07^{b}
BF	73.15 ± 0.185^{b}	6.77 ± 0.10^{b}	20.07 ± 0.236^{a}

HO: hot gelation-olive oil; HS: hot gelation-sunflower oil; HC: hot gelation-canola oil; CO: cold gelation-olive oil; CS: cold gelation-sunflower oil; CC: cold gelation-canola oil; BF: beef fat. ^{a,c}Different letters in the same column indicate a significant difference ($p<0.05$). Data were presented as the mean ± standard deviation.

In addition, vegetable oils exhibit some polarity despite being largely nonpolar. Canola oil has total polar compounds at around 2.18–12.98%, depending on the processing (Farhoosh and Pazhouhanmehr, 2009). Thus, it was assumed that these polar compounds, which oil brings, would influence the hydrophilicity of the emulsion gels.

Particle size

The particle size of PPEG ranged from 4.33 to 7.38 μm (Table 3). Compared with the previous study, which reported particle sizes of 40–90 μm, the particle sizes of PPEGs in this study were much smaller (Li *et al*., 2024a). The small particle size of PPEG indicates the good stability of the system (Li *et al*., 2024a) that was obtained due to the long homogenization time. HO possessed the smallest particle size among all PPEGs at 4.339 ($p<0.05$), whereas PPEG prepared by the cold gelation technique shows a relatively greater size with CS ($p<0.05$) as PPEG with the biggest particle size. Heating at temperatures exceeding 55°C led to the disruption of both intramolecular and intermolecular disulfide bonds in the protein, resulting in protein unfolding, dissociation of protein aggregates, and a reduction in particle size (Qiao *et al*., 2023). PPEGs prepared with olive oil (HO and CO) are smaller than those prepared with sunflower or canola oil when the same gelation technique is used. As the unsaturation degree increased, the number of double bonds increased, and the particle size increased (Han *et al*., 2021).

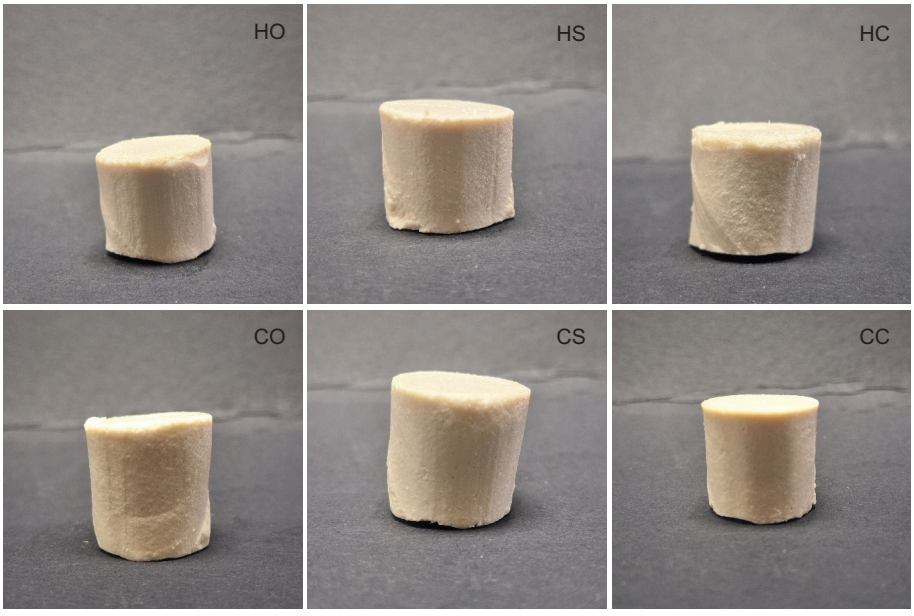

Figure 1. Pea protein emulsion gel (PPEG) prepared using the hot and cold gelation technique with various oil types (olive oil, sunflower oil, and canola oil). HO: hot gelation-olive oil; HS: hot gelation-sunflower oil; HC: hot gelation-canola oil; CO: cold gelation-olive oil; CS: cold gelation-sunflower oil; CC: cold gelation-canola oil.

Texture profile and gel strength

The texture profile and gel strength of PPEG are given in Table 4. The results of the analysis showed that the use of olive oil and the hot gelation technique (HO = 2882.03 g) can produce an emulsion gel with a hardness that is similar to that of natural BF (2910.47 g) ($p>0.05$). PPEGs prepared by the hot gelation technique exhibited a harder texture than cold-treated PPEGs. The use of olive oil increased the hardness of PPEG more than sunflower oil or canola oil. Among PPEGs prepared using the hot gelation technique, HO exhibited a significantly higher hardness (2882.03 g) compared to HC (2320.70 g) ($p<0.05$), but it was similar to HS (2512.93 g) ($p>0.05$). A similar trend was observed in cold-treated PPEGs. It could be explained by the oil's saturation level. SFAs are a group of fatty acids that consist of single-bond hydrocarbon chains and are solid at room temperature. Therefore, HO and CO, which contained higher SFA levels and were almost twice as high as HS, HC, CS, and CC, had higher hardness than the other PPEGs in the same gelation technique.

Springiness determines the ability of emulsion gels to return to their original shape after deformation during compression (Zhang *et al*., 2020). The springiness values of PPEGs range from 0.904 in CC to 0.966 in HS. PPEGs have a lower springiness than egg-SPI proteins stabilized emulsion gels in a previous study (Zhang *et al*., 2020). They reported a loss of the emulsion gel's ability to spring back due to the use of high oil content (more than 15%) as it was applied in this study (30%), thereby resulting in a lower springiness value (Zhang *et al*., 2020). However, PPEGs had significantly higher springiness compared to BF (0.385) ($p<0.05$). BF contains high SFA, which lowers springiness, as also shown by hydrogenated fat, which has a springiness of 0.40. This study found a negative correlation between SFA and springiness, and also a positive correlation between unsaturated fatty acids with springiness (Devi and Khatkar, 2017). HS showed the highest springiness among all PPEGs ($p<0.05$), while CS had higher springiness in cold-treated PPEGs. This finding aligns with a study that reported that dough made with sunflower oil has the highest springiness compared to dough made with butter, hydrogenated fat, palm oil, coconut oil, and groundnut oil (Devi and Khatkar, 2017).

