Current Research in Food Science 5 (2022) 1084–1090

Contents lists available at ScienceDirect

Current Research in Food Science

journal homepage: www.sciencedirect.com/journal/current-research-in-food-science

Research Paper

Combined effects of high-pressure processing and pre-emulsified sesame oil incorporation on physical, chemical, and functional properties of reduced-fat pork batters

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ARTICLE INFO

Handling editor: Xing Chen

Keywords:
Emulsion stability
Pre-emulsified sesame oil
Relaxation time
Water mobility
β-sheet

ABSTRACT

In this study, the changes in emulsion stability, colour, textural properties, and protein secondary structure of reduced-fat pork batters (50% pork back-fat and 50% pre-emulsified sesame oil) treated under different pressures (0.1, 200 and 400 MPa) were investigated. The emulsion stability, cooking yield, L^* value, texture properties, initial relaxation times of T_{2b}, T_{21}, and T_{22}, and peak ratios of P_{21} in the samples treated under 200 and 400 MPa significantly increased ($p < 0.05$) compared with those at 0.1 MPa, but the a^* and b^* values, and the peak ratio of P_{22} significantly decreased ($p < 0.05$). The sample treated at 200 MPa exhibited the best emulsion stability, textural properties, water-holding capacity and sensory scores among the samples. High-pressure processing induced structural changes from α-helical to β-sheet, β-turn, and random coil structures, enhancing protein-water incorporation and lowering water mobility. High-pressure processing and pre-emulsified sesame oil improved the techno-functional properties and emulsion stability of reduced-fat pork batters.

1. Introduction

The demand for emulsified meat products has increased rapidly in recent years, and certain parts of the globe have enjoyed consumer acceptance (Kang et al., 2014; Devarajan et al., 2015). Traditional emulsified meat products contain a high fat content (>25%) to ensure appealing texture and flavour (Kang et al., 2017; Jeon et al., 2015). However, excessive intake of animal fat can increase the risk of obesity, hypertension, cardiovascular diseases, and other associated diseases (Tan and Teng, 2021; Ghanemi et al., 2021; Jeon et al., 2015). Some approaches, such as replacement with water, lean meat, food hydrocolloids, non-meat proteins, plant oils, and pre-emulsion oils, have been reported to reduce animal fat content (Lu et al., 2021; Chen et al., 2020; Kang et al., 2017). Among the various methods for replacing animal fat, pre-emulsion oil is the best (Kang et al., 2017). Pre-emulsion technology is used to stabilise non-meat fat used for incorporation into the meat matrix and has been studied to replace animal fat using pre-emulsified oils in different emulsified meat products (Ge et al., 2021; Serdaroglu et al., 2020; Salcedo-Sandoval et al., 2013; Jimenez-Colmenero, 2007). A previous study reported that pork batters with pre-emulsified oil resulted in lower fat and energy content and improved texture of the pork batter (Kang et al., 2017). However, the application scope of this method is limited.

Sesame oil is widely used in the food industry because it has a characteristic flavour and is a prevalent source of healthy oils in many Asian and European countries (Sowmya et al., 2009; Kang et al., 2017). It has a high polyunsaturated fat content, abundant lignan compounds, and α-tocopherol. The intake of sesame oil is associated with a decreased risk of hypertension and cardiovascular disease (Devarajan et al., 2015; Wu et al., 2009). Moreover, sesamolin, sesamol and α-tocopherol have antioxidant activities and are very stable against deterioration by oxidation; therefore, sesame oil is an ideal animal fat substitute for reduced-fat meat products (Wan et al., 2015; Shao et al., 2020). Previous studies have reported that the use of pre-emulsified sesame oil to replace animal fat, enabled the lowering of fat and energy content, improving the texture of the reduced-fat meat batter (Zhuang et al., 2016; Kang et al., 2017). High-pressure processing is a non-thermal technology that has been successfully applied to several meat products, and its applications in the food industry have increased in recent years (Roobab et al., 2021, 2022). It modifies muscle proteins based on the decline in

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https://doi.org/10.1016/j.crfs.2022.06.009
Received 25 January 2022; Received in revised form 24 June 2022; Accepted 24 June 2022
Available online 6 July 2022

protein volume and involves changes in protein conformation, surface hydrophobicity, and total sulfhydryl groups (Pinton et al., 2021; Li et al., 2020b). Thus, appropriate high-pressure processing conditions can improve the water- and fat-holding capacities, textural properties, and processing characteristics of meat products (Velazquezet al., 2021; Yang et al., 2021). Some studies have reported that moderate pressure (≤200 MPa) improves the water-holding capacity and gel properties of myofibrillar proteins, whereas excess pressure (>400 MPa) disruptes the gel network and lowers the textural properties (Kang et al., 2021; Grossi et al., 2016). Therefore, the objectives of the present study were to determine the changes in the water-holding capacity and gel properties of reduced-fat pork batter produced by high-pressure processing (0.1, 200, and 400 MPa) and pre-emulsified sesame oil and thereby to establish a strategy to produce reduced-fat pork batter with desirable quality.

