

Potential of beef tallow/palm oil blend as Chongqing hotpot oil from a physicochemical and flavor perspective

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ARTICLE INFO

Keywords:

Beef tallow
Palm oil
Chongqing hotpot oil
Key volatile compounds

ABSTRACT

Beef tallow is an important raw material in Chongqing hotpot seasoning but raises great concern on health due to the cholesterol issue. Herein, palm oil was expected to replace beef tallow at weight ratios of 2:1, 1:1, and 1:2 without reducing hotpot flavor. The blending of palm oil to beef tallow effectively decreased cholesterol content to 33.20 mg 100 g⁻¹, as well as the level of saturated fatty acids to 50 % in hotpot oil. The fading in brightness and yellowness of oil models occurred owing to heat treatment. The blending oil at 2:1 showed similar hardness, melting and crystallization behaviors to beef tallow, probably due to the similar fat crystal network. The volatile compounds of hotpot seasoning made from the oil were closer to that from neat beef tallow. These findings may provide a new strategy to develop healthier and tastier base oil for the production of Chongqing hotpot seasoning.

1. Introduction

Chinese hotpot is a traditional cuisine with a history of more than 2000 years, and has gained popularity worldwide for its appealing taste. Chongqing hotpot is a typical hotpot in China, especially in the south-western regions, which is characterized by a hot, spicy, and flavorful soup. It is made from beef tallow (BT), Pixian pea sauce, chilis, pepper, ginger, garlic, and other spices as raw materials through a complex process of frying or cooking (Zhang et al., 2021). As reported by Pang et al. (2023), Chongqing hotpot has been a signature local food regularly consumed by a population of almost 110 million, and more than 150,000 Chongqing hotpot restaurants have been opened across China. In addition, the further growth of the consumption of hotpot seasoning is expected, which is estimated to increase globally with a total production of 668.9 billion yuan by 2025 (Liu et al., 2023).

As a carrier of flavor substances, beef tallow has been commonly used in Chongqing hotpot seasoning, accounting for about 40–50 % of the total components, which plays an essential role in the formation of the hotpot flavor (Guo et al., 2023). Beef tallow is a type of edible animal fat made from beef adipose tissue through high temperature processing. It contains a variety of fatty acids, vitamins, minerals, and other nutrients, and also has desirable physical properties including good heat

stability, strong antioxidant, and unique flavor (Li et al., 2024). There has been a growing body of studies into volatile compositions and sensory properties of beef tallow in hotpot. Ye et al. (2022) found that beef tallow was a vital precursor for odor development in hotpot, and could be involved in fat oxidation and Maillard reaction, resulting in the formation of specific volatile compounds that provided characteristic hot flavors. Sun et al. (2021) identified characteristic aroma components of beef tallow from Chinese hotpot seasoning, and found that 2-furfurylthiol, 2-acetylthiazole, anethole, (*E*)-2-decenal, and 1,8-cineole were the key odorants for the overall aroma of beef tallow. However, beef tallow contains approximately 50 % saturated fatty acids, as well as 50–300 mg cholesterol/100 g fat, which could cause diet-related diseases (e.g., hypertension and obesity) (Yavari et al., 2009). Shifting towards healthier hotpot seasoning, especially by reducing the consumption of beef tallow without reducing the flavor, is urgently needed for the long-term sustainability of the hotpot industry.

Vegetable oil with low cholesterol content is expected to replace beef tallow partially and produce healthier hotpot oil. Palm oil (PO) is the most consumed vegetable oil in the world and usually extracted from the oil palm's fruit flesh. Currently, few scientific findings suggested palm oil as a risk factor for cardiovascular disease, and it was then regarded as a viable alternative for the use of solid fat formulation by virtue of its

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<https://doi.org/10.1016/j.fochx.2025.102371>

Received 30 August 2024; Received in revised form 1 March 2025; Accepted 10 March 2025

Available online 18 March 2025

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fatty acid composition (Fattore & Fanelli, 2013). Li et al. (2018) produced a low trans margarine fat analog with the blend of palm oil and soybean oil at a mass ratio of 4:3, and the resulting oil showed the potential in formulating healthier margarine as a healthy alternative to beef tallow. However, when the blend of palm oil and beef tallow was used to produce hotpot seasoning, different types of hotpot oils could contribute to flavor differences. That may be associated with the type and content of volatile compounds, the mutual synergistic or inhibitory effects between volatiles (Zou et al., 2023). Therefore, it is of significance to compare the changes of volatile compounds in Chongqing hotpot seasoning made from different oils, which may provide a more general and applicable reference to the selection of hotpot oils from a flavor perspective.

In this study, the differences of oil models in physicochemical properties (such as oxidation status, color, hardness, melting and crystallization behaviors, etc.) were compared in detail. The characteristic flavors of hotpot seasoning made from different oils were used to evaluate the potency of beef tallow/palm oil blend as the base oil for the production of Chongqing hotpot seasoning. More specifically, the fatty acid composition of oil models was determined by a gas chromatography, and the melting and crystallization behavior were evaluated using differential scanning calorimetry (DSC). Polarized light microscopy was used to study the crystal morphology of oil samples. Additionally, the overall aroma characteristics of different oil models were analyzed by electronic nose (E-nose), and principal component analysis (PCA) was performed to clarify the odor variations among samples with various weight ratios. The key volatile compounds in five kinds of hotpot oil were finally identified and quantified by SPME/GC-MS.

2. Materials and methods

2.1. Materials

Beef tallow was purchased from Shuai Ke Food Co., Ltd. (Chongqing, China). Palm oil and mixed seasonings packet were purchased from a local supermarket. Isopropanol, chloroform, thiobarbituric acid (TBA), and 1,1,3,3-tetraethoxypropane were obtained from Maclin Biochemical Technology Co., Ltd. (Shanghai, China). All other chemicals were analytical-grade purity and were used without any further processing.

