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Formulation of a novel hot pot dipping sauce enriched with pepper seed press cake: Physical properties and flavor characteristics

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ABSTRACT

Novel hot pot dipping sauces enriched with pepper seed press cake (PSPC) in five proportions were prepared and evaluated in terms of their physical properties and flavor characteristics. The findings indicated that enriching the sauce increased the content of palmitic and linoleic acids, enhanced storage stability, and improved the rheological behavior and textural properties. The maximum concentration of N-heterocyclic compounds was detected when PSPC was added at 5 g/100 g and 10 g/100 g. A suitable amount of PSPC could improve the mouthfeel and intensify the flavors of umami and saltiness. In comparing sauces with different amounts of PSPC added (0–20 g/100 g), the quality, aroma, and taste were better and overall acceptance was highest when PSPC was added in the range of 5 g/100 g to 10 g/100 g. This study provides a possible application of PSPC for improving the flavor, texture, nutritional quality, and storage stability of hot pot dipping sauce.

1. Introduction

Hot pot has a long history in China and has evolved over time. As a traditional Chinese food, its taste, cultural background, social significance, and rich ingredients are all reasons for its popularity (Fig. 1). Dipping sauces are essential when people eat hot pot; they not only improve the flavor but also protect oral and gastrointestinal health. Sesame paste plays a pivotal role in hot pot dipping sauce. To enrich the flavor, people will also add auxiliary ingredients such as peppers.

Sesame (*Sesamum indicum* L.), an annual herbaceous plant belonging to the Pedaliaceae family, is mostly farmed in India, Sudan, China, and Myanmar (Jin, Zhao, et al., 2022; Tounsi et al., 2019). Its seeds are utilized, especially for the creation of pastes. Sesame paste, also called tahini, is made by grinding roasted sesame seeds into a paste. Sesame paste is a widely used condiment throughout Asia, particularly in China, due to its distinct flavor and abundant nutritional properties. It is used in both savory and sweet preparations, processed foods, and home cooking. In northern China, sesame paste is favored by consumers and occupies a major position in hot pot seasoning. With the improvement in living standards, people are becoming more discriminating in their tastes, and able to afford better quality products (Yilmaz, 2020; Zhou et al., 2023). At present, most people usually add auxiliary ingredients to sesame paste for flavoring before consumption. Several researchers have investigated methods for producing foods with sesame paste with specific features or better flavor. For example, a unique snack bar was developed using sesame paste and date syrup as ingredients (Baqeri et al., 2020); sesame paste was mixed with carob molasses to produce a promising nutritious and healthy food (Tounsi et al., 2019); α-linolenic acid concentration of sesame paste was raised by adding flaxseed (Hou et al., 2023).

Red pepper (*Capsicum annuum* L.) has been cultivated around the world for its nutrition and unique, spicy flavor; it is commonly eaten as a vegetable, used as medicine, or processed into a condiment (Gu et al., 2017). Pepper seeds, which make up 40–50 % of total pepper weight, are a by-product of pepper product manufacturing. Pepper seeds were reported to contain 13.0–19.0 % protein, 18–30 % oil, 40–65 % total dietary fiber, and a variety of minerals and vitamins, among other nutrients (Cvetkovic et al., 2022). Most of these seeds are discarded as waste because there are few known uses for them (Yilmaz et al., 2017). Utilizing this waste would be beneficial from an environmental point of view and efficient from an economic point of view. After thorough analyses, several academics have concluded that pepper seed oil is highly

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valuable (Cvetkovic et al., 2020; Zou et al., 2015). Pepper seed press cake (PSPC), a valuable by-product of the extraction of high-quality edible oil from pepper seeds, retains a wide range of nutrients from the raw material almost intact. It has been found that PSPC has good nutritional and functional properties, and it has great potential for application in food formulations with value-added possibilities and advantages (Cvetkovic et al., 2022; Yilmaz et al., 2017). However, to date, there have been few investigations into the use of PSPC in food products. This study was the first to explore the possibility of incorporating PSPC into hot pot dipping sauce.

This study developed novel hot pot dipping sauce formulations that were enriched with PSPC. With modern scientific analytical techniques, the flavor and quality of these sauces were evaluated objectively. This study aimed to select the optimal amount of PSPC to be added to produce new hot pot dipping sauces that are healthy, flavorful, and acceptable to consumers. The results of this study offer a means of not only improving hot pot dipping sauces in terms of taste, texture, storage stability, and nutrition but also of utilizing a by-product (PSPC), thereby providing a practical way to reduce waste.

2. Materials and methods

2.1. Materials

Pepper seeds were purchased from Weifang Huahe Foods Co. (Shandong, China). In our laboratory, as described in a previous paper (Zhang et al., 2019), the pepper seeds were roasted at 170 °C and then pressed using a hydraulic oil press (270B, Luoyang Luofeng Hydraulic Technology Co., China). The cake remaining after oil extraction (pepper seed press cake, PSPC) was used for this study. The PSPC contained 0.03 g/100 g water, 18.70 g/100 g protein, 12.38 g/100 g fat, and 4.43 g/100 g ash. The sesame seeds (cultivar: ZhuZhi-22) came from the Henan Academy of Agricultural Sciences, Henan Province, China. They contained 1.65 g/100 g water, 24.37 g/100 g protein, and 50.51 g/100 g fat. Fresh seeds were kept refrigerated at 4 °C until analysis.

2.2. Processing of sauces

The roasted PSPC was crushed with a crusher (800C, Red Sun Electromechanical Co., China) and passed through a metal sieve (60 mesh). The sesame seeds (500 g) were roasted (170 °C for 40 min) using an electric skillet with an automatic stirrer and then cooled to room temperature. The PSPC and roasted sesame seeds were thoroughly combined in the following ratios: 5 g/100 g, 10 g/100 g, 15 g/100 g, and 20