2. Materials and methods

2.1. Preparation of pre-emulsified sesame oil

Cold-pressed sesame oil (Saturated fatty acids, 15%; Oleic acid, 38%; Linoleic acid, 46.2%; Linolenic acid, 0.4%) was provided by Kerry Grain and Oil (Shenzhen) co., Ltd, (China). Soy protein isolate (91.56 ± 0.43% protein) was purchased from Shandong Soy Foods co., Ltd, (China). The pre-emulsified sesame oil was prepared according to the method of Kang et al. (2017) with minor modifications. Briefly, 320 g of water at 60–65 °C and 20 g of soy protein isolate were mixed uniformly using a homogenizer (T25, IKA, Germany) at 5000 rpm for 2 min. Once complete, the mixture was cooled to 5 °C and homogenized at 1500 rpm for 30 s in a bowl cutter (Stephan UMC-5C, Germany). Then the sesame oil was added slowly while homogenization was continued for 3 min and poured into double plastic (nylon/PE) bags. Finally, the mixture was stored at 2 ± 2 °C until use.

2.2. Preparation of reduced-fat pork batter using high-pressure

Chilled pork leg meat (protein, 20.31 ± 0.62%; fat, 6.95 ± 0.41%; moisture, 71.27 ± 0.72%) was purchased from Xinxiang Gaojin Food co., LTD, (Xinxiang, China). All visible connective tissue and fat were trimmed from the meat. The lean meat was mixed and passed through a grinder (MM-12, Guangdong, China) fitted with a plate having 6 mm diameter holes. Then, the meat was vacuum packaged (1.0 kg each) using double plastic (nylon/PE) bags and store at −20 °C until use within 2 weeks. The fresh pork back-fat (protein, 1.58 ± 0.11%; fat, 90.35 ± 0.70%; moisture, 8.16 ± 0.27%) was purchased from Xinxiang Gaojin Food co., LTD, (Xinxiang, China) and grounded twice using a plate having 6 mm diameter holes (final temperature less than 6 °C). Analytically pure sodium tripolyphosphate and sodium chloride were purchased from JSC Chemical Technology Co., Ltd., China.

The pork batter was prepared with pork meat 1000 g, pork back-fat 125 g, pre-emulsified sesame oil 125 g, sodium tripolyphosphate 4 g, sodium chloride 13.5 g, and ice water 100 g. The ground meat was thawed at 4 °C approximately 12 h prior to use. The pork batter was processed by a beating machine (MC-6, Shandong, China) according to the method of Kang et al. (2014). Briefly, the thawed meat, sodium tripolyphosphate, sodium chloride and ice water were beaten at 200 rpm for 10 min, following, added the back-fat and pre-emulsified sesame oil, and beaten at 200 rpm for 5 min (final temperature less than 10 °C). After that, the pork batter was vacuum packaged using a plastic bag (nylon/PE) and treated by a high-pressure vessel (S-FL-850-9-W/FPG5620YHL, Stansted Fluid Power Ltd., Stansted, UK). The pure water was used as a transmission medium, and the temperature was controlled through a thermo-stating circulator bath. The compression rate was approximately 4 MPa/s, and the decompression step was reached immediately (<3 s). The pork batter was treated under 200 and 400 MPa (10 ± 2 °C) for 10 min, respectively. The untreated sample (0.1 MPa) was set as control. After that, the pork batter was cooked in an 80 °C water bath for 20 min (to reach a core temperature of 72 °C) and thereafter cooled to room temperature using the running water.