2.2. Sample preparation

Preparation of Chongqing hotpot oil samples was performed according to the method of Zou et al. (2022) with modifications. The oil models were prepared by mixing beef tallow and palm oil. Weight ratios of beef tallow to palm oil were 2:1, 1:1, and 1:2 to match textural and sensory properties of traditional hotpot. 400 g of hot water was added to the mixed oil. Then, the mixtures were stirred and simmered at 100 °C for 15 min. When standing for 5 min, the oil models were obtained from the upper oil layer.

2.3. Measurement of acid value (AV), peroxide value (PV), malondialdehyde (MDA), and cholesterol

The quality parameters of different oil models were determined according to the method reported by Zhang et al. (2022) with modifications. 15 g of oil samples were heated at 100 °C for 18 h using an H CJ-6E numerical show constant temperature oil.

bath (Changzhou Enpei Instrument Co., Ltd., China). The changes of oil models in AV, PV, MDA, and cholesterol contents were detected at 3 h intervals.

2.4. Determination of color

The color changes of oil models during heat treatment were determined using a NH310 portable colorimeter (Shenzhen, China). The

values of L^* , a^* , and b^* were recorded for each sample, which represented that the color ranged from luminosity (–) to brightness (+), from greenness (–) to redness (+), and from blueness (–) to yellowness (+), respectively. The total color change (ΔE) of the oils was calculated according to the following equation (Shao et al., 2015):

$$\Delta E = \sqrt{(L_i^* - L_0^*)^2 + (a_i^* - a_0^*)^2 + (b_i^* - b_0^*)^2}$$

where L_0^* , a_0^* , and b_0^* are the initial color values of samples, and L_i^* , a_i^* , and b_i^* denote the final color values of samples.

2.5. Assay of fatty acids composition

Fatty acid methyl esters (FAMES) derived from oil models were analyzed by a 7890 A gas chromatography (Agilent Technologies, Palo Alto, USA) equipped with a flame ionization detector and a DB-WAX capillary column. The oven temperature was held at 150 °C for 3 min and then increased to 240 °C at a heating rate of 10 °C min^{–1}. The temperature of the injector and detector was 250 °C.

2.6. DSC measurement

The thermal properties of oil models were evaluated on a DSC (DSC-1, Mettler-Toledo corp., Switzerland) under a nitrogen atmosphere at a flow rate of 50 mL min^{–1}. Approximately 5 mg of samples in 40 mL aluminum pans were heated to 70 °C until the complete melting of oil crystal structure and then cooled to –50 °C with a ramp rate of 10 °C min^{–1}.

2.7. Morphology observation

An aliquot of sample deposited on a microscope slide was observed under an ECLIPSE E600W POL polarized light microscopy (Nikon, Tokyo, Japan) with a hot stage (Linkam ED600, UK) at 10 °C. A built-in camera was used to photograph crystal morphology of oil models with a 100× magnification.

2.8. Hardness test

Oil samples were compressed twice to 60 % of the original height at a time interval of 5 s, and the hardness was recorded on a Rapid TA texture analyzer (Tengba Technology Co., Ltd., Shanghai, China) with a cylindrical probe (P/50) under a trigger force of 5 g. The pre-test speed, test speed, and after-test speed were set at 2.0, 1.0, and 2.0 mm s^{–1}, respectively (Huang et al., 2019).

2.9. E-nose measurement

An E-nose device (C-Nose, BosinTech Co. Ltd., Shanghai, China) was employed to assess the flavor of oil models at room temperature. 5.0 g of each oil sample in a 20 mL sealed vial was equilibrated at 40 °C in a water bath for 10 min. Clean and dry air was used as carrier gas at a flow rate of 1.0 L min^{–1} (Han et al., 2022).

2.10. Determination of volatile compounds by SPME/GC-MS

Before the experiments, oil models were heated to 80 °C and were added to make hotpot seasonings, respectively. Then, volatile compounds in hotpot seasoning with the oil samples were extracted using a solid phase micro-extraction (SPME) fiber (50/30 μm DVB/CAR/PDMS, Supelco Co., USA), and were further analyzed by a QP2010 SE GC-MS system (Shimadzu, Kyoto, Japan) equipped with a Rtx-Wax column of 30 m × 0.25 mm I.D. and 0.25 μm film thickness (Restek Corp., Bellefonte, PA, USA). The initial oven temperature was kept at 40 °C for 2 min, and was then increased to 100 °C at a rate of 3 °C min^{–1}. When standing for 2 min, the temperature was finally increased to 280 °C at a

rate of $5\text{ }^{\circ}\text{C min}^{-1}$ and was held for 5 min. The flow rate of carry gas (helium) was fixed at 1.0 mL min^{-1} . Mass spectra was set in the electron impact mode with an energy voltage of 70 eV and an ion source temperature of $250\text{ }^{\circ}\text{C}$, and was operated in the 35–400 m/z range (Zhou et al., 2025).

2.11. Statistical analysis

All the samples were freshly prepared and measured in triplicate. Experimental data was expressed as means \pm standard deviations and was further analyzed by One-way analysis of variance (ANOVA). Statistical significance was confirmed when the p -value was <0.05 . In addition, PCA was conducted to interpret the signal responses of the sensors in *E*-nose to the odor variations among oil models at different weight ratios using Origin 2018. A heat map was generated using TBtools software (version 2.110) to show similarities and differences in the concentration and composition of volatile compounds among hotpot oils.