Cohesiveness determines the strength of the internal bond, which shows the ability of food to hold and stick together when it is under mechanical action (Chandra and Shamasundar, 2015). HS has the highest cohesiveness among all PPEGs ($p<0.05$), with a value of 0.849, while cold-treated PPEGs showed a relatively lower

Table 3. Oil-binding capacity (OBC), water-holding capacity (WHC), and particle size of beef fat and pea protein emulsion gel (PPEG) prepared from different oil types (olive oil, sunflower oil, and canola oil) using different gelation techniques (hot and cold gelation techniques).

Sample	OBC (%)	WHC (%)	Particle size (μm)
HO	99.77 ± 0.11^{b}	98.53 ± 0.36^{a}	4.33 ± 1.002^{c}
HS	99.87 ± 0.07^{ab}	99.24 ± 0.57^{a}	5.71 ± 0.325^{b}
HC	99.93 ± 0.05^{ab}	99.64 ± 0.29^{a}	5.49 ± 0.222^{bc}
CO	99.91 ± 0.03^{ab}	98.36 ± 2.15^{a}	6.64 ± 0.422^{ab}
CS	99.95 ± 0.03^{ab}	99.86 ± 0.09^{a}	7.38 ± 0.297^{a}
CC	99.91 ± 0.09^{ab}	99.74 ± 0.14^{a}	6.80 ± 0.216^{ab}
BF	99.97 ± 0.00^{a}	99.81 ± 0.10^{a}	ND

HO: hot gelation-olive oil; HS: hot gelation-sunflower oil; HC: hot gelation-canola oil; CO: cold gelation-olive oil; CS: cold gelation-sunflower oil; CC: cold gelation-canola oil; BF: beef fat. ND: no data. ^{a,c}Different letters in the same column indicate a significant difference ($p<0.05$). Data were presented as the mean ± standard deviation.

Table 4. Texture profile and gel strength of beef fat and pea protein emulsion gel (PPEG) prepared from different oil types (olive oil, sunflower oil, and canola oil) using different gelation techniques (hot and cold gelation techniques).

Sample	Hardness (g)	Springiness	Cohesiveness	Chewiness	Gel strength (g)
HO	2882.03 ± 167.78^{a}	0.949 ± 0.01^{ab}	0.806 ± 0.006^{ab}	2108.70 ± 331.07^{abc}	161.42 ± 1.79^{c}
HS	2512.93 ± 153.51^{ab}	0.966 ± 0.015^{a}	0.849 ± 0.011^{a}	2323.04 ± 265.56^{a}	186.32 ± 5.34^{b}
HC	2320.70 ± 264.44^{b}	0.954 ± 0.006^{ab}	0.826 ± 0.031^{ab}	2159.15 ± 424.99^{ab}	163.27 ± 7.70^{c}
CO	2213.04 ± 144.53^{bc}	0.913 ± 0.018^{b}	0.821 ± 0.023^{ab}	1510.43 ± 171.55^{bcd}	111.50 ± 12.18^{d}
CS	2201.15 ± 100.19^{bc}	0.947 ± 0.009^{ab}	0.701 ± 0.033^{c}	1452.63 ± 161.17^{cd}	119.40 ± 4.05^{d}
CC	1845.36 ± 33.08^{c}	0.904 ± 0.016^{b}	0.774 ± 0.018^{b}	1293.69 ± 129.45^{d}	117.09 ± 4.29^{d}
BF	2910.47 ± 159.09^{a}	0.385 ± 0.03^{c}	0.261 ± 0.025^{d}	295.89 ± 66.43^{e}	276.60 ± 12.84^{a}

HO: hot gelation-olive oil; HS: hot gelation-sunflower oil; HC: hot gelation-canola oil; CO: cold gelation-olive oil; CS: cold gelation-sunflower oil; CC: cold gelation-canola oil; BF: beef fat. ^{a,d}Different letters in the same column indicate a significant difference ($p<0.05$). Data were presented as the mean ± standard deviation.

cohesiveness. Interestingly, BF exhibited significantly lower cohesiveness than all PPEGs ($p<0.05$). HS presented the highest chewiness value among all PPEGs ($p<0.05$). HO, HS, and HC emulsion gels that underwent heat treatment exhibited high chewiness, with values of 2108.70, 2323.04, and 2159.15, respectively. The chewiness value also indicated the elasticity of emulsion gels. The electrostatic attraction between pea protein and gelatine enhances the interface adsorption, which further increases the protein aggregation and the viscoelasticity of the emulsion gel (Zou *et al*., 2024). BF showed the lowest chewiness compared to all PPEGs ($p<0.05$).

Gel strength reflects the quality of the emulsion gel, including its ability to retain both oil and water. HS (186.32 g) had the highest gel strength compared with other PPEGs ($p<0.05$). Overall, the hot gelation technique yields PPEG with stronger gel networks ($p<0.05$). This aligns with the previous study on desalted duck egg white/gelatine gel, which compares the effects of hot and cold gelation on gel properties. Although heating enhances gel strength, it cannot exceed the strength of the BF network (276.60 g), which is almost twice that of HS. However, it shows the nearest gel strength to BF as the control.