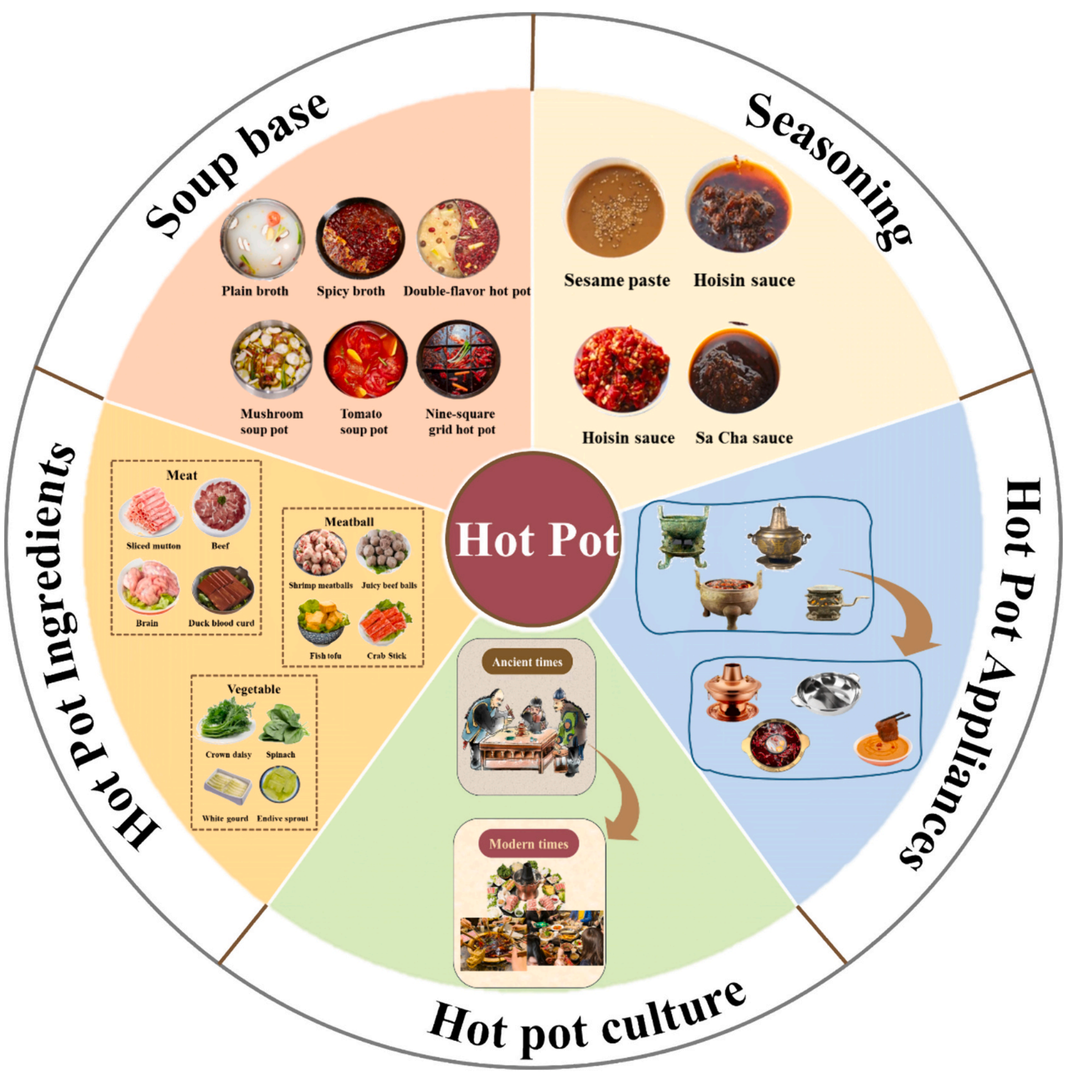

Fig. 1. Introduction to hot pot.

g/100 g. Each mixture was then processed in a colloid mill (JM-L80, Longxin, China) into a sauce. The sesame seeds were milled alone as a control group. The five samples were named SP (for sesame seeds alone) and SP5, SP10, SP15, and SP20, according to the amount of PSPC per 100 g sesame seeds. All samples were analyzed immediately after preparation.

2.3. Physicochemical properties

2.3.1. Proximate composition

The moisture content of the samples was determined by drying them in an oven (105 °C, 4 h). The fat content of samples was determined by the Soxhlet technique and was extracted with petroleum ether. The protein content of five paste samples was determined with the Kjeldahl method (Chang et al., 2024).

2.3.2. Fatty acid composition

The fatty acid of the paste samples was measured using a gas chromatograph (GC, Agilent 7890B, America) (Zhang et al., 2024). Methylation was carried out using a boron trifluoride-methanol solution. The chromatographic column was an HP88 column (100 m × 0.25 mm × 0.2 μm). The temperatures of the GC inlet and FID detector were 240 °C and 280 °C, respectively. Column conditions: The GC was first heated from 170 °C to 220 °C (4 °C/min) and then to 240 °C (1 °C/min). The carrier gas was helium (99.99 % purity, 1 mL/min). The identification of these fatty acid compositions and relative content (%) were identified by comparing fatty acid methyl ester standard compounds and peak area normalization methods, respectively.

2.3.3. Amino acid

The method described by Jin, Guo, et al. (2022) was used for the amino acid composition. Briefly, each sample (30 mg) was hydrolyzed using 6 mol/L hydrochloric acids (110 °C, 22 h). Then the cooled and filtered hydrolyze were dried in a tube concentrator at 45 °C and dissolved in 1 mL citrate buffer (pH 2.2). Finally, it was measured by an Amino Acid Auto-Analyzer (S—433D, Sykam, Germany).

2.3.4. Accelerated oxidation experiment of sauces

The accelerated oxidation experiments of the sauces were determined with reference to the method of Zhang et al. (2023). 15 g of sauce samples were weighed, respectively, packed into bottles, and subjected to an accelerated oxidation experiment in an oven (63 °C, 30 d).

The oil was extracted from the samples using hexane and then concentrated using a rotary evaporator. The extracted oil was analyzed immediately. The acid value (AV) and peroxide value (POV) were determined with reference to the method of Yang et al. (2024). The oxidation stability index (OSI) of the samples (3 g) was measured at 110 °C using Rancimat 734 equipment (Metrohm, Herisau, Switzerland). The airflow rate was 20 L/h (Zhang et al., 2021).

2.4. Particle size distribution

Particle size analyses of samples were carried out using the method described by Jin, Guo, et al. (2022) and determined by using a particle size analyzer (3000, Mastersizer, England). In short, 1 g of the sample was combined with water and then transferred to the dispersion circulation tank of the instrument for measurement.

2.5. Colloidal stability and oil separation height

Referring to the method of Hou et al. (2020), in brief, each centrifuge tube was filled with samples (20 *g*) and centrifuged (4000 rpm/min,10 min) (Mod 3-5 N, Hunan Hengnuo Instrument Equipment Co., China). The supernatant—the top layer, comprising oil—was removed and weighed. The oil separation rate was the percentage of separated oil, compared to the total weight of the sample.

The samples were pipetted into 25 mL tubes and stored at room temperature (25 °C). The height of the separated oil was measured and photographed at storage times of 0, 40, 80, and 120 days.

2.6. Rheological behavior

The rheological behavior of samples was assessed using a rheometer (MARS40, Thermo Fisher, USA). The samples were stirred well before the experiments; all rheological measurements were performed at 25 °C.