3. Results and discussion

3.1. Changes of oil models in oxidation status and cholesterol content

As shown in Fig. 1A, beef tallow had the highest AV of 2.25 mg g^{-1} . The addition of palm oil decreased the AV of the blending oil, and the corresponding values were 1.68 (2:1), 1.42 (1:1), and 1.21 (1:2) mg g^{-1} , respectively. No obvious change of different oil models in AV was observed during 18 h of heating process, indicating that no rancidity occurred in oil samples as a result of triglyceride hydrolysis during heat

treatment. Similar results were reported by the previous literature, in which no significant change in oil sample AV was observed under any of the heating treatment conditions (Zhang et al., 2021). The PV of the blending oil was also decreased by the addition of palm oil. The PV of oil samples remained unchanged and then showed a rising trend when heated more than 9 h (Fig. 1B), suggesting that the formation rate of primary oxidation products of oil models might be increased with heating time increasing over 9 h (Suri et al., 2020). However, the MDA content of different oil samples was significantly increased by heating treatment, but the MDA content was still much lower than 0.25 mg in 100 g sample according to the National Standard of China (GB 10146–2015). In addition, the cholesterol content of beef tallow was decreased by mixing palm oil, which may be very positive to reduce the incidence of cardiovascular disease (Xu et al., 2021). A decreased trend of cholesterol content in all oil models was observed during a heating period of 18 h. That might be associated with the formation of cholesterol derivative, resulting from the oil oxidation (Nourbehesht et al., 2018). Zou et al. (2022) mixed beef tallow with palm stearin to make Sichuan hotpot oil and also found that the addition of palm stearin could significantly reduce the cholesterol content.

3.2. Changes in color during heat treatment

Color was considered as a direct indicator to evaluate the quality of hotpot oil. As shown in Fig. 2, the blending of palm oil to beef tallow at various weight ratios greatly influenced color values. The a^* and b^* values of beef tallow were decreased by the addition of palm oil, while the L^* values did not change significantly until the weight ratio reached up to 2:1. When oil models were heated for 18 h, the a^* values showed a

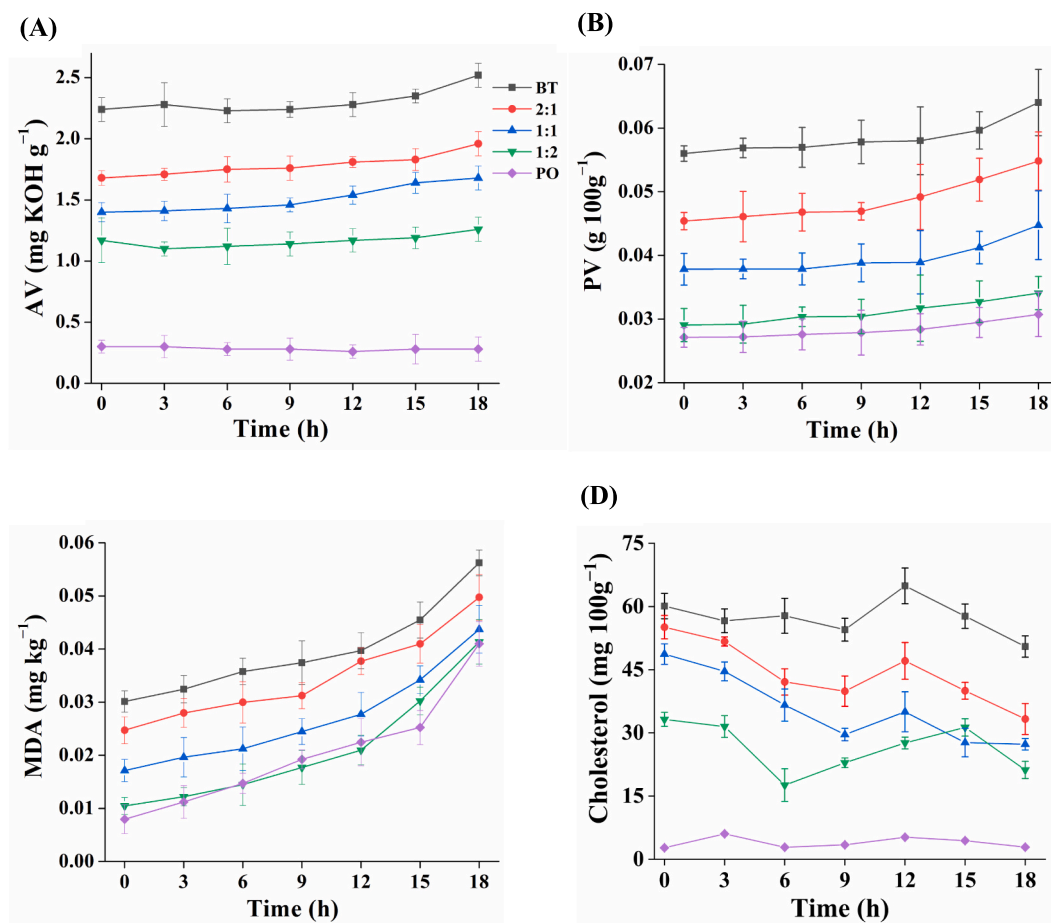


Fig. 1. Changes of different oil models in (A) acid value (AV), (B) peroxide value (PV), (C) malondialdehyde (MDA) content, and (D) cholesterol content during the heat treatment.