When protein is denatured by heating, it loses its secondary and tertiary structures. This phenomenon increases the formation of new intermolecular and hydrophobic interactions. Thus, this results in an increase in the cross-linking of hydrophobic interactions, hydrogen bonds, and disulfides (Ren *et al*., 2022; Xu *et al*., 2023). The cross-linked gel network forms a harder, firmer, and stiffer gel network structure (Dai *et al*., 2021; Xu *et al*., 2021). In conclusion, heating can be used to improve the gel properties, specifically hardness, gel strength, and cohesiveness, of plant-protein emulsion gels (Hashemi *et al*., 2023; Ma and Chen, 2023). The cold gelation technique resulted in larger deformation, leading to a softer structure that facilitates stretching (Dai *et al*., 2021).

Fatty acid composition

The fatty acid profiles of BF and PPEGs from various oil types and gelation techniques are presented in Table 5. The fatty acid composition of PPEG and BF was in line with their fat content (Table 1). Vegetable oils, such as olive oil, sunflower oil, and canola oil, are rich sources of MUFA and PUFA, while BF consists mainly of SFA. As seen, BF contained 60112.21 mg/100 g of SFA, mainly stearic acid (C18:0) and palmitic acid (C16:0), which accounted for 30092.43 mg/100 g and 23526.21 mg/100 g, respectively. This finding aligns with a study that compared BF and an emulsion gel as fat replacers in the production of fermented sausages (Öztürk-Kerimoğlu *et al*., 2021). In contrast, PPEGs contained lower SFA ranging from 1627.9 to 3239.80 mg/100 g. Among the three vegetable oils used, olive oil is the one with the highest SFA (Akkaya, 2018; Barthet, 2016; Boskou *et al*., 2006), and this is also reflected in the HO and CO. Palmitic (C16) was the predominant SFA found in all PPEGs. It differed in the fatty acid profile of BF, which was primarily dominated by stearic acid (C18). Compared to all PPEGs, BF has more MUFA at 23387.19 mg/100 g and mainly consists of oleic acid (C18:1) at 21494.09 mg/100 g.

It was recorded that PUFA in all PPEGs is higher than in BF. PUFAs in PPEGs range from 1640.23 to 8006.94 mg/100 g, while in BF, they are only 1100.61 mg/100 g. HS and CS, which used sunflower oil, have a considerably higher content of PUFA, especially compared to HO and CO, which used olive oil (Akkaya, 2018) with linoleic acid as the main PUFA present. As shown in the analysis results, PPEGs prepared by the hot gelation technique (HO, HS, and HC) had lower MUFA and PUFA content than those prepared by the cold gelation technique (CO, CS, and CC). This is due to the presence of a high number of double bonds in the structure of vegetable oils, which makes them more chemically reactive than SFA (Öztürk-Kerimoğlu *et al*., 2021). By applying the cold gelation technique, MUFA and PUFA in the PPEGs could be preserved. BF contains linoleic (trans) acid (C 18:2n6t) at 286.99 mg/100 g, while all PPEGs do not have this trans fatty acid. It can be concluded that the use of vegetable oils in the emulsion gel formulation would reduce the presence of trans fatty acids.

DSC

The DSC curves of PPEG with various oil types and gelation techniques are shown in Figure 2. DSC is widely used to analyze the thermal transformation in meat (Li *et al*., 2024a). As shown, the melting curve of BF shows an endothermic peak between 40 and 60°C and reaches the peak at 49.92°C, which is similar to the previous study of beef body fat (Akta and Kaya, 2001). In contrast, PPEGs exhibited differences in the melting curves with BF. This is due to the significant difference in fatty acid composition between BF and PPEG.

The endothermic peak of emulsion gels had increased significantly, with the main peak at around 96–97°C compared to BF. This temperature point marks the protein's denaturation, exposing hydrophobic regions and sulfhydryl groups, and indicating the formation of a gel network. The use of gelatine as a hydrocolloid in all emulsion gels contributed to the high melting point of

Table 5. Fatty acid composition of beef fat and pea protein emulsion gel (PPEG) from different oil types (olive oil, sunflower oil, and canola oil) using different gelation techniques (hot and cold gelation techniques).

Fatty acid (mg/100 g)	Sample						
	BF	HO	HS	HC	CO	CS	CC
C 4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C 6	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C 8	0.00	0.00	1.48	0.00	0.00	2.77	0.00
C 10	31.45	0.00	0.00	1.23	0.00	0.00	2.27
C 11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C 12	81.03	3.57	8.32	4.41	3.63	3.75	5.52
C 13	12.50	0.00	0.00	0.00	0.00	0.00	0.00
C 14	2767.69	5.01	14.56	12.65	10.89	13.92	26.45
C 15	589.26	0.00	0.00	3.23	0.00	0.00	6.55
C 16	23526.21	2050.45	887.11	794.87	2418.83	973.64	1290.99
C 17	1634.32	13.96	5.52	22.14	16.23	5.12	40.20
C 18	30092.43	557.33	522.00	352.96	658.73	546.13	612.12
C 20	942.31	76.64	40.93	98.38	89.63	42.54	169.71
C 21	99.42	0.00	0.00	0.00	0.00	0.00	0.00
C 22	161.64	20.97	105.87	47.29	24.43	106.39	81.98
C 23	100.34	3.42	4.33	2.96	3.97	2.54	4.94
C 24	73.61	11.14	36.97	22.42	13.46	38.83	38.46
∑ SFA	**60112.21**	**2742.49**	**1627.9**	**1362.54**	**3239.80**	**1735.63**	**2279.19**
C14:1	398.82	0.00	0.00	0.00	0.00	0.00	0.00
C 15:1	288.92	0.00	0.00	0.00	0.00	0.00	0.00
C 16:1	757.24	175.08	17.52	35.89	208.67	20.33	57.26
C 17:1	218.50	19.83	0.00	16.40	23.50	0.00	28.78
C 18:1n9t	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C 18:1n9c	21494.09	11180.55	4739.25	9653.39	13047.47	4984.48	16771.36
C 20:1n9	196.87	41.82	23.72	169.50	57.19	24.11	306.38
C 22:1n9	0.00	0.00	0.00	0.00	0.00	0.00	8.13
C 24:1	32.75	0.00	7.13	24.29	1.91	10.03	41.97
∑ MUFA	**23387.19**	**11417.28**	**4787.62**	**9899.47**	**13338.74**	**5038.95**	**17213.88**
C 18:2n6t	286.99	0.00	0.00	0.00	0.00	0.00	0.00
C 18:2n6c	361.99	1535.11	7148.14	3212.67	1799.79	7368.50	5655.62
C 18:3n6	0.00	0.00	0.00	5.35	0.00	0.00	9.18
C 18:3n3	121.89	102.94	27.38	1310.74	119.00	30.94	2324.21
C 20:2	0.00	0.00	0.00	7.75	0.00	0.00	15.63
C 20:3n6	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C 20:3n3	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C 20:4n6	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C 20:5n3	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C 22:2C	0.00	0.00	8.71	0.00	0.00	0.00	0.00
C 22:6n3	329.74	2.18	1.05	1.45	2.67	25.95	2.30
∑ PUFA	**1100.61**	**1640.23**	**7185.28**	**4537.96**	**1921.46**	**7425.39**	**8006.94**