Shear stress and apparent viscosity were measured within the shear rate range from 0.1 s^{-1} to 100 s^{-1}.

Storage and loss moduli were recorded between 0.1 Hz to 10 Hz.

Flow behavior was described as follows:

$$\tau = K\dot{\gamma}^{n} \quad (1)$$

where τ is the shear stress (Pa), K is the consistency coefficient (Pa·s^n), $\dot{\gamma}$ is the shear rate (s^{-1}), and n is the flow behavior index.

2.7. Texture measurements

The textural parameters of the samples were evaluated using a TA-XT2 Plus texture analyzer (Stable Micro System, Godalming, UK). The textural characteristics were measured using a P25 probe. Measurement parameters: pre-test, mid-test, and post-test speeds were 1 mm/s; pressure was 5 g; downward distance was 10 mm.

2.8. Volatile compound extraction by HS-SPME

2.8.1. Volatile compound extraction by HS-SPME

Headspace solid-phase microextraction (HS-SPME) was optimized as described by Yin et al. (2022). 2 g of each sauce sample and 30 μL of 1 mg/mL 4-nonanol (internal standard) were loaded in headspace vials and closed with Teflon septums. The samples were equilibrated in a 70 °C water bath with shaking (1000 rpm) for 40 min. Volatile compounds were extracted in the headspace of the samples (30 min) using a divinylbenzene/carboxen/polydimethylsiloxane (DVB/CAR/PDMS) fiber (film thickness: 50/30 μm, length: 1 cm) (Sigma-Aldrich, Shanghai, China). After extraction, fibers were immediately inserted into the GC inlet (250 °C) and desorbed for 5 min.

2.8.2. Gas chromatography-mass spectrometry (GC–MS) analysis

The collected volatile compounds in sauces were analyzed using a 7890B GC–MS system (Agilent Technologies, USA). The chromatographic column was HP-5MS (30 m × 0.25 mm × 0.25 μm) and the capillary columns were VF-WAXms (30 m × 0.25 mm × 0.25 μm). The initial temperature of the GC oven was 40 °C (held for 5 min), ramping up to 130 °C (held for 5 min) at a rate of 3 °C/min, and then to 250 °C (held for 5 min) at a rate of 10 °C/min. The temperature of the GC injection port, ion source, interface, and quadrupole were set at 250 °C, 230 °C, 280 °C and 150 °C, respectively. Ionization energy was set to 70 eV, and the scanning speed and range were 2.0 scan/s and 33–400 *m/z*, respectively.

2.8.3. Identification and quantification of volatile compounds

Volatile compounds were initially determined by comparing their mass spectra with those in the NIST 17 library (≥80 % match) with reference to the method of Gao et al. (2022). The n-alkanes (C7-C40) were run under the same GC–MS conditions to obtain the RI (linear retention index) of volatile compounds. Relative concentrations of volatile compounds were determined using the internal standard method as reported by Yin et al. (2021).

2.9. E-nose analysis

Samples (2 *g*) were transferred into centrifuge tubes (50 mL), sealed with parafilm, and left at room temperature for 30 min. Then samples were injected by direct headspace aspiration and analyzed using PEN 3 E-nose (Win Muster Airsense Analytics Inc., Schwerin, Germany). Detection parameters: sampling time, 1 s/group; sensor cleaning time, 100 s; sample preparation time, 5 s; injection flow rate, 400 mL/min; sample analysis time, 100 s. Ten sensors (W1C, W5S, W3C, W6S, W5C, W1S, W1W, W2S, W2W, W3S) (Table S1) automatically recorded the response points of the E-nose, and the data of the maximum response values were selected for analysis.

2.10. E-tongue analysis and sensory evaluation

E-tongue analysis of the samples was performed using the approach of Yu et al. (2022). The sample (20 g) was mixed with water (100 mL) to extract flavor substances. It was subsequently centrifuged, filtered, and the aqueous phase obtained was measured with the E-tongue (SA402B, Insent Company, Japan) detection.

For human sensory evaluation, twelve panelists (6 males and 6 females, aged 20–29 years) from the Henan University of Technology were selected. Each had at least two years of experience in sensory evaluation of food products. Samples (20 g) were randomly numbered and placed in brown glass bottles with lids. Panelists were asked to rate their overall acceptance (texture and aroma) and spiciness of each sample on a 10-point scale, with 0 representing unsatisfactory and 10 representing highly preferred.

2.11. Statistical analysis

SPSS 26.0 software (SPSS Inc., Chicago, USA) was used to analyze the data, and the mean ± standard deviation was the output. To ascertain group differences, Duncan's multiple range tests were employed, with P values <0.05 being significant. Each set of data was gathered in triplicate.

3. Results and discussion

3.1. Component analyses of the sauces

Table 1 displays the composition of the five sauce samples. All of the samples had moisture contents of less than 1 g/100 g, which is within China's national guideline for the manufacturing of sesame paste. Currently, low-fat food is in line with the current trend, and the addition of PSPC decreased the fat level in the sauces (Yilmaz, 2020). Protein is categorized as one of the three major nutrients in the human diet and is a very important part of daily dietary intake. SP had a protein level of 44.58 g/100 g; however, adding PSPC caused the protein content of the sauce samples to decrease. This is because PSPC has less protein (18.70 g/100 g) than sesame seeds (24.37 g/100 g). In the five sauce samples, eight different fatty acids were identified (Table 1). The two main fatty acids were oleic acid (37.96–39.61 g/100 g) and linoleic acid (44.32–45.94 g/100 g). The addition of PSPC significantly affected the fatty acid composition and content of sauces, in particular gradually raising the levels of palmitic and linoleic acids. Available published studies have found that pepper seeds contain high levels of linoleic acid, which is essential in the diet to prevent conditions such as atherosclerosis, high blood pressure, and high cholesterol (Cvetkovic et al., 2020). As the end product of protein hydrolysis, the types and contents of amino acids are important indicators of the nutritional value of food. After acid hydrolysis, a total of 17 different amino acids were detected in the five samples, with asparagine, glutamine, and arginine being the most prevalent (Table 1). The total amino acid content of SP was 39.76 g/100 g; however, adding PSPC caused the amino acid content of the sauce samples to decrease. This was because the protein content of PSPC was lower than that of sesame, which affected the overall amino acid richness. Notably, there was no significant difference in the amino acid content between SP and SP5 ($P > 0.05$). Therefore, in order to ensure that the nutritional value of the food is not lost, we should consider carefully when adding PSPC to ensure a reasonable ratio to maintain the balance and adequacy of amino acids in the food.

Table 1
Physicochemical properties of the five sauce samples.