2.3. Emulsion stability

Emulsion stability was determined using the procedure proposed by Fernándz-Martín, López-lópez, Cofrades and Colmenero (2009). Approximately 25 g of raw batter was put in a 50 mL centrifuge tube and centrifuged at 500×*g* at 4 °C for 15 min (Model 225, Fischer Scientific, Pittsburgh, Pa., U.S.A.) to eliminate any air bubbles. Each sample was cooked in an 80 °C water bath for 20 min, then removed from the water bath, uncapped and the left inverted for 50 min on paper tissues to release any exudate at 20 °C. The total fluid released (TR) was expressed as % of the initial sample weight; the smaller the TR, the better the emulsion stability. The water released component (WR, % of the initial sample weight) was determined from the dry matter content of the TR after heating at 105 °C for 16 h. The fat released component (FR, % of the initial sample weight) ignored any minor protein or salt components and was taken as the difference between TR and WR. Four technical replicates per sample were measured.

2.4. Cooking yield

After overnight storage at 4 °C, the lost water and fat from the cooked batter were wiped away. The cooked batter was weighed. Then, the cooking yield was calculated according to the formula:

$$\text{Cooking yield } (\%) = \text{Weight of cooked batter/Weight of raw batter} \times 100$$

Five technical replicates per sample were measured.

2.5. Colour measurement

The core colour of each cooked batter was measured using a Minolta chromameter (CR-400, Minolta Camera Co., Japan), calibrated with a white plate (L*, 98.06; a*, −0.12; b*, 1.33). Six fresh slices of cooked batter per sample were evaluated within 60 s.

2.6. Texture profile analysis (TPA)

After 4 °C storage overnight, the cooked batters were left at 20 °C for 2 h. Then, the batters were cut into a cylinder (diameter, 25 mm; height, 20 mm). A texture analyzer with a P/36 R probe (TA-XT.plus, Stable Microsystem Ltd., Surrey, UK) was used to measure the TPA of the batters. The setting parameters were as follows: pre-test speed 5.0 mm/s; test speed 2.0 mm/s; post-test speed 5.0 mm/s; strain 50% and trigger force 5 g. The values of hardness (N), springiness, adhesiveness and chewiness (N.mm) were obtained. Five technical replicates per sample were measured.

2.7. Low-field nuclear magnetic resonance (NMR) measurement

After storage at 4 °C overnight, the cooked batters were left at 32 °C for 2 h. Then, approximately 2 g of the batter was put in a 15 mm glass tube and inserted into the NMR probe of an NMR analyzer (PQ001, Niumag Electric Corporation, Shanghai, China). The analyzer was operated at the resonance frequency of 22.6 MHz at 32 °C. Spin-spin relaxation time (T_2) was measured making a τ-value of 350 μs. Data from 10,000 echoes were acquired as 32 scan repetitions. The repetition time between subsequent scans was 8000 ms. Post processing of NMR T_2 data distributed exponential fitting of Carr-Purcell-Meiboom-Gill decay curves was performed by Multi-Exp Inv Analysis software (Niumag Electric Corp., Shanghai, China). Four technical replicates per sample were measured.

2.8. Raman spectroscopy

Raman experiments were determined using a modified procedure of Zhu et al. (2018). The spectra were obtained in the range of 400 cm^{-1} to 3600 cm^{-1}. Spectra were smoothed, baselines corrected and normalized against the phenylalanine band at 1003 cm^{-1} (Herrero, 2008) using Labspec version 3.01c (Horiba/Jobin. Yvon, Long-jumeau, France). The secondary structures of the cooked batter proteins were determined as percentages of α-helice, β-sheet, β-turn, and random coil or unordered conformations (Alix et al., 1988). With this aim, the water spectrum was subtracted from the spectra by following the same criteria as that described previously (Herrero et al., 2008).

2.9. Sensory evaluation

The twelve members of the sensory panel were selected and trained according to Meilgaard et al. (1991). The cooked batters were left at 20 °C for 2 h after 4 °C storage overnight and assessed by the panel for assessment of appearance, springiness, hardness, juiciness, and overall acceptability using a nine-point hedonic scale (9, extremely desirable; 1, extremely undesirable).

2.10. Statistical analysis

The whole experiment was repeated four times at different times (n = 4) upon various high pressure (0.1, 200 and 400 MPa) treatment. The data were analyzed using the one-way ANOVA program. The difference between means was considered significant at $p < 0.05$. Significant differences between means were identified by the Least Significant Difference (LSD) procedure using the statistical software package SPSS v.18.0 for Windows (SPSS Inc., Chicago, USA). Duncan's test for multiple mean comparisons and Pearson product moment correlation (R) were performed to determine the relationships between data obtained for the percentage of the secondary structure of proteins and texture results.