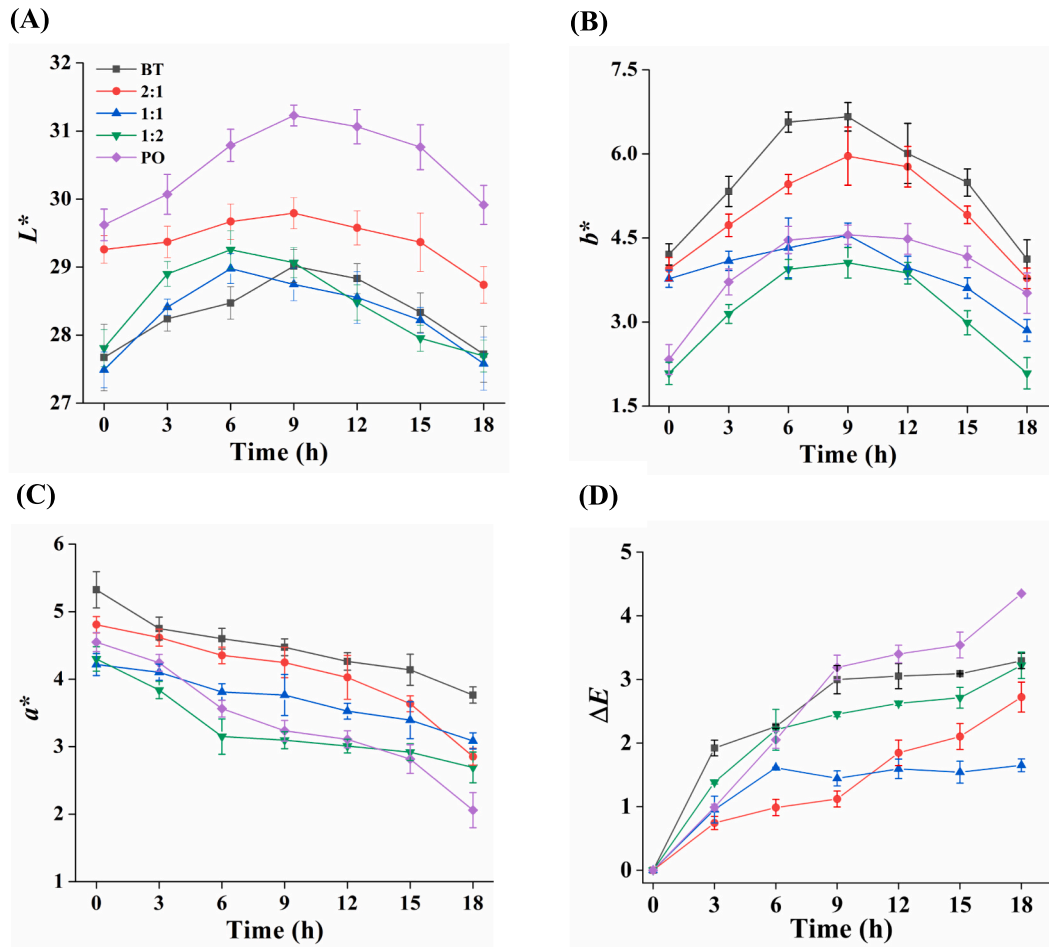


Fig. 2. Changes of oil models at various ratios in color values: (A) L^* , (B) a^* , (C) b^* , and (D) ΔE .

declining trend. That might be associated with the generation of oxidation products, which might be degraded to volatile compounds with low molecular weight (Zepka et al., 2009). However, a similar trend was observed for b^* and L^* values. The b^* and L^* values of oil models increased during 9 h of heating process but decreased with heating time ranging from 9 to 18 h, indicating the fading in brightness and yellowness of oil models caused by heat treatment. Similar results have been reported by Zheng et al. (2018), who found that the deepening in the color of oil with an increase in heating temperature or time. Moreover, the ΔE values of oil models were increased rapidly at the beginning of the heating, and then the growth rate decreased gradually with the increasing heating time. The blending of palm oil to beef tallow decreased the ΔE values of samples to less than 3, indicating that total color differences could not be easily distinguished (Obón et al., 2009).

3.3. Fatty acid composition

As expected, there were eight fatty acids detected in oil samples, including myristic acid, palmitic acid, palmitoleic acid, heptadecanoic acid, stearic acid, oleic acid, linoleic acid, α -linolenic acid (Table 1). The levels of saturated fatty acids in beef tallow and palm oil were 58.2 % and 46.0 %, in agreement with the previous findings by Li et al. (2018). The predominant saturated fatty acids in beef tallow were palmitic acid and stearic acid with the contents of 25.51 % and 26.82 %, respectively, while palm oil mainly consisted of palmitic acid (40.32 %) and oleic acid (43.03 %). The level of unsaturated fatty acid in palm oil was significantly higher than that in beef tallow. Thus, the levels of saturated fatty acids in blending oil were decreased to 54.3 % (2:1), 51.5 % (1:1), and 50.0 % (1:2), respectively, largely because of the addition of palm oil

Table 1

Fatty acid composition of oil models at various weight ratios.

Fatty acids content (%)	BT	2:1	1:1	1:2	PO
Myristic acid (C14:0)	2.93 ± 0.01 ^a	2.14 ± 0.09 ^b	1.73 ± 0.13 ^c	1.43 ± 0.03 ^d	0.79 ± 0.18 ^e
Palmitic acid (C16:0)	25.51 ± 0.17 ^d	30.41 ± 1.35 ^c	33.41 ± 0.04 ^b	35.73 ± 0.01 ^b	40.32 ± 1.47 ^a
Palmitoleic acid (C16:1)	1.29 ± 0.01 ^a	1.34 ± 0.09 ^a	0.96 ± 0.21 ^b	0.70 ± 0.87 ^c	0.12 ± 0.03 ^d
Heptadecanoic acid (C17:0)	1.70 ± 0.01 ^a	1.23 ± 0.67 ^b	0.85 ± 0.09 ^c	0.62 ± 0.25 ^d	nd
Stearic acid (C18:0)	26.82 ± 0.66 ^a	19.82 ± 2.37 ^b	14.81 ± 0.01 ^c	11.73 ± 0.57 ^d	4.51 ± 1.03 ^e
Oleic acid (C18:1)	4.98 ± 1.34 ^d	34.61 ± 0.76 ^c	37.41 ± 0.23 ^b	39.02 ± 0.79 ^b	43.03 ± 0.02 ^a
Linoleic acid (C18:2)	2.94 ± 0.54 ^d	5.44 ± 0.88 ^c	7.06 ± 1.62 ^b	7.99 ± 0.01 ^b	10.44 ± 0.05 ^a
α -Linolenic acid (C18:3)	0.26 ± 0.01 ^a	0.19 ± 0.01 ^b	0.17 ± 0.08 ^b	0.16 ± 0.04 ^b	0.13 ± 0.09 ^b
Saturated fatty acid	58.2 ± 0.12 ^a	54.3 ± 2.34 ^b	51.5 ± 0.89 ^c	50.0 ± 0.03 ^c	46.0 ± 2.11 ^d
Unsaturated fatty acid	41.8 ± 0.28 ^d	45.7 ± 1.01 ^c	48.5 ± 0.02 ^b	50.0 ± 0.05 ^b	54.0 ± 1.60 ^a

Results are expressed as mean values ± standard deviation of three replicates. Different letters in each row indicate significant difference ($p < 0.05$). nd, not detected.

with a high content of oleic acid. Similarly, Mba et al. (2017) investigated the fatty acid composition of canola oil, palm oil, and their blend, and found that the blending oil showed an intermediate level between

canola oil and palm oil. Mao et al. (2022) found that the saturated and unsaturated fatty acid ratio of palm oil was well balanced, and the blending of palm oil to beef tallow could provide the ability to meet the plasticity requirements of shortening products.