SFA: saturated fatty acid; MUFA: monounsaturated fatty acid; PUFA: polyunsaturated fatty acid. BF: beef fat; HO: hot gelation-olive oil; HS: hot gelation-sunflower oil; HC: hot gelation-canola oil; CO: cold gelation-olive oil; CS: cold gelation-sunflower oil; CC: cold gelation-canola oil.

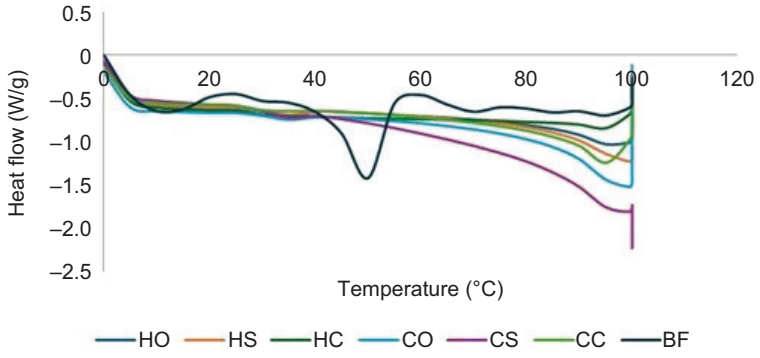

Figure 2. Differential scanning calorimetry (DSC) curve of emulsion gel prepared from different oil types (olive oil, sunflower oil, and canola oil) using different gelation techniques (hot and cold gelation techniques). HO: hot gelation-olive oil; HS: hot gelation-sunflower oil; HC: hot gelation-canola oil; CO: cold gelation-olive oil; CS: cold gelation-sunflower oil; CC: cold gelation-canola oil; BF: beef fat.

emulsion gels, as it was also reported from previous studies (Asyrul-Izhar *et al*., 2023a; Eyiler Yilmaz *et al*., 2017). The high water content of emulsion gels, which was around 53–55%, was also shifting the endothermic peak to a higher temperature (Wang *et al*., 2022). The application of the cold gelation technique resulted in a slight decrease in the melting temperature, indicating that cold-prepared emulsion gels would be easier to melt than hot-prepared emulsion gels, though the shift was insignificant. However, due to the complexity of emulsion gels in terms of the ingredients, it can be stated that emulsion gels are thermally stable up to 96°C, as also reported from the previous study (Asyrul-Izhar *et al*., 2023a). In addition, a single endothermic peak reflects the formation of thermodynamically more stable crystals (Kouzounis *et al*., 2017).

Microstructure

The microstructure of PPEGs and BF is shown in Figure 3. It was observed that the structure of BF is rougher and coarser compared with all PPEGs. The network structure is relatively tight, with no pores observed. This compact structure of BF led to better gel strength (Li *et al*., 2024a) and was confirmed by the measured gel strength value (Table 3).

PPEGs, prepared by the hot gelation technique, exhibited a spongier appearance with varying pore sizes. HS showed a relatively homogenous and compact structure compared to the other PPEGs. There were fewer spongy structures in HS compared to HO and HC. A similar phenomenon from a previous study was also reported, that emulsion gel with the use of sunflower oil has a compact structure of gel network (Li *et al*., 2024a). In addition, heating PPEG to 90°C induced the protein molecules to form a stronger crosslinking network that covered the oil droplets.

PPEGs prepared by the cold gelation technique exhibit a smoother matrix structure, as indicated by CO, CS, and CC. There are oil droplets distributed widely on the network as a result of the interaction between oil droplets and protein as a filler, forming a continuous structure, which led to a springier gel (Li *et al*., 2024a). However, the network formed does not fully cover oil droplets due to weaker oil–protein interactions. Therefore, some oil droplets were exposed to the environment, resulting in lower gel strength.

PCA

PCA was performed to determine the relationship between oil type and gelation technique on pH, color, WHC, OBC, texture profile, and gel strength of PPEG.

The eigenvalues 1 and 2 represented 79.2% of the variability. PC1 explains 63.5% of the variance, while PC2 explains 15.7% of the variance. In PC1 and PC2, all variables showed relatively low loadings ($r \approx 0.65$), indicating that the variance captured by these components is distributed across multiple attributes and does not contribute significantly to particular attributes.