Parameters		Samples*				
		SP	SP5	SP10	SP15	SP20
Moisture (g/100 g)		0.95 ± 0.01^{a}	0.95 ± 0.02^{a}	0.95 ± 0.00^{a}	0.96 ± 0.01^{a}	0.98 ± 0.01^{a}
Oil (g/100 g)		58.91 ± 0.01^{a}	55.12 ± 0.00^{b}	52.57 ± 0.00^{c}	50.30 ± 0.00^{d}	48.03 ± 0.00^{e}
Protein (g/100 g)		44.58 ± 0.12^{a}	44.02 ± 0.12^{ab}	43.43 ± 0.22^{b}	41.90 ± 0.44^{c}	39.51 ± 0.31^{d}
Fatty acid (%)	C16:0	8.96 ± 0.01^{d}	8.97 ± 0.00^{d}	9.00 ± 0.01^{c}	9.04 ± 0.02^{b}	9.08 ± 0.01^{a}
	C16:1	0.11 ± 0.00^{c}	0.11 ± 0.00^{c}	0.11 ± 0.00^{b}	0.11 ± 0.00^{b}	0.12 ± 0.00^{a}
	C18:0	5.38 ± 0.02^{a}	5.32 ± 0.01^{b}	5.28 ± 0.00^{c}	5.24 ± 0.02^{d}	5.21 ± 0.01^{e}
	C18:1	39.61 ± 0.07^{a}	39.21 ± 0.00^{b}	38.74 ± 0.01^{c}	38.34 ± 0.06^{d}	37.96 ± 0.01^{e}
	C18:2	44.32 ± 0.05^{e}	44.65 ± 0.02^{d}	45.12 ± 0.05^{c}	45.55 ± 0.01^{b}	45.94 ± 0.01^{a}
	C20:0	0.59 ± 0.00^{b}	0.61 ± 0.01^{a}	0.58 ± 0.00^{c}	0.58 ± 0.00^{cd}	0.57 ± 0.00^{d}
	C20:1	0.32 ± 0.00^{b}	0.33 ± 0.00^{a}	0.33 ± 0.00^{a}	0.32 ± 0.00^{b}	0.31 ± 0.00^{c}
	C21:0	0.21 ± 0.00^{a}	0.20 ± 0.00^{bc}	0.20 ± 0.00^{bc}	0.20 ± 0.00^{b}	0.20 ± 0.00^{c}
Amino acid (g/100 g)	Asparagine	3.42 ± 0.08^{a}	3.41 ± 0.10^{a}	3.33 ± 0.04^{a}	3.30 ± 0.01^{a}	3.00 ± 0.14^{b}
	Threonine	1.51 ± 0.01^{a}	1.47 ± 0.01^{ab}	1.45 ± 0.02^{ab}	1.41 ± 0.01^{b}	1.31 ± 0.06^{c}
	Serine	1.99 ± 0.01^{a}	1.96 ± 0.01^{a}	1.92 ± 0.02^{a}	1.88 ± 0.04^{a}	1.69 ± 0.10^{b}
	Glutamine	8.85 ± 0.01^{a}	8.64 ± 0.01^{ab}	8.56 ± 0.05^{b}	8.24 ± 0.08^{c}	7.36 ± 0.20^{d}
	Glycine	2.00 ± 0.01^{a}	1.97 ± 0.01^{a}	1.91 ± 0.01^{b}	1.83 ± 0.01^{c}	1.62 ± 0.02^{d}
	Alanine	1.99 ± 0.01^{a}	1.97 ± 0.02^{a}	1.89 ± 0.01^{b}	1.79 ± 0.02^{c}	1.58 ± 0.04^{d}
	Cystine	0.09 ± 0.00^{a}	0.08 ± 0.01^{ab}	0.07 ± 0.01^{ab}	0.07 ± 0.01^{ab}	0.05 ± 0.01^{b}
	Valine	1.92 ± 0.04^{a}	1.83 ± 0.01^{b}	1.79 ± 0.01^{b}	1.71 ± 0.02^{c}	1.60 ± 0.05^{d}
	Methionine	1.08 ± 0.04^{a}	1.01 ± 0.01^{ab}	1.00 ± 0.01^{b}	0.96 ± 0.01^{b}	0.84 ± 0.05^{c}
	Isoleucine	1.62 ± 0.02^{a}	1.55 ± 0.03^{ab}	1.51 ± 0.02^{b}	1.36 ± 0.01^{c}	1.25 ± 0.05^{d}
	Leucine	2.96 ± 0.01^{a}	2.92 ± 0.02^{ab}	2.86 ± 0.06^{ab}	2.72 ± 0.04^{b}	2.44 ± 0.16^{c}
	Tyrosine	1.60 ± 0.08^{a}	1.49 ± 0.01^{ab}	1.44 ± 0.04^{b}	1.44 ± 0.01^{b}	1.22 ± 0.04^{c}
	Phenylalanine	1.95 ± 0.01^{a}	1.91 ± 0.02^{a}	1.84 ± 0.01^{a}	1.82 ± 0.01^{a}	1.63 ± 0.11^{b}
	Histidine	1.41 ± 0.01^{a}	1.36 ± 0.02^{ab}	1.34 ± 0.03^{b}	1.32 ± 0.01^{b}	1.18 ± 0.03^{c}
	Lysine	1.04 ± 0.02^{a}	0.96 ± 0.03^{ab}	1.04 ± 0.01^{ab}	1.07 ± 0.03^{bc}	1.01 ± 0.01^{c}
	Arginine	4.99 ± 0.01^{a}	4.95 ± 0.01^{a}	4.76 ± 0.06^{ab}	4.59 ± 0.08^{b}	4.07 ± 0.19^{c}
	Proline	1.59 ± 0.01^{a}	1.49 ± 0.02^{b}	1.43 ± 0.03^{bc}	1.37 ± 0.03^{c}	1.26 ± 0.06^{d}
	Total	39.98 ± 0.31^{a}	38.93 ± 0.12^{ab}	38.10 ± 0.33^{bc}	36.85 ± 0.21^{c}	33.06 ± 1.33^{d}

* SP, SP5, SP10, SP15, and SP20 represent the sauce samples with 0 g/100 g, 5 g/100 g, 10 g/100 g, 15 g/100 g, and 20 g/100 g of pepper seed press cake, respectively. Data are expressed as mean ± standard deviation (SD). $^{a–e}$ superscript indicates significant ($P < 0.05$) differences among the different samples.