3. Results and discussion

3.1. Emulsion stability

The effect of emulsion stability (TR, WR and FR) on reduced-fat pork batters treated under different pressures is shown in Table 1. The TR, WR, and FR of the samples treated by high pressure significantly decreased ($p < 0.05$) compared to those under 0.1 MPa. Furthermore, the TR, WR, and FR of the sample treated under 400 MPa were higher than those treated under 200 MPa. This may be due to the fact that the muscle proteins and soy protein isolate were unfolded when treated by high pressure, and their emulsion capacity can be thus improved (Tang and Ma, 2009). For example, the emulsifying activity of soy protein isolate significantly increased after treatment at 200 MPa, leading to enhanced emulsified stability. Wang et al. (2007) reported that more hydrophobic and sulfhydryl groups being exposed after treatment under 200 MPa before heating, the gel properties of myosin are significantly increased. A similar result was reported by Li, Kang, Sukmanov and Ma (2021a), who found that high-pressure (200 MPa, 10 min) and soy protein isolate combination could increase the total and reactive sulfhydryl groups and surface hydrophobicity of the pork myofibrillar protein system, causing an increase in its water-holding capacity. Thus, the sample treated at 200 MPa exhibited the highest emulsion stability.

Table 1
Emulsion stability of reduced-fat pork batters treated by different pressures.

Sample	TR (%)	WR (%)	FR (%)
0.1 MPa	8.63 ± 0.40^{a}	7.05 ± 0.26^{a}	1.61 ± 0.18^{a}
200 MPa	5.51 ± 0.36^{c}	4.41 ± 0.19^{c}	1.08 ± 0.14^{b}
400 MPa	6.25 ± 0.44^{b}	5.17 ± 0.31^{b}	1.13 ± 0.20^{b}

TR: total fluid release; WR: water-released component; FR: fat-released component.
Each value represents the mean ± standard deviation, n = 4.
[a-c] Different parameter superscripts in the same column indicate significant differences ($p < 0.05$).

3.2. Cooking yield

The cooking yield reflects the ability of emulsified meat products to hold water and fat and is an essential product quality factor. The cooking yield of reduced-fat pork batters treated at different pressures is shown in Fig. 1. The cooking yield of the samples treated by high pressure significantly increased ($p < 0.05$) compared with that at 0.1 MPa, with the cooking outcome of the sample treated under 400 MPa being lower than that under 200 MPa. This result is in agreement with the emulsified stability of pork batter (Table 1). A possible reason for this is that high-pressure processing can unfold muscle proteins, prompting more proteins to dissolve and form a three-dimensional network that entraps water molecules during heating (Wang et al., 2019; Carballo et al., 2000). Some researchers have reported that because of the improvement in the solubilisation and denaturation of muscle proteins, there is an increase in water- and fat-holding capacity in meat batter treated under high-pressure processing occurred (Kang et al., 2021; Yang et al., 2016; Velazquez et al., 2021). Nevertheless, excessive pressure destroys the hydrogen bonds of partially denatured protein polymers and divides them into oligomers or monomers structures (Souza et al., 2011). Zhang et al. (2017) reported that the smallest particle size of myofibrillar proteins treated under 200 MPa was generated and formed a gel with a denser and homogeneous network. However, over 300 MPa, the proteins were excessively denatured and formed a gel with larger cavities and heterogeneity.

3.3. Colour

The effect of colour on cooked reduced-fat pork batters treated at different pressures is shown in Table 2. The L* value of the samples treated by high pressure significantly increased ($p < 0.05$), and the *a** and *b** values significantly decreased ($p < 0.05$) compared with that at