Figure 4C shows that BF, located far to the left of the plot, was associated with high values of fat, redness, yellowness, hardness, gel strength, WHC, and OBC. In contrast, all PPEGs were located on the opposite side. Specifically, HC,

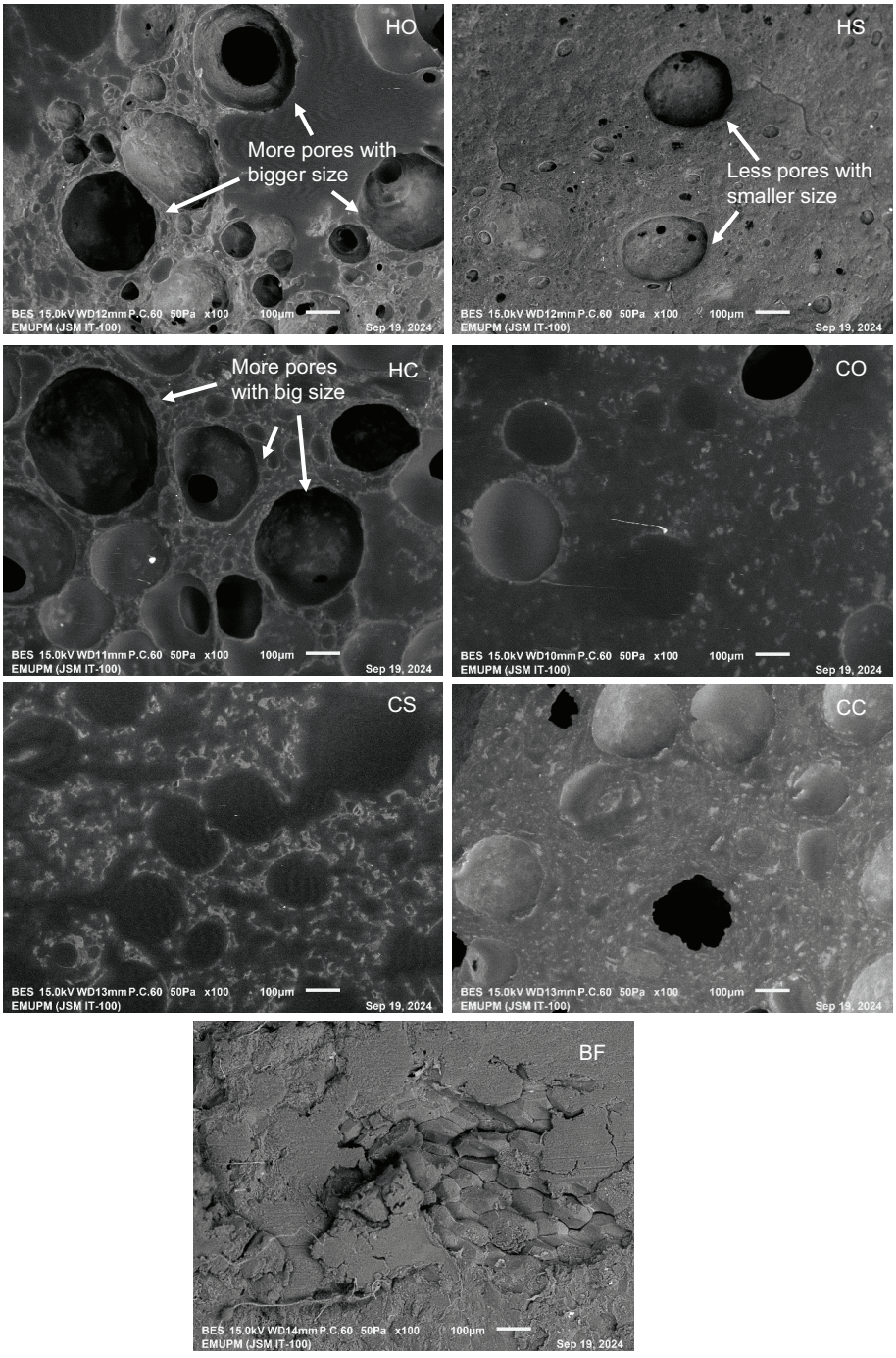

Figure 3. Microstructure of PPEG prepared using hot and cold gelation techniques with various oil types (olive oil, sunflower oil, and canola oil) and beef fat. HO: hot gelation-olive oil; HS: hot gelation-sunflower oil; HC: hot gelation-canola oil; CO: cold gelation-olive oil; CS: cold gelation-sunflower oil; CC: cold gelation-canola oil; BF: beef fat. Magnification 100×.

CO, CS, and CC were associated with higher protein, lightness, and pH values, indicating that cold-treated PPEGs have a brighter appearance than hot-treated PPEGs, whereas HO and HS were associated with high cohesiveness, chewiness, and springiness. Although the PPEGs did not exhibit much similarity to BF in terms of textural properties, HS showed the closest characteristics to BF, characterized by high cohesiveness, chewiness, and springiness.