3.2. Accelerated oxidation experiment

AV represents the amount of free fatty acids in lipids and can reflect the lipid quality of sauces. It can be seen from Fig. S1a that the AV of different samples increased with the addition of PSPC at the same storage time. The AV of SP20 was significantly higher than that of other samples, which could be attributed to the increase of polyunsaturated fatty acids with the increase of PSPC. Meanwhile, the milling time of the samples was prolonged with the increase in PSPC, which enhanced the degree of rancidity in the oils (Hou et al., 2023). POV is a measure of the content of primary oxidation products (e.g. hydroperoxides) in oils. However, hydroperoxides are not stable during the oxidation of oils, and they are further decomposed into secondary oxidation products, such as aldehydes and ketones (Zhang et al., 2023). As can be seen from Fig. S1b, the POV of different samples decreased with the addition of PSPC at the same storage time. This may be due to the fact that the addition of PSPC introduced certain antioxidant components that stabilize hydroperoxides and reduce their decomposition. Oxidative stability index (OSI), which reflects oil storage stability. As shown in Fig. S1c, the OSI of different samples increased with the addition of PSPC at the same storage time, which indicated that PSPC improved the oxidative stability of the samples. This may be attributed to the antioxidant components (e.g., total phenolic, vitamin E) in PSPC, which may limit the chain reactions of lipid oxidation and delay the oxidation of oils (Zhang et al., 2023).

3.3. Particle size distribution

The stability of a sauce system is correlated with particle size. The particles of these sauces were evenly distributed but not uniform in size. Fig. 2a displays the distribution of particle sizes in the several samples. All the samples showed a multimodal distribution, which is the same as the results of Jin, Zhao, et al. (2022). The sauces had an average particle size that varied between 0.10 and 454.00 μm, and particles of size <100.00 μm constituted the major portion. As shown in Fig. 2b, the addition of PSPC to the sauces resulted in increases in D10, D50, and D90 from 6.67, 23.80, and 109.00 μm to 7.07, 39.21, and 253.00 μm, respectively. However, there was no significant difference between the D10's of the five samples ($P > 0.05$). This may be because different base fractions of sesame and PSPC had different effects on the hardness, brittleness, and reticulation of the seeds (Cai et al., 2023). Sesame seeds have high oil content, and sesame oil forms a film on the surface of the sauce during the milling process. This oil has a lubricating effect and promotes flow so that the milling of the sauce is more complete. With the increase of the PSPC, the overall oil content of the sauce decreased, the interaction between solid particles was enhanced, and the grinding was incomplete (De Graef et al., 2011). In a sauce, particle size directly impacts quality. Smaller particles can lead to particle adhesion and significant oil separation. Larger particles are generally associated with less desirable taste and shorter shelf life. Therefore, particle size is of great significance in producing sauces.

3.4. Colloidal stability and oil separation height

When the sauce is a multiphase system consisting of hydrophilic solids suspended in an oil phase, during storage, oil is naturally released and freed to the upper part of the sauce, where it forms a layer. Solid particles of greater density sink. The separation of oil and solids in sauce adversely affects its quality. Therefore, the degree of separation of a multiphase sauce is an essential index of its quality.

Fig. 3a shows the colloidal stability of the five samples. The separation rate gradually decreased with the addition of PSPC. 17.95 g/100 g was the greatest separation rate (SP), while 7.04 g/100 g was the lowest (SP20).

Fig. 3b and Table S2 show the change in oil separation height during storage for the five samples. As storage time increased, small particles aggregated into large particles that sank, which caused the oil to rise, increasing the separation height of the oil. At 120 days of storage, the oil separation heights of SP, SP5, SP10, SP15, and SP20 were 6.0 mm, 5.1 mm, 4.5 mm, 3.8 mm, and 1.6 mm, respectively. The oil separation height gradually decreased with the increase of PSPC, which was in agreement with the conclusion obtained from the measurement of centrifugal oil-solid separation rate. This result may be correlated with the particle size of the samples in that the greater the particle size of the sauce, the lower the oil separation height. Therefore, the appropriate average particle size and distribution are the key indexes to ensure suspension stability, and the addition of PSPC can effectively improve the oil-sauce separation problem of traditional sesame paste.

3.5. Rheological behavior

3.5.1. Static rheological properties

Rheological analysis of sauce, a semi-solid food product, can provide critical information for quality control, process optimization, product

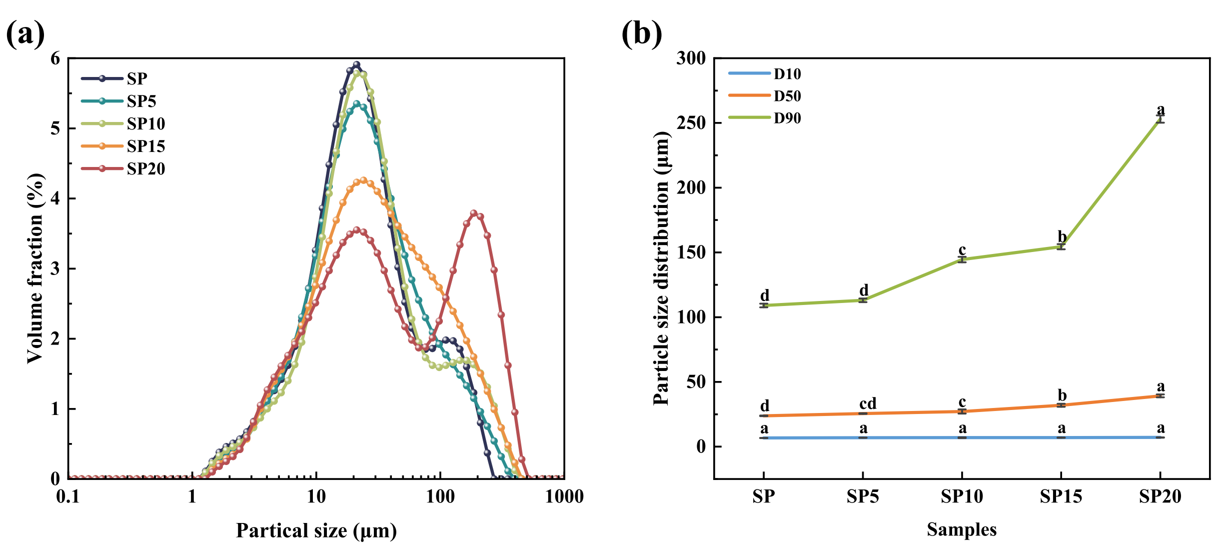

Fig. 2. Particle size distribution of the five sauce samples. (D10 represents the size for which the volume of particles smaller than this size is 10 % of all particles; D50 represents the size for which 50 % of particles exceed this value; and D90 represents the size for which the volume of particles smaller than this size is 90 % of all particles; $^{a–d}$ superscript indicates significant ($P < 0.05$) differences among the different samples).