3.4. Thermal analysis

As shown in Fig. 3A, three broad endothermic peaks were observed in the melting process of beef tallow, and the corresponding temperatures (T_m) to melting peaks were 4.97, 13.08, and 43.41 °C, respectively. However, the melting curve of palm oil showed one sharp endothermic peak and two broad endothermic peaks centered at the temperature of 0.34, 6.60, and 20.38 °C, respectively. When beef tallow was mixed with palm oil, the three melting peaks of the blending oil occurred at the temperature ranging from 1.80 to 40.77 °C. In particular, the endothermic peaks of the beef tallow/palm oil blend at the weight ratio of 2:1 were similar to that of beef tallow, in accordance with the previous finding of Zou et al. (2022). Moreover, the endothermic enthalpy (ΔH_m) of beef tallow were 4.69, 1.44, and 57.35 J/g, and the values of palm oil were 5.64, 8.66, and 25.17 J/g, while the ΔH_m values of blending oil

varied from 1.63 to 48.04 J/g due to the mixing of palm oil to beef tallow (Table 2). Fig. 3B presents the crystallization behavior of oil samples at various weight ratios. All the oil samples showed two crystallization peaks at the phase transition temperature of -1.90 - 4.69 and 13.33–27.38 °C, showing a slight hysteresis in the process of phase transformation between the peak temperature of crystallization peak and melting peak (Mao et al., 2023). With the increasing ratio of palm oil in the samples, two crystalline peaks of the blending oil shifted to the left, and the corresponding ΔH_c values were 28.50–39.38 and 7.59–12.01 J/g, suggesting that fatty acid composition in the blends had a great impact on the melting and crystallization behavior (Meng et al., 2010).

3.5. Crystal microstructure and hardness

The binary blends of beef tallow and palm oil were crystallized at 10 °C, and the crystal microstructures were observed under polarized light microscopy (Fig. 4A - E). Neat beef tallow showed a dense network formed from both clustered globular crystals and small needle-like crystals, while neat palm oil presented the morphology of fine feathery spherulites. When beef tallow was mixed with palm oil, the change of the blending oil in the microstructure occurred. The crystals aggregated to form larger clusters and higher density at the weight ratio of 2:1. That might be associated with a eutectic growth behavior, i.e., the 2-position of triacylglycerols component of palm oil grew on the peripheral of beef tallow seed crystals (Mahisanunt et al., 2020). As the weight ratio was changed to 1:1, the increased content of palm oil induced the formation of crystal nucleus with larger size, which could affect the texture and plasticity of oil samples (Nguyen et al., 2021). However, with the increasing ratio of palm oil content to 1:2, little change of crystals in the shape and size was observed, and the small crystal particles almost disappeared. Moreover, beef tallow and palm oil had the hardness of 252.03 and 7.47 g, respectively. The addition of palm oil into beef tallow decreased the hardness as the weight ratio of palm oil in the blends increased. However, the blending oil at the weight ratio of 2:1 showed no significant change in the hardness of beef tallow, probably due to the similar fat crystal network, which might be considered more desirable for Chongqing hotpot oil (Liu et al., 2010).

3.6. Aroma attribute analysis of oil models

Fig. 5A shows the response signal intensity of each sensor in the E-nose to the aroma compounds of oil models. All the five samples showed similar signals in the profile of the radar map from 6 sensors including sn-07, sn-17, sn-18, and sn-19. However, each sensor responded differently to the samples. Sensors sn-07 and sn-17 had the highest response values, followed by the sensors sn-18 and sn-19, indicating that the odor intensity of corresponding volatile compounds to sensors sn-07 and sn-17 was higher (Chen et al., 2023; Jin et al., 2023). As the weight ratio of palm oil in models increased, the response value of sensor sn-07 and sn-17 increased, and a slight change of sensors sn-18 and sn-19 in the response intensity was observed, suggesting that the mixing of palm oil with beef tallow increased the content of short-chain alkanes and hydrogen-containing compound, and had a certain impact on the level of some aroma compounds such as aromatic hydrocarbon, esters, alcohols, aldehydes, and ketones (Shen et al., 2023).

To further clarify the odor variations among oil samples with various mixing ratios, PCA was performed on the E-nose response values of samples. The results displayed that the cumulative variance contribution rate of the two principal components was 97.6 % (Fig. 5B), indicating that the majority of odor information in all samples could be elucidated by the first two principal components (Sun et al., 2024). The score plot showed a clear distribution of the oils according to the mixing weight ratio. Beef tallow had a negative value for PC1 and partly overlapped the x-axis. Palm oil showed negative PC1 and PC2 values, and was thus located in the third quadrant of the score plot. For the beef tallow/palm