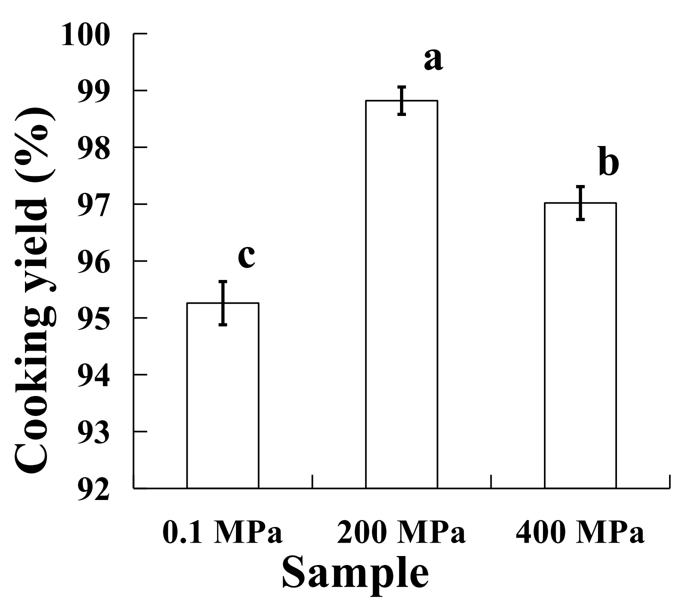

Fig. 1. Cooking yield (%) of reduced-fat pork batters treated by different pressures. Each value represents the mean ± standard deviation, n = 4. [a-c] Different parameter superscripts in the figure indicate significant differences ($p < 0.05$).

Table 2
The color (L*, a*, and b* values) of cooked reduced-fat pork batters treated by different pressures.

Sample	L* value	a* value	b* value
0.1 MPa	70.31 ± 0.83[c]	3.83 ± 0.27[a]	9.36 ± 0.19[a]
200 MPa	75.46 ± 0.65[a]	2.91 ± 0.36[b]	8.05 ± 0.25[b]
400 MPa	72.23 ± 0.79[b]	2.12 ± 0.32[c]	7.25 ± 0.21[c]

Each value represents the mean ± standard deviation, n = 4.
[a-c] Different parameter superscripts in the same column indicate significant differences ($p < 0.05$).

0.1 MPa. The L* value of the sample treated at 400 MPa was lower than that of the sample treated at 200 MPa, and the *a** and *b** values decreased significantly ($p < 0.05$) with increasing pressure. A possible reason is that changes in protein conformation and molecular interactions, such as electrostatic bonds, hydrogen bonds, and hydrophobic interactions, resulted from high-pressure processing, which could then increase/decrease the technological and functional properties of muscle proteins (Li et al., 2020a). A similar result was reported by Li, Sukmanov, Kang and Ma (2021b), where the *L** value of cooked batter treated with high pressure before heating significantly increased, and the *a** and *b** values significantly decreased when the pressure exceeded 200 MPa. Yang et al. (2016) also found that the colour of reduced-fat sausage treated at 200 MPa was lighter than that treated at 0.1 MPa. Additionally, it is well known that the pigment myoglobin is oxidised during high-pressure processing, and these changes are reflected in the *L**, *a**, and *b** values (Tobin, O'Sullivan, Hamill and Kerry, 2012). According to the cooking yield (Fig. 1), the sample treated at 200 MPa contained more water and reflected more light than the other samples, which increased the *L** value (Grossi et al., 2011). Gupta et al. (2018) also emphasised that high-pressure processing had a detrimental effect on colour because of the intra- and inter-molecular interactions, denaturation, or oxidation of proteins to varying degrees under different pressures.

3.4. TPA

The effect of high pressure on TPA in cooked reduced-fat pork batters treated at different pressures is shown in Table 3. The hardness, springiness, cohesiveness, and chewiness of the cooked reduced-fat pork batters significantly increased ($p < 0.05$) compared with that of the 0.1 MPa, and the hardness, springiness, cohesiveness, and chewiness of the samples treated at 400 MPa were lower than those treated at 200 MPa. This occurred because more hydrophobic and sulfhydryl groups were exposed. The muscle proteins unfolded and stretched after treatment under moderate pressure (≤300 MPa), and the exposed hydrophobic residues cross-linked to aggregate, leading to more free sulfhydryl groups that reacted to form disulphide bonds during the heating process (Zhang et al., 2017; Kang et al., 2021). Kang, Lu et al. (2021) reported that moderately pressure-treated pork batter had a stronger gel structure, but a higher pressure-treated (>300 MPa) gel had a weaker structure; thus, the hardness and chewiness increased as the pressure increased from 0.1 MPa to 300 MPa, and then decreased gradually from 300 MPa to 500 MPa. Sazonova et al. (2019) observed a significant decrease in protein extractability in meat batter when treated at over 200 MPa, with muscle protein denaturation and aggregation, which limited their processing properties. Zheng et al. (2017) reported a similar result; chicken batters subjected to high-pressure processing exhibited significantly increased hardness, springiness, cohesiveness, chewiness, and resilience compared to the samples treated at 0.1 MPa. Moreover, a significant increase in the free sulfhydryl group content of the soy protein isolate occurred when treated at 200 MPa, but more free sulfhydryl groups were progressively and significantly decreased with the increase in pressure (Wang et al., 2007). In summary, reduced-fat pork batters treated at 200 MPa had a stronger gel structure, and that of the gel treated at 400 MPa was weaker.