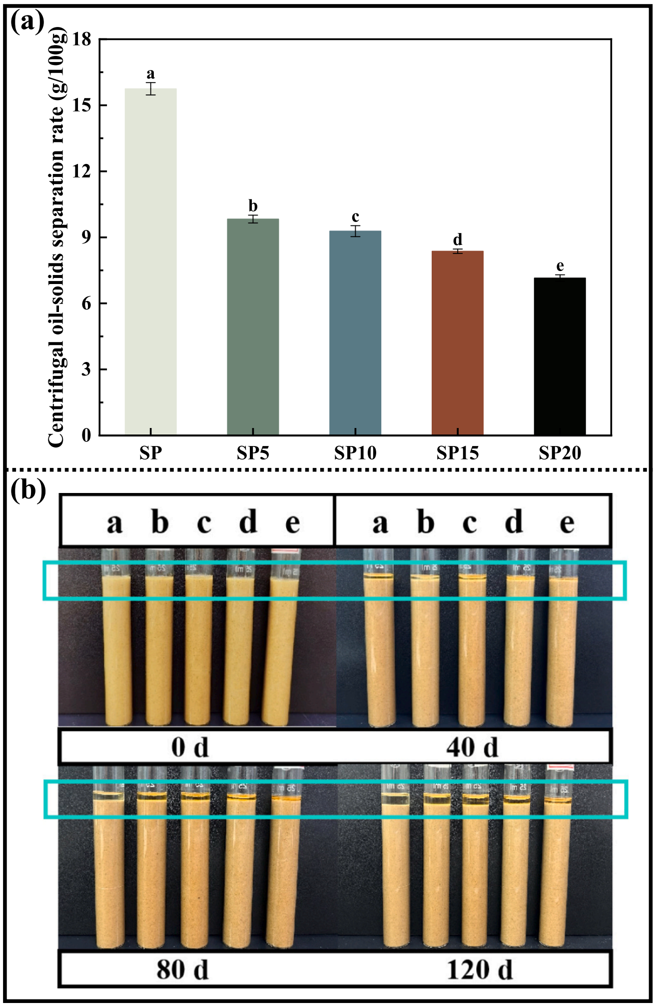

Fig. 3. Colloidal stability (g/100 g) (a) and storage experiments (b). (a, b, c, d, and e represent the compound sauce samples with 0 g/100 g, 5 g/100 g, 10 g/100 g, 15 g/100 g, and 20 g/100 g of PSPC, respectively. [a–e] superscript indicates significant ($P < 0.05$) differences among the different samples).

development, and shelf-life assessment. In summary, this information can help food manufacturers provide better products and meet consumer needs and expectations (Koehler et al., 2024).

As shown in Fig. 4a, the shear stress of the five samples increased nonlinearly with increasing shear rate. This shows that all the samples behaved as non-Newtonian fluids. SP and SP20 showed the minimum and maximum shear stresses, respectively, at the same shear rate. It can be hypothesized that the intermolecular forces were weak for SP and that the addition of PSPC increased molecular interactions, hence the sauce with the greatest amount of PSPC (SP20) showed the maximum shear stress (Jin, Guo, et al., 2022).

Shear thinning occurred for all five samples, as demonstrated by Fig. 4b, where the apparent viscosity dropped constantly over the shear rate range of 0.1–100 s^{-1}. When the shear rate was certain, the more PSPC present, the greater the viscosity. This may be because the addition of PSPC decreased the relative fat content. This means the solid particles were closer together, which led to an increase in the viscosity of the sauce (De Graef et al., 2011).

K, n, and R^2 were obtained by power-law modeling to compare the flow behavior of the five sauces. The results are shown in Fig. 4e. R^2 ranged from 0.9939 to 0.9985, indicating that all samples showed a good fit. There was no obvious variation between the n values of the five samples. The K value is a crucial criterion for measuring the flow characteristics of food products. The lower the K value the better the flow of the sample. The K value of the SP samples was very low; it gradually increased with the addition of PSPC. These figures indicate that SP was the thinnest while SP20 was the stickiest. All samples had clear pseudoplastic fluid features and non-Newtonian mechanical properties. In summary, the amount of PSPC added had a significant, linear effect on the flow behavior of sauces. The sauce remained a non-Newtonian fluid after the addition of PSPC, but the rheological properties were more stable. This means that the amount of PSPC added can be adjusted to produce food products with flow characteristics that consumers prefer.

3.5.2. *Viscoelastic behavior*

The elastic modulus G' and the viscous modulus G'' are important parameters for predicting processing performance and evaluating product quality. $G'' \geq G'$, indicates that the sample has a liquid-like behavior. $G'' \leq G'$ indicates that the sample has the properties of a viscoelastic solid. Fig. 4c and d present the viscoelastic behavior (G', G'') of five sauces. G' and G'' ranged from 377.00 Pa to 2953.00 Pa, and 134.00 Pa to 1525.00 Pa, respectively. For every sauce sample, it was found that G' was higher than G'', indicating that the samples exhibited stronger elastic properties over the measured temperature range. The G' and G'' measurements of SP were the lowest and gradually increased with the addition of PSPC to the other samples. This result may be associated with the particle size and internal interactions within the sauce (Yang et al., 2024). Particle size and distribution in sauces directly affected their viscoelastic behavior. The addition of PSPC altered the particle size distribution in the sauces, which enhanced the inter-particle interactions and increased the intermolecular entanglement force, causing the sauces to exhibit stronger elastic properties.

3.6. *Texture profile analysis*

Food texture is the sensory embodiment, or expression, of the material and structural properties of food. Texture directly affects the oral behavior, flavor release, and sensory pleasure of food, and is an important factor influencing consumer preference and acceptability of food (Baqeri et al., 2020). The textural properties of the novel sauce were assessed, including hardness, adhesiveness, gumminess, chewiness, resilience, and cohesion (Table 2). In particular, the hardness of the sauce reflects the solid nature of the food and its ability to resist compression; it affects how easily a food can be chewed and how readily enzymes can produce flavor from it. Adhesiveness is a measure of the stickiness of the food; levels that are either too high or too low negatively affect quality in terms of consumer preferences. Resilience refers to the capacity of food to resume its prior form and structure after being chewed or bitten. Gumminess describes the consistency and fluidity of a food. Chewiness reflects the amount of energy required to chew a solid sample into a form that can be swallowed; it is determined by elements such as hardness and viscosity. Cohesion refers to the maintenance, of the internal structure of food during chewing. In this study, the hardness, adhesiveness, gumminess, and chewiness of the sauce samples rose considerably with the addition of PSPC. The resilience of the samples fell dramatically (8.06 to 1.31), and the cohesion of the five samples did not change greatly. There are two possible reasons why adding PSPC altered the texture of SP. Firstly, this may be due to elevated levels of macromolecules such as fibers, which enhanced intermolecular forces (Baqeri et al., 2020). Secondly, milling caused the cells to release oil, which formed a film of oil on the surface of the solid particles and changed the stickiness of the sauces, thus affecting their textural properties (Hanim et al., 2016). The findings from the rheological measurement and the textural analysis agreed with each other. The data from the sensory evaluation (Fig. 6c) indicated that sample SP5 was the most favored.