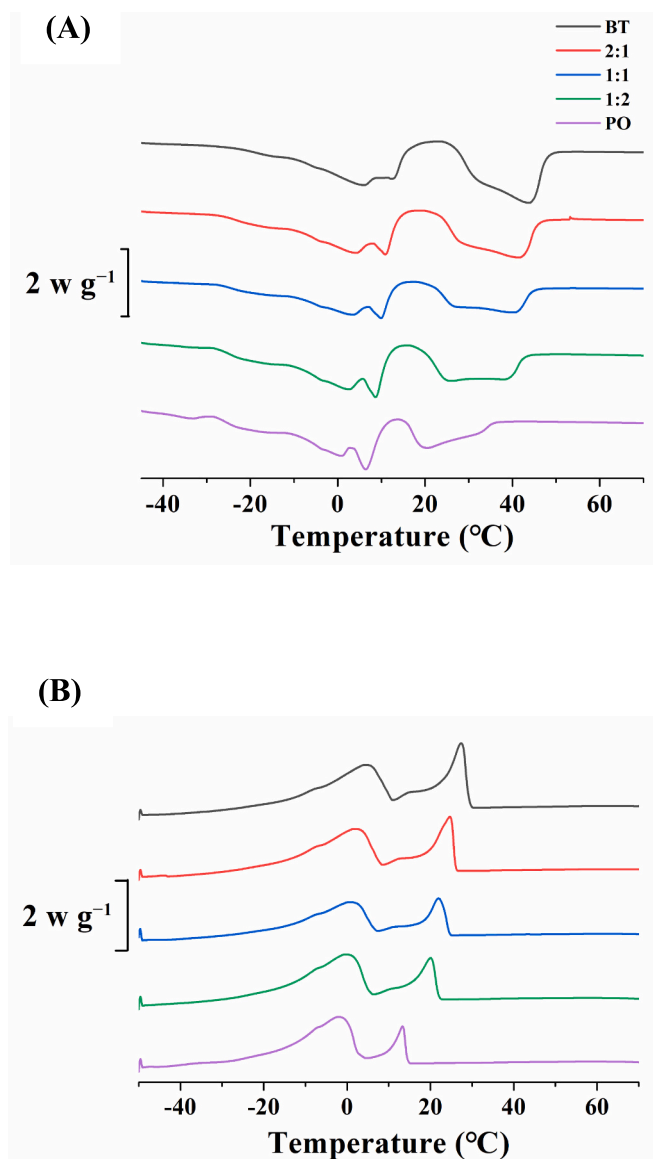
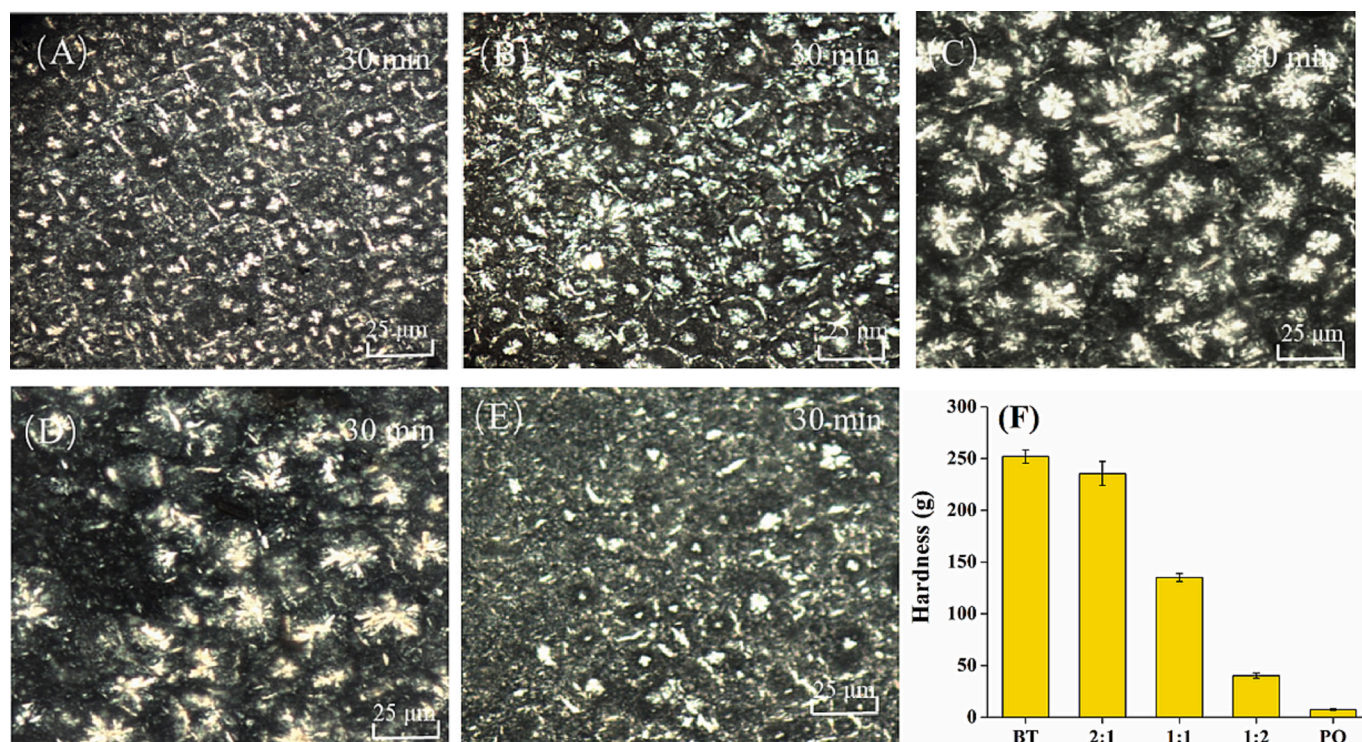


Fig. 3. (A) The melting and (B) crystallization curves of oil models at various ratios.

Table 2

Melting and crystallization characteristics of different oil models.