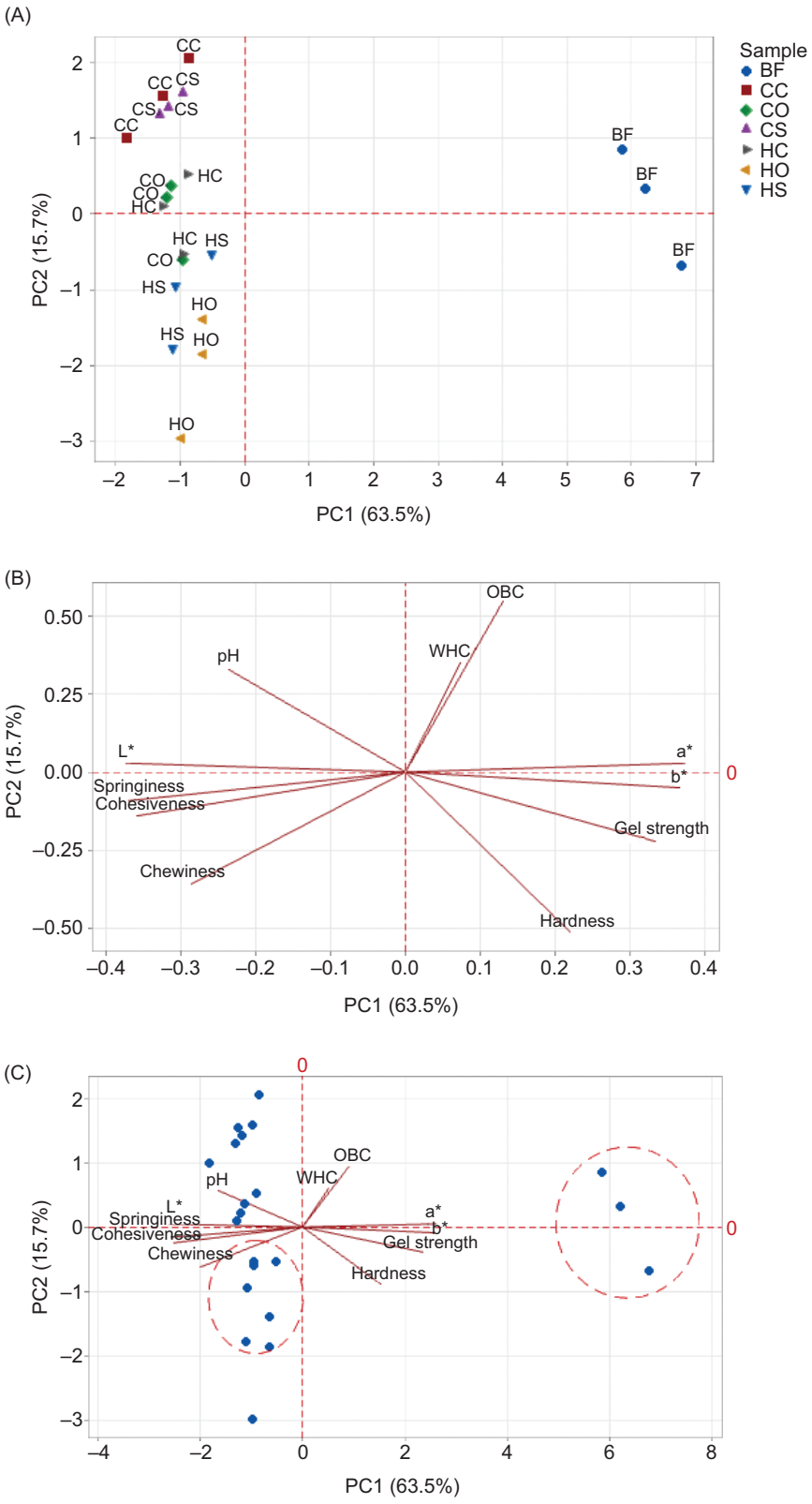

Figure 4 (A) Score plot, (B) loading plot, and (C) biplot of principal component analysis based on the effect of oil type and gelation technique on PPEG characteristics. HO: hot gelation-olive oil; HS: hot gelation-sunflower oil; HC: hot gelation-canola oil; CO: cold gelation-olive oil; CS: cold gelation-sunflower oil; CC: cold gelation-canola oil; BF: beef fat.

Conclusions

PPEGs were prepared from various vegetable oils (olive oil, sunflower oil, and canola oil) using two gelation techniques (hot and cold gelation). The application of the hot gelation technique yielded a stronger, harder gel by forming new intra- and interchain disulfide bonds, thereby strengthening the structure. Sunflower oil, which is mainly composed of PUFAs, resulted in better properties of emulsion gels. PPEG prepared from sunflower oil using the hot gelation technique showed the closest properties to those of natural BF, as characterized by high chewiness, springiness, and cohesiveness. Their microstructures were homogeneous, compact, and less spongy than those of other hot-treated emulsion gels. However, it is insufficient to replicate the properties of BF solely on the basis of gel strength and hardness. The development of PPEG resulted in a fat replacer with lower SFA content and higher MUFA and PUFA content, making it healthier than natural BF. Pea protein provides a plant-based and environmentally friendly structuring protein. Furthermore, peas are affordable and widely available in the market. The technologies applied, such as the heat-applied gelation process and emulsification steps, are compatible with standard industrial equipment, making this system highly feasible for mass production.

Data Availability

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

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The author didn't use Artificial Intelligence for language editing, clarity improvement, or any other function for paper improvement.

Authors' Contributions

Leonie Margaretha Widya Pangestika was in charge of conceptualization, methodology, formal analysis, visualization, and writing—original draft. Fatema Hossain Brishti was responsible for investigation, supervision, validation, and writing—review and editing. Ezzat Mohamad Azman looked into methodology, software, supervision, visualization, and writing—review and editing. Nazamid Saari was responsible for investigation, supervision, and writing—review and editing. Lihui Du did writing—review and editing. Daodong Pan was concerned with writing—review and editing. Mohammad Rashedi Ismail-Fitry was involved in funding acquisition, investigation, project administration, resources, supervision, validation, and writing—review and editing.

Conflict of Interests

The authors declare no competing interests.

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References

Akkaya, M.R. 2018. Fatty acid compositions of sunflowers (*Helianthus annuus* L.) grown in east Mediterranean region. La. Riv. Ital. Delle Sostanze Grasse. pp. 249–247.Akta, N. and Kaya, M. 2001. Detection of beef body fat and margarine in butterfat by differential scanning calorimetry. J. of Thermal Anal. Calorim. 66: 795–801.

AOAC (2005). Official Methods of Analysis, 18th edn. Washington D.C.: Association of Official Analytical Chemists.

Asyrul-Izhar, A.B., Bakar, J., Sazili, A.Q., Goh, Y.M., Ismail-Fitry, M.R. 2023a. Emulsion gels formed by electrostatic interaction of gelatine and modified corn starch via pH adjustments: Potential fat replacers in meat products. Gels 9: 1–8. https://doi.org/10.3390/gels9010050

Asyrul-Izhar, A.B., Bakar, J., Sazili, A.Q., Meng, G.Y., Ismail-Fitry, M.R. 2023b. Incorporation of different physical forms of fat replacers in the production of low-fat/reduced-fat meat products: Which is more practical? Food Rev. Int. 39: 6387–6419. https://doi.org/10.1080/87559129.2022.2108439

Barthet, V.J. 2016. Canola: Overview, in: Reference Module in Food Sciences. pp. 1–5.