Table 3
Texture profile analysis of cooked reduced-fat pork batters treated by different pressures.

Sample	Hardness (N)	Springiness	Cohesiveness	Chewiness (N.mm)
0.1 MPa	66.31 ± 1.06[c]	0.92 ± 0.00[c]	0.74 ± 0.01[c]	45.34 ± 0.91[c]
200 MPa	72.09 ± 0.95[a]	0.94 ± 0.01[a]	0.78 ± 0.00[a]	52.71 ± 0.83[a]
400 MPa	68.83 ± 1.01[b]	0.93 ± 0.00[b]	0.76 ± 0.01[b]	48.52 ± 1.05[b]

Each value represents the mean ± standard deviation, n = 4.
[a-c] Different parameter superscripts in the same column indicate significant differences ($p < 0.05$).

3.5. Low-field NMR

The effects of relaxation time and peak ratio on cooked reduced-fat pork batter treated at different pressures are shown in Fig. 2 and Table 4. The three peaks of T_{2b}, T_{21}, and T_{22} are named bound water (water tightly associated with protein and macro-molecular constituents), immobilised water (intra-myofibrillar water and water within the protein structure), and free water (extra-myofibrillar water), respectively, and they were located at 0–10, 10–200, and 200–1000 ms on the inversion map of the nuclear magnetic intensity, respectively (Fig. 2) (Kang et al., 2022; Kang et al., 2016a,b). In this study, the initial relaxation times of T_{2b}, T_{21}, and T_{22} in the cooked reduced-fat pork batters treated under 200 and 400 MPa were smaller ($p < 0.05$) than those treated under 0.1 MPa, indicating that the water in the batters treated at 200 and 400 MPa was closely tied (Ruiz-Cabrera et al., 2004; Sánchez-Alonso et al., 2012). The sample treated under 200 MPa had the shortest initial relaxation times of T_{2b}, T_{21}, and T_{22} among the treatments, implying that the sample treated under 200 MPa had a good gel structure and water- and fat-holding capacity, which is in agreement with the results for TPA, emulsion stability, and cooking yield (Tables 1 and 3, Fig. 1).

The peak ratios of P_{2b} in the cooked reduced-fat pork batters did not significantly different ($p > 0.05$). The peak ratios of P_{21} in the samples treated under 200 and 400 MPa were greater ($p < 0.05$), and the peak ratios of P_{22} were smaller ($p < 0.05$) than those at 0.1 MPa. The sample treated under 200 MPa had the greatest peak ratio of P_{21} and the smallest peak ratio of P_{22}. This result agreed with those of the initial relaxation times (Table 4) and cooking yield (Fig. 1), indicating that the water, soy protein isolate, and muscle proteins in the sample treated at

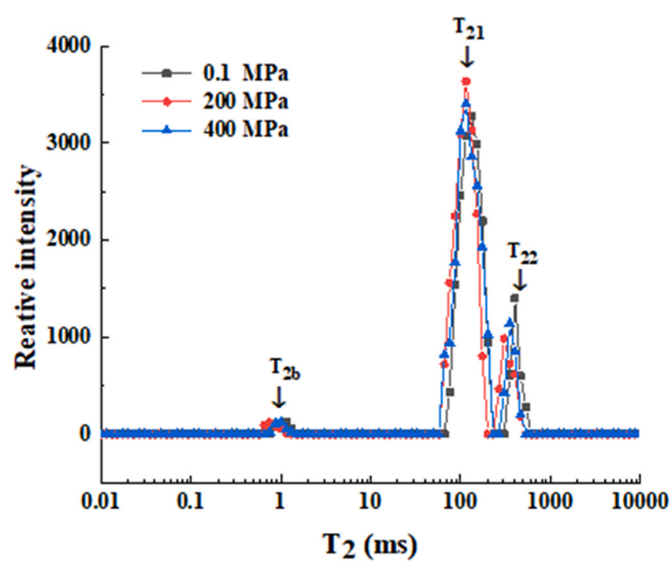

Fig. 2. The changes in relaxation times and peak ratio of cooked reduced-fat pork batters treated by different pressures.