Fats	Melting property				Crystallization property					
	Peak 1		Peak 2		Peak 3		Peak 1		Peak 2	
	T_m (°C)	ΔH_m (J/g)	T_m (°C)	ΔH_m (J/g)	T_m (°C)	ΔH_m (J/g)	T_c (°C)	ΔH_c (J/g)	T_c (°C)	ΔH_c (J/g)
BT	4.97 ± 0.02 ^a	4.69 ± 0.67 ^b	13.08 ± 0.06 ^a	1.44 ± 0.71 ^d	43.41 ± 0.13 ^a	57.35 ± 0.22 ^a	4.69 ± 0.04 ^a	31.41 ± 1.71 ^c	27.38 ± 0.29 ^a	14.49 ± 0.09 ^a
2:1	4.25 ± 0.01 ^a	3.59 ± 0.66 ^c	10.89 ± 0.02 ^b	1.63 ± 0.63 ^d	40.68 ± 0.03 ^b	48.04 ± 0.96 ^b	2.12 ± 0.01 ^b	35.09 ± 2.35 ^b	24.65 ± 0.56 ^b	12.01 ± 0.77 ^b
1:1	3.61 ± 0.05 ^b	2.80 ± 1.16 ^d	10.14 ± 0.09 ^b	4.02 ± 0.12 ^c	40.77 ± 0.01 ^b	11.74 ± 1.00 ^c	0.66 ± 0.01 ^c	28.50 ± 2.84 ^d	21.96 ± 0.32 ^c	7.59 ± 1.29 ^c
1:2	1.80 ± 0.05 ^c	2.70 ± 1.48 ^d	8.78 ± 0.09 ^c	6.27 ± 1.64 ^b	25.61 ± 0.03 ^c	40.90 ± 0.28 ^c	-0.19 ± 0.01 ^d	39.38 ± 1.41 ^a	20.07 ± 0.40 ^c	8.42 ± 0.78 ^c
PO	0.34 ± 0.26 ^d	5.64 ± 0.98 ^a	6.60 ± 0.61 ^d	8.66 ± 0.11 ^a	20.38 ± 0.18 ^d	25.17 ± 1.07 ^d	-1.90 ± 0.01 ^e	38.00 ± 0.25 ^a	13.33 ± 0.19 ^d	6.88 ± 0.88 ^c

Results are expressed as mean values ± standard deviation of three replicates. Different letters in each column indicate significant difference ($p < 0.05$).**Fig. 4.** Crystal morphology of different oil models at 10 °C (scale bar: 25 μm).

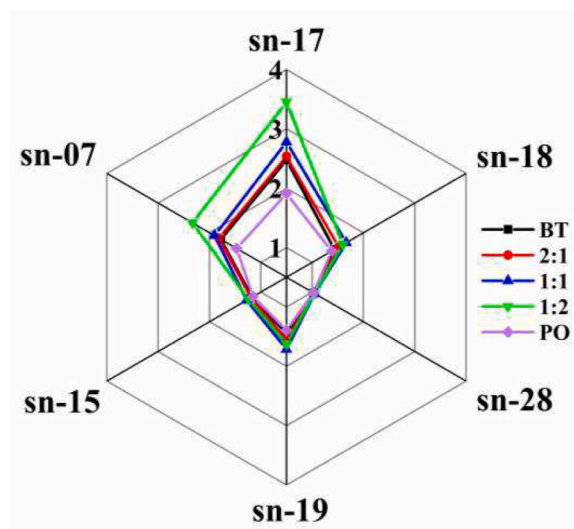
oil blend, the oil at the weight ratio of 2:1 partially overlapped on the y-axis and was closest to the distribution of beef tallow, indicating the typical similar characteristics to beef tallow (Yuan et al., 2023). However, the blending oil at 1:1 had positive and negative contributions to PC1 and PC2, respectively, which were located in the second quadrant of the plane. The oil at 1:2 had positive PC1 and PC2 values and was placed in the first quadrant of the plane, showing the distinctive behavior among all oils (Suri et al., 2020). Moreover, the oils at 1:1 and 1:2 were located on the right side of the biplot, indicating that the samples were positively correlated with the six sensors. The oil at 1:2 was positively correlated with sensors sn-07 and sn-17, while the oil at 1:1 was positively correlated with the other four sensors (Shao et al., 2023).

3.7. Volatile compounds identified by SPME/GC-MS

The volatiles were extracted from five hotpot oil samples by SPME and were identified by GC-MS. As shown in Fig. 6A, the identified volatiles in hotpot with beef tallow, blending oil at various weight ratios, and palm oil were grouped as alcohols, aldehydes, acids, esters, ketones,

hydrocarbons, and others. In total, 58 volatile compounds were identified and quantitated in hotpot oil with beef tallow, of which aldehydes and hydrocarbons were the main volatile compounds, accounting for 27.08 % and 48.03 % of the total volatiles, respectively. The volatile compounds with high concentration from the two classes were trans-2-decenal (103.20 μg kg⁻¹), 2,3-dihydro-1H-indene-4-formaldehyde (84.85 μg kg⁻¹), nonanal (47.61 μg kg⁻¹), (-)-isocaryophyllene (85.13 μg kg⁻¹), octamethyl cyclotetrasiloxane (75.14 μg kg⁻¹), and 2,2,4,4,6,6-hexamethylcyclotrisilazane (71.80 μg kg⁻¹) (Table 1S). A total of 39 volatile compounds were detected in hotpot with palm oil. The major compounds in the volatiles were alcohols, aldehydes, and hydrocarbons, among which linalool (64.83 μg kg⁻¹), (-)-4-terpenol (25.42 μg kg⁻¹), citral (29.75 μg kg⁻¹), trans-2-decenal (25.83 μg kg⁻¹), myrcene (101.70 μg kg⁻¹), (-)-isocaryophyllene (88.72 μg kg⁻¹), dodecamethylcyclohexasiloxane (93.30 μg kg⁻¹) had higher composition. Compared to palm oil, beef tallow showed the higher composition of aldehydes and the lower composition of ketones. These aldehydes had the odor descriptions like nutty, tallow, burning, and fruit (Song et al., 2014).

(A)



(B)