3.7. *Comparison of volatile components*

Flavor has direct and crucial impacts on consumer preference and

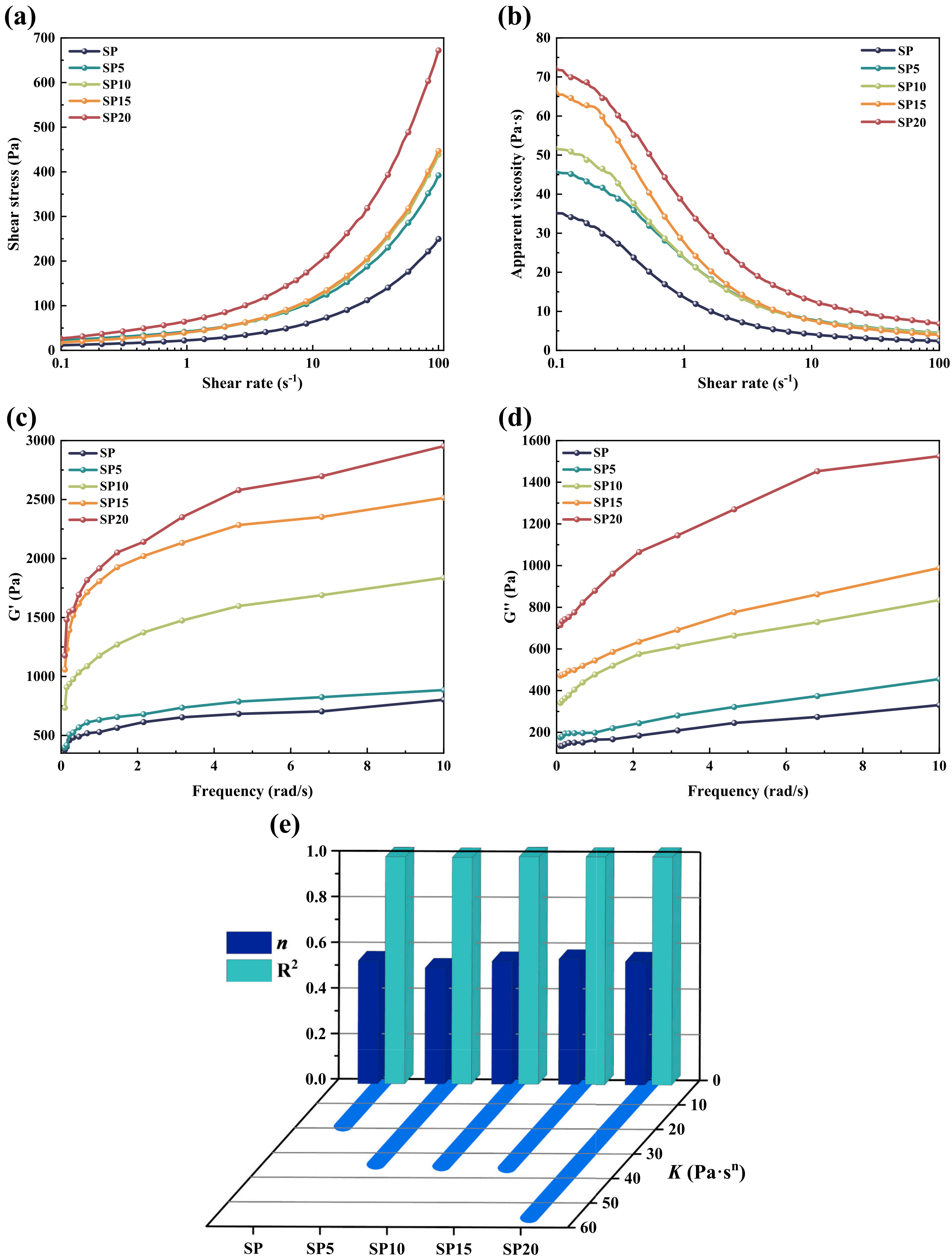

Fig. 4. Rheological properties of the five sauce samples. G' indicates storage moduli (Pa); G'' indicates loss moduli (Pa); K indicates the consistency coefficient ($Pa\cdot s^n$); n indicates the flow behavior index; and R^2 indicates correlation coefficient.

Table 2
Textural properties of the sauce samples.

Parameters	Samples*				
	SP	SP5	SP10	SP15	SP20
Hardness (g)	22.80 ± 0.38^{d}	26.45 ± 3.05^{cd}	28.60 ± 0.76^{bc}	30.68 ± 0.11^{b}	43.02 ± 0.37^{a}
Adhesiveness (g.*sec*)	29.03 ± 3.20^{d}	42.42 ± 5.11^{c}	50.96 ± 4.74^{c}	75.39 ± 0.11^{b}	130.91 ± 1.12^{a}
Resilience (%)	8.06 ± 0.66^{a}	4.76 ± 0.28^{b}	4.42 ± 0.76^{b}	2.60 ± 0.01^{c}	1.31 ± 0.02^{d}
Gumminess	16.61 ± 0.09^{d}	20.32 ± 0.09^{c}	21.76 ± 1.65^{bc}	22.55 ± 0.74^{b}	29.54 ± 0.20^{a}
Chewiness	15.50 ± 0.01^{c}	17.98 ± 0.18^{bc}	19.41 ± 0.75^{b}	20.76 ± 2.11^{b}	27.50 ± 0.80^{a}
Cohesion	0.73 ± 0.01^{a}	0.78 ± 0.09^{a}	0.76 ± 0.04^{a}	0.74 ± 0.02^{a}	0.69 ± 0.01^{a}

* SP, SP5, SP10, SP15, and SP20 represent the sauce samples with 0 g/100 g, 5 g/100 g, 10 g/100 g, 15 g/100 g, and 20 g/100 g of pepper seed press cake, respectively. Data are expressed as mean ± standard deviation (SD). $^{a–d}$ superscript indicates significant ($P < 0.05$) differences among the different samples.

satisfaction. The flavor of the sauce is the result of the joint action of many volatile compounds, which is directly correlated with the type and concentration of these compounds. To determine which volatile components were present in the sauces, the volatile components were examined by HS-SPME-GC–MS. 84 volatile compounds were identified (Table S3) and categorized into N-heterocyclic, O-heterocyclic, S-heterocyclic, and nonheterocyclic compounds. As listed in Fig. 5b, the volatile compound compositions of SP5 and SP10 were relatively close to each other, and those of SP15 and SP20 were relatively close to each other. The main substances determine the main flavor of the samples. This provides a research direction for optimizing the flavor of new hot pot dipping sauces.