Boskou, D., Blekas, G., Tsimidou, M. 2006. Olive Oil Composition, in: Olive Oil. pp. 41–72.

Chandra, M. V, Shamasundar, B.A. 2015. Texture Profile Analysis and Functional Properties of Gelatin from the Skin of Three Species of Fresh Water Fish Texture Profile Analysis and Functional Properties of Gelatin from the Skin of Three Species of Fresh Water Fish. Int. J. Food Prop. 18: 572–584. https://doi.org/10.1080/10942912.2013.845787

Chao, D. and Aluko, R.E. 2018. Modification of the structural, emulsifying, and foaming properties of an isolated pea protein by thermal pretreatment. CyTA-J. Food. 16: 357–366. https://doi.org/10.1080/19476337.2017.1406536

Dai, Y., Zhao, J., Gao, J., Deng, Q., Wan, C., Li, B., Zhou, B. 2021. Heat- and cold-induced gels of desalted duck egg white/gelatin mixed system: Study on rheological and gel properties. Food Hydrocoll. 121: 1–11. https://doi.org/10.1016/j.foodhyd.2021.107003

Devi, A. and Khatkar, B. 2017. Effects of fatty acids composition and microstructure properties of fats and oils on textural properties of dough and cookie quality. J. Food Sci. Technol. 55: 321–330. https://doi.org/10.1007/s13197-017-2942-8

Eyiler Yilmaz, E., Vural, H., Jafarzadeh Yadigari, R. 2017. Thermal, microscopic, and quality properties of low-fat frankfurters and emulsions produced by addition of different hydrocolloids. Int. J. Food Prop. 20: 1987–2002. https://doi.org/10.1080/10942912.2016.1230743

Farhoosh, R. and Pazhouhanmehr, S. 2009. Relative contribution of compositional parameters to the primary and secondary oxidation of canola oil. Food Chem. 114: 1002–1006. https://doi.org/10.1016/j.foodchem.2008.10.054

Gök, V., Akkaya, L., Obuz, E., Bulut, S. 2011. Effect of ground poppy seed as a fat replacer on meat burgers. Meat Sci. 89: 400–404. https://doi.org/10.1016/j.meatsci.2011.04.032

Guldiken, B., Saffon, M., Nickerson, M.T., Ghosh, S. 2023. Improving physical stability of pea protein-based emulsions near the isoelectric point via polysaccharide complexation. Food Hydrocoll. 145: 109029. https://doi.org/10.1016/j.foodhyd.2023.109029

Han, Z., Xu, S., Sun, J., Yue, X., Wu, Z., Shao, J.H. 2021. Effects of fatty acid saturation degree on salt-soluble pork protein conformation and interfacial adsorption characteristics at the oil/water interface. Food Hydrocoll. 113. https://doi.org/10.1016/j.foodhyd.2020.106472

Hashemi, B., Assadpour, E., Zhang, F., Mahdi, S. 2023. A comparative study of the impacts of preparation techniques on the rheological and textural characteristics of emulsion gels (emulgels). Adv. Colloid. Interface Sci. 322: 103051. https://doi.org/10.1016/j.cis.2023.103051

Huang, L., Ren, Y., Li, H., Zhang, Q., Wang, Y., Cao, J., Liu, X. 2022. Create fat substitute from soybean protein isolate/konjac glucomannan: The impact of the protein and polysaccharide concentrations formulations. Front. Nutr. 9: 1–13. https://doi.org/10.3389/fnut.2022.843832

Kouzounis, D., Lazaridou, A., Katsanidis, E. 2017. Partial replacement of animal fat by oleogels structured with monoglycerides and phytosterols in frankfurter sausages. Meat Sci. 130: 38–46.

Li, K., Wang, L.M., Cui, B.B., Chen, B., Zhao, D.B., Bai, Y.H. 2024a. Effect of vegetable oils on the thermal gel properties of PSE-like chicken breast meat protein isolate-based emulsion gels. Food Chem. 447. https://doi.org/10.1016/j.foodchem.2024.138904

Li, S., Chen, G., Shi, X., Ma, C., Liu, F. 2022. Comparative study of heat-and enzyme-induced emulsion gels formed by gelatin and whey protein isolate: Physical properties and formation mechanism. Gels. 8. https://doi.org/10.3390/gels8040212

Li, X., Chen, X., Cheng, H. 2024b. Impact of κ-carrageenan on the cold-set pea protein isolate emulsion-filled gels: Mechanical property, microstructure, and in vitro digestive behavior. Foods. 13. https://doi.org/10.3390/foods13030483

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 Hydrocoll. 102. https://doi.org/10.1016/j.foodhyd.2019.105569

Lin, D., Kelly, A.L., Miao, S. 2020. Preparation, structure-property relationships and applications of different emulsion gels: Bulk emulsion gels, emulsion gel particles, and fluid emulsion gels. Trends Food Sci. Technol. 102: 123–137. https://doi.org/10.1016/j.tifs.2020.05.024

Lu, Z.X., He, J.F., Zhang, Y.C., Bing, D.J. 2019. Composition, physicochemical properties of pea protein and its application in functional foods. Crit. Rev. Food Sci. Nutr. 8398. https://doi.org/10.1080/10408398.2019.1651248

Ma, Y. and Chen, F. 2023. Plant protein heat-induced gels: Formation mechanisms and regulatory strategies. Coatings. 13: 1–19.