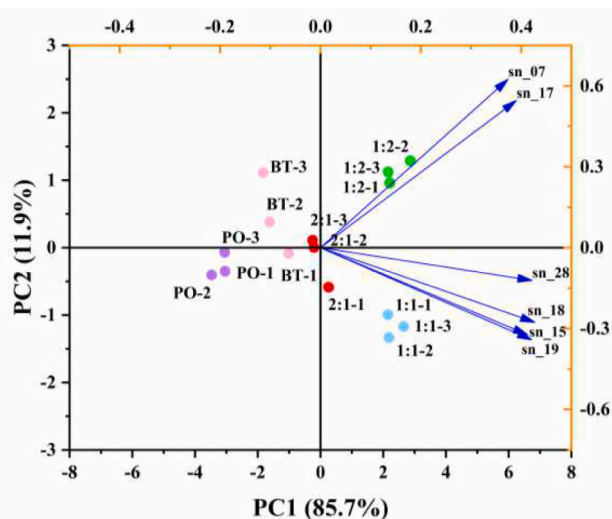
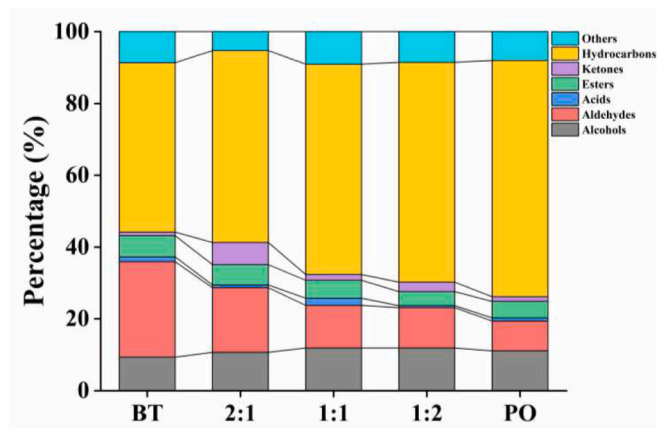


Fig. 5. (A) The radar chart and (B) PCA biplot of the electronic nose test for different oil models.

When the blending oils were used as hotpot oil, the alterations of five hotpot oils in the concentration and composition of volatile compounds were exhibited in a heat map. The oil samples from the five models were well distinguished by hierarchical cluster (Fig. 6B), and beef tallow and the blending oil at 2:1 were always grouped as closely, in agreement with those in the PCA (Dong et al., 2021). There were altogether 56 volatiles identified in the blending oil at 2:1, which mainly covered 5 alcohols, 12 aldehydes, 2 acids, 3 esters, 3 ketones, and 27 hydrocarbons. The main volatiles of the blending oil at 2:1 were similar to that of beef tallow, but the concentration of some volatile compounds such as nonanal ($41.74 \mu\text{g kg}^{-1}$), (-)-isocaryophyllene ($90.06 \mu\text{g kg}^{-1}$), and 2,2,4,4,6,6-hexamethylcyclotrisilazane ($59.58 \mu\text{g kg}^{-1}$) changed. In addition, some specific ketones like piperitone ($8.22 \mu\text{g kg}^{-1}$) and 2-hydroxy-4,6-dimethoxyacetophenone ($6.58 \mu\text{g kg}^{-1}$) only appeared in the blending oil, which might provide the aroma properties of mint and Chinese pepper to the flavor of hotpot seasoning (Zhang et al., 2024). That could be associated with the types and composition of numerous

(A)



(B)

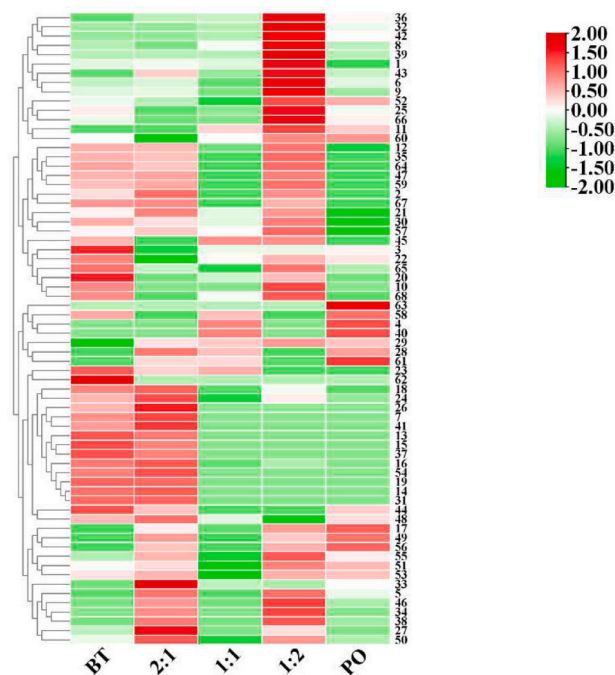


Fig. 6. (A) The proportion and (B) heat map of volatile flavor compounds in different oil samples. Red color represents a high content, and green color indicates a low content. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

volatiles in oil samples, which could participate in further thermal reactions as flavor precursors and produce a variety of volatile compounds that contributed to the flavor of overall sensory system (Song et al., 2017). As the weight ratio of palm oil to beef tallow was further increased, the types and related amount of flavor compounds in hotpot varied significantly among samples, in accordance with the result of *E*-nose measurement, indicating that oil models greatly influenced the flavor of hotpot oil, and the blending oil at 2:1 might be a potential replacer of neat beef tallow in Chongqing hotpot seasoning without reducing the flavor.

4. Conclusions

In this work, the impact of palm oil on the quality characteristics of Chongqing hotpot seasoning was investigated. The mixing of palm oil with beef tallow decreased the contents of cholesterol and saturated fatty acids in beef tallow, and increased the content of short-chain alkanes and hydrogen-containing compounds. The differences between the flavor of five oil models were completely distinguished by E-nose. The major volatile compounds in hotpot oil were hydrocarbons, followed by aldehydes, alcohols, esters, ketones, and acids. The concentration and composition of volatile compounds in hotpot seasoning significantly varied depending on the weight ratio of palm oil to beef tallow. The blending oil at 2:1 had similar melting and crystallization behaviors, hardness, crystal microstructure, as well as main volatiles to beef tallow compared with other oil models, which might be expected to develop as a resource for producing healthier and tastier Chongqing hotpot oil.

CRedit authorship contribution statement

Cen Zhang: Writing – review & editing, Writing – original draft, Methodology. **Wenjing Lu:** Formal analysis. **Di Chen:** Software. **Yuhao Zhang:** Formal analysis. **Jie Li:** Formal analysis. **Zhongjun Gou:** Formal analysis. **Chaogeng Xiao:** Validation, Supervision.

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.

Acknowledgements

This study was financially supported by the Key Research and Development Program of Zhejiang Province (Grant No. 2022C04033).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.fochx.2025.102371>.

Data availability

The authors do not have permission to share data.

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