Table 4
The initial relaxation time (ms) and peak ration (%) of cooked reduced-fat pork batters treated by different pressures.

Sample	Relaxation time (ms)			Peak ration (%)		
	T_{2b} (ms)	T_{21} (ms)	T_{22} (ms)	P_{2b} (%)	P_{21} (%)	P_{22} (%)
0.1 MPa	0.92 ± 0.03^{a}	74.50 ± 1.56^{a}	326.31 ± 13.37^{a}	2.71 ± 0.31^{a}	85.73 ± 0.81^{c}	11.62 ± 0.23^{a}
200 MPa	0.66 ± 0.02^{c}	63.21 ± 2.08^{c}	243.65 ± 14.31^{c}	2.47 ± 0.27^{a}	90.38 ± 0.72^{a}	7.11 ± 0.19^{c}
400 MPa	0.74 ± 0.03^{b}	68.41 ± 1.92^{b}	270.26 ± 12.87^{b}	3.05 ± 0.34^{a}	87.41 ± 0.96^{b}	9.37 ± 0.26^{b}

Each value represents the mean ± standard deviation, n = 4.
[a-c] Different parameter superscripts in the same column indicate significant differences ($p < 0.05$).

200 MPa were tightly associated with each other and then reduced the water loss during the heating process (Li, Kang, Sukmanov and Ma, 2021a; Ma et al., 2015). A possible reason is that the sulfhydryl groups, surface hydrophobicity of the soy protein isolate, and muscle proteins increased when treated by high-pressure processing. The protein solution also increased, favouring the formation of a good structure and enhanced water-holding capacity (Chan et al., 2011). When treated under 200 MPa, more aggregations were formed due to the protein-protein interaction, the solubility of the soy protein isolate and muscle proteins decreased, and the gel structure worsened with an increase in the free water content and fluidity of water.

3.6. Raman spectroscopy

The percentage of protein secondary structure in cooked reduced-fat pork batters treated with different pressures is shown in Table 5. The percentages of α-helices, β-sheets, β-turns, and random coil structures in the cooked meat batters were affected by pressure. The content of the α-helice structure of the samples treated with high pressure significantly decreased ($p < 0.05$), and the content of the β-sheet, β-turns, and random coil structures significantly increased ($p < 0.05$) compared with those at 0.1 MPa. It is possible that treatment under 200 and 400 MPa modified the soy protein isolate and muscle proteins by changing the non-covalent bonds, especially hydrogen bonding, surface hydrophobicity, and sulfhydryl group content (Cao et al., 2012). Some researchers have found that the α-helix, β-sheet, β-turn, and random coil structure contents of proteins are sensitive to changes in the hydrogen-bonding scheme involving the peptide linkages of the amide I band, and an increase in hydrogen bonding can cause more α-helical structures to change into the β-sheet structures during protein denaturation with the soy protein isolate (Wei et al., 2019; Perisic et al., 2013; Ngarize et al., 2004). Furthermore, the content of the α-helice structure did not significantly different ($p > 0.05$) with the increase in pressure, the β-sheet structure of the sample treated under 400 MPa was lower, and the β-turn and random coil structures were higher than that at 200 MPa. The results indicated that a significant increase in the β-turn and random coil structure content was accompanied by a concomitant decrease in the β-sheet structure content with treatment under 400 MPa. Moreover, a significant positive correlation between β-sheet structure content and hardness (R = 0.76), springiness (R = 0.81), and chewiness (R = 0.84) was observed in the cooked reduced-fat pork batters. It is well known that the β-sheet structure is the basis for forming a gel structure. Thus, reducing the content of the β-sheet structure caused the gel structure to worsen, leading to a decrease in hardness, springiness, cohesiveness, and chewiness (Table 3).

Table 5
Percentages of protein secondary structures (α-helice, β-sheet, β-turns, random coil) of cooked reduced-fat pork batters treated by different pressures.

Sample	α-helice (%)	β-sheet (%)	β-turn (%)	Random coil (%)
0.1 MPa	52.62 ± 2.34^{a}	19.37 ± 1.08^{c}	15.28 ± 0.47^{c}	10.60 ± 0.25^{c}
200 MPa	43.64 ± 2.36^{b}	26.52 ± 1.37^{a}	17.52 ± 0.55^{b}	12.06 ± 0.22^{b}
400 MPa	44.08 ± 2.62^{b}	22.31 ± 1.31^{b}	19.84 ± 0.39^{a}	13.77 ± 0.30^{a}

Each value represents the mean ± standard deviation, n = 4.
[a-c] Different parameter superscripts in the same column indicate significant differences ($p < 0.05$).