Nourmohammadi, N., Austin, L., Chen, D. 2023. Protein-based fat replacers: A focus on fabrication methods and fat-mimic mechanisms. Foods. 12: 1–17. https://doi.org/10.3390/foods12050957

Öztürk-Kerimoğlu, B., Kavuşan, H.S., Benzer Gürel, D., Çağındı, Ö., Serdaroğlu, M., 2021. Cold-set or hot-set emulsion gels consisted of a healthy oil blend to replace beef fat in heat-treated fermented sausages. Meat Sci. 176. https://doi.org/10.1016/j.meatsci.2021.108461

Pintado, T. and Cofrades, S. 2020. Quality characteristics of healthy dry fermented sausages formulated with a mixture of olive and chia oil structured in oleogel or emulsion gel as animal fat replacer. Foods. 9. https://doi.org/10.3390/foods9060830

Pintado, T., Ruiz-Capillas, C., Jiménez-Colmenero, F., Carmona, P., Herrero, A.M. 2015. Oil-in-water emulsion gels stabilized with chia (Salvia hispanica L.) and cold gelling agents: Technological and infrared spectroscopic characterization. Food Chem. 185: 470–478. https://doi.org/10.1016/j.foodchem.2015.04.024

Qiao, X., Liu, F., Kong, Z., Yang, Z., Dai, L., Wang, Y., Sun, Q., McClements, D.J., Xu, X. 2023. Pickering emulsion gel stabilized by pea protein nanoparticle induced by heat-assisted pH-shifting for curcumin delivery. J. Food Eng. 350. https://doi.org/10.1016/j.jfoodeng.2023.111504

Ren, Y., Huang, L., Zhang, Y., Li, H., Zhao, D., Cao, J., Liu, X. 2022. Application of emulsion gels as fat substitutes in meat products. Foods. 11: 75–93. https://doi.org/10.1007/978-1-4419-9374-8_8

Schumacher, T., Steinmacher, T., Koster, E., Wagemans, A., Weiss, J., Gibis, M. 2025. Physico-chemical characterization of ten commercial pea protein isolates. Food Hydrocolloids. 162. https://doi.org/10.1016/j.foodhyd.2024.110996

Seddiek, A.S., Chen, K., Zhou, F., Esther, M.M., Elbarbary, A., Golshany, H., Uriho, A., Liang, L. 2025. Whey protein hydrogels and emulsion gels with anthocyanins and/or goji oil: Formation, characterization and in vitro digestion behavior. Antioxidants. 14. https://doi.org/10.3390/antiox14010060

Serdaroğlu, M., Nacak, B., Karabiyikoğlu, M. 2017. Effects of beef fat replacement with gelled emulsion prepared with olive oil on quality parameters of chicken patties. Korean J. Food Sci. Anim. Resour. 37: 376–384. https://doi.org/10.5851/kosfa.2017.37.3.376

Totaro, M.P., Summo, C., Miccolis, M., Faccia, M., Angelis, D. De, Natrella, G., Caponio, F. 2025. Optimization of the rheological properties of fat replacers based on inulin at different degrees of polymerization and their application in beef burgers. Foods. 14.

Utama, D.T., Jeong, H., Kim, J., Lee, S.K. 2018. Formula optimization of a perilla-canola Oil (O/W) emulsion and its potential application as an animal fat replacer in meat emulsion. Korean J. Food Sci. Anim. Resour. 38: 580–593.

Wahab, N.Q.A., Pangestika, L.M.W., Ismail-Fitry, M.R. 2024. Partial incorporation of black jelly mushroom (Auricularia polytricha) as a plant-based ingredient in the production of hybrid patties using meat from different species. Int. J. Food Sci. Technol. 1–10. https://doi.org/10.1111/ijfs.17516

Wang, L., Wen, Y., Su, C., Gao, Y., Li, Q., Du, S., Yu, X. 2022. Effect of water content on the physical properties and structure of walnut oleogels. RSC Adv. 12: 8987–8995. https://doi.org/10.1039/d2ra00920j

Xu, Q., Qi, B., Han, L., Wang, D., Zhang, S., Jiang, L., Xie, F., Li, Y. 2021. Study on the gel properties, interactions, and pH stability of pea protein isolate emulsion gels as influenced by inulin. LWT– Food Sci. Technol. 137.

Xu, Y., Sun, L., Zhuang, Y., Gu, Y., Cheng, G., Fan, X., Ding, Y., Liu, H. 2023. Protein-stabilized emulsion gels with improved emulsifying and gelling properties for the delivery of bioactive ingredients: A review. Foods. 12. https://doi.org/10.3390/foods12142703

Yang, J., Zamani, S., Liang, L., Chen, L. 2021. Extraction methods significantly impact pea protein composition, structure and gelling properties. Food Hydrocoll. 117: 106678. https://doi.org/10.1016/j.foodhyd.2021.106678

Yashini, M., Sunil, C.K., Sahana, S., Hemanth, S.D., Chidanand, D.V. 2019. Protein-based fat replacers—A review of recent advances protein-based fat replacers. Food Rev. Int. 9129: 1–27. https://doi.org/10.1080/87559129.2019.1701007

Zeng, L., Lee, J., Jo, Y.J., Choi, M.J. 2023. Effects of micro- and nano-sized emulsions on physicochemical properties of emulsion–gelatin composite gels. Food Hydrocoll. 139. https://doi.org/10.1016/j.foodhyd.2023.108537

Zhang, M., Yang, Y., Acevedo, N.C. 2020. Effect of oil content and composition on the gelling properties of egg-SPI proteins stabilized emulsion gels. Food Biophys. 15: 473–481. https://doi.org/10.1007/s11483-020-09646-8

Zou, Q., Zheng, Y., Liu, Y., Luo, L., Chen, Y., Ran, G., Liu, D. 2024. Preparation of cassia bean gum/soy protein isolate composite matrix emulsion gel and its effect on the stability of meat sausage. Gels. 10: 1–17.

Zou, Y., Thijssen, P.P., Yang, X., Scholten, E. 2019. The effect of oil type and solvent quality on the rheological behavior of zein stabilized oil-in-glycerol emulsion gels. Food Hydrocoll. 91: 57–65. https://doi.org/10.1016/j.foodhyd.2019.01.016