3.7. Sensory evaluation

The sensory quality indices of the cooked reduced-fat pork batters treated by different pressures are shown in Table 6. The high-pressure processing and pre-emulsified sesame oil combination influenced the sensory attributes of cooked reduced-fat pork batter. Compared to the sample of 0.01 MPa, the appearance and juiciness scores of the preparation at 200 MPa significantly increased ($p < 0.05$), and the preparation at 400 MPa did not significant different ($p > 0.05$). The reason is that consumers prefer emulsion meat products with a brighter appearance, and the juiciness scores are closely related to the emulsion stability of the raw meat batter (Hsu and Yu, 2002; Kang et al., 2020). In this study, the appearance and juiciness scores were in agreement with the results for colour (Table 2) and emulsion stability (Table 1). Moreover, there were some differences between the results of the mechanical test and the sensory evaluation, due to the differences in sensitivity between the mechanical and sensory tests. Meanwhile, compared to the sample of 0.01 MPa, the springiness and hardness scores of the preparation at 400 MPa did not significantly difference ($p > 0.05$), and the preparation at 200 MPa significantly increased ($p < 0.05$); the preparation 200 MPa had the highest score. The springiness and hardness scores were similar to those parameters of TPA (Table 3). The springiness and hardness are the most important properties of emulsion meat products, and consumers prefer the products with desirable hardness and elasticity (Lages et al., 2021). For this reason, the overall acceptability score of preparation at 200 MPa was the highest, and this study demonstrated that treatment with 200 MPa could improve the sensory properties of reduced-fat pork batter.

4. Conclusion

This study showed that high-pressure treatment and pre-emulsified sesame oil significantly affected the emulsion stability, gel properties, and protein conformation of reduced-fat pork batters. The L* value, cooking yield, and texture properties of the sample treated with high pressure significantly increased, and the TR, WR, FR, and *a** and *b** values significantly decreased compared to those at 0.1 MPa. Additionally, the emulsion stability and textural properties of the samples treated at 200 MPa were the highest. This caused the initial relaxation times of T_{2b}, T_{21}, and T_{22} in the samples treated at 200 MPa to be the shortest, and an increased content of β-sheets, β-turns, and random coil structures, leading to a decrease in the mobility of water. The result of sensory evaluation found that the sample treated with 200 MPa had the

Table 6
Comparisons of sensory quality indices of cooked reduced-fat pork batters treated by different pressures.

Sample	Appearance	Springiness	Hardness	Juiciness	Overall acceptability
0.1 MPa	7.65 ± 0.21^{b}	7.70 ± 0.15^{b}	7.53 ± 0.18^{b}	7.81 ± 0.17^{b}	7.53 ± 0.17^{c}
200 MPa	8.17 ± 0.18^{a}	8.31 ± 0.19^{a}	8.19 ± 0.15^{a}	8.22 ± 0.12^{a}	8.27 ± 0.16^{a}
400 MPa	7.86 ± 0.24^{ab}	7.98 ± 0.18^{b}	7.80 ± 0.16^{b}	8.05 ± 0.16^{ab}	7.95 ± 0.19^{b}

Each value represents the mean ± standard deviation, n = 4.
[a-b] Different parameter superscripts in the same column indicate significant differences ($p < 0.05$).

highest sensory scores. Overall, the results suggest that 200 MPa and pre-emulsified sesame oil incorporation can improve the gel and functional properties of reduced-fat pork batters, which is the benefit of expanding the production of reduced-fat emulsified meat products in the food and meat industry.

Ethical guidelines

Ethics approval was not required for this research.

Data availability

Research data are not shared.

CRediT authorship contribution statement

Guang-Hui Liu: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft. **Jing-Chao Fan:** Conceptualization, Methodology, Validation, Supervision, Data curation, Visualization. **Zhuang-Li Kang:** Conceptualization, Methodology, Validation, Supervision, Project administration, Writing – review & editing, Data curation, Visualization. **Igor Mazurenko:** Conceptualization, Methodology, Supervision, Writing – review & editing, Data curation, Visualization.

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.

Acknowledgments

This study was supported by Natural Science Foundation of Henan Province (no. 212300410344).

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