3.7.1. N-heterocyclic compounds

As shown in Table S3, N-heterocyclic compounds detected in the five sauce samples included 18 pyrazines, 10 pyrroles, 4 pyridines, and 3 azoles. Among them, pyrazines contributed the most compared to other compounds; pyrazines give foods roasted, nutty aromas, and are considered desirable. During heat treatment, they are formed by the Maillard reaction of oxygenated heterocyclic compounds (amino acids, proteins, etc.) with sugars (Wang et al., 2024). Table S3 showed the pyrazine compounds in the five samples; they were 2-methylpyrazine, 2,5-dimethylpyrazine, 2,6-dimethylpyrazine, 2,3,5-trimethylpyrazine, 3-ethyl-2,5-dimethylpyrazine, 2,3-dimethyl-5-ethylpyrazine, and 2,3,5,6-tetramethylpyrazine. These volatile compounds have been reported in foods that have been heated, including sunflower oil (Yin et al., 2022), sesame oil (Yin et al., 2021), and red pepper seed oil (Zhang et al., 2019). The total concentration of pyrazine compounds reached the maximum in SP10 and SP5, followed by SP. Between SP5 and SP10, there was no discernible difference ($P > 0.05$) in the overall concentration of pyrazines. The results showed that the addition of PSPC was able to increase the concentration of N-heterocyclic compounds and enhance the roasted and nutty aromas of the sauces.

The sauce samples included several other N-heterocyclic compounds, including pyrrole, pyridine, and azole compounds. These compounds have been shown to be products of the Maillard reaction in the amino acid-sugar model system, and they impart a roasted and smoky aroma (Li et al., 2023). It is not clear, however, whether these compounds are major aroma components. Of the five sauces, the concentration of pyrrole and pyridine compounds was largest in SP5, whereas the concentration of azole compounds was greatest in SP10. The overall concentration of N-heterocyclic compounds exhibited a trend of increase followed by a decrease, as shown in Fig. 5a. This may be because the mixing of substances changes the partition coefficients of the volatile compounds, thus showing different interaction effects (Liu et al., 2024).

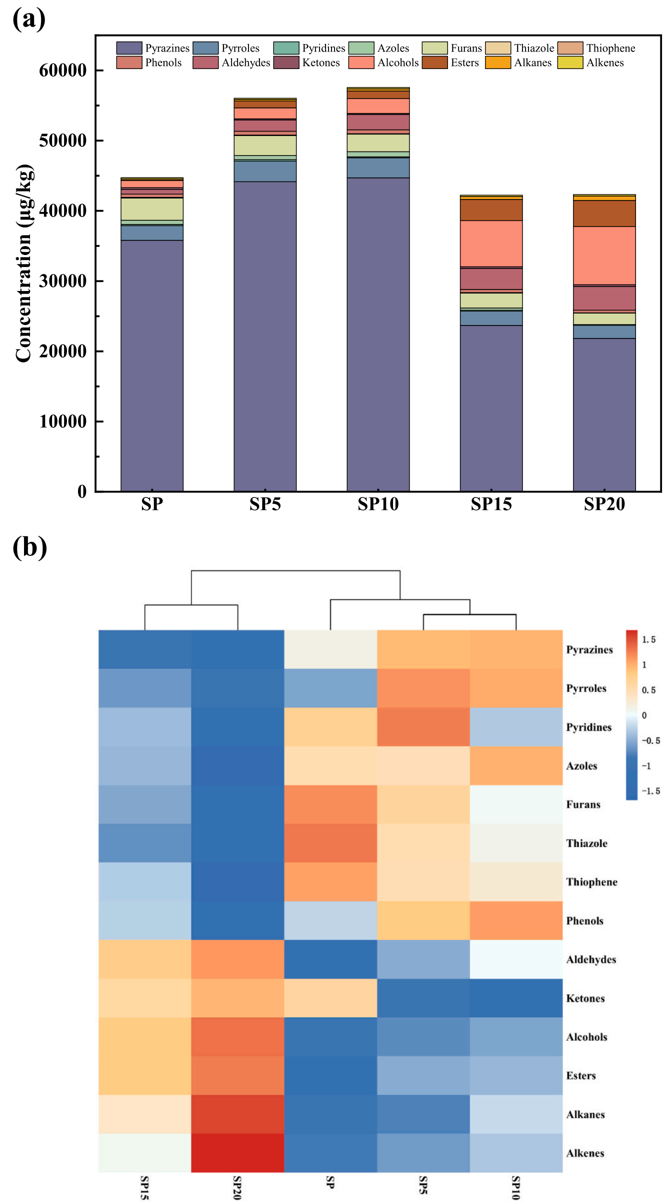

Fig. 5. Concentration (a) and heatmap analysis (b) in five sauce samples.

3.7.2. O-heterocyclic compounds

Furans, oxygen-containing heterocyclic compounds, play an important role in the flavor formation of thermally processed foods and are capable of imparting caramel-like, sweet, and fruity aromas. The production of furan compounds is mainly dependent on the Maillard reaction (the interaction of amino acids and reducing sugars at high temperatures) and the caramelization reaction (the dehydration and degradation of sugars at high temperatures), in which sugars are an essential ingredient (Kim et al., 2023). A total of five furans were detected in five samples. Among them, furfural is the most abundant furan compound, which is produced by the degradation of maltose. It has been identified as an aroma-active substance in sesame paste, providing woody and roasted aromas (Yang et al., 2024). 5-Methyl furfural, which is produced by the thermal degradation of sugars and is capable of imparting almond, roasted, and sweet aromas to foods. It has been identified as an aroma-active compound in roasted sesame (Wang et al., 2024) and sunflower oils (Yin et al., 2022). 2-Valerylfuran may be further generated by the reaction of furfural with other compounds, which further enriches the flavor of thermally processed foods.

Furan-2-carbohydrazide and 2-acetyl-2-methyltetrahydrofuran were only detected in a few samples at lower concentrations. All furan compounds showed a tendency to decrease with the addition of PSPC, which could be attributed to the fact that the increase in PSPC reduces the sugar content of the sauce, which in turn affects its final flavor.

3.7.3. S-heterocyclic compounds

Sulfur-containing heterocyclic compounds, with strong characteristic odors and low thresholds, significantly affect the overall flavor composition of foods. They are formed by Strecker degradation or by the Maillard reaction of amino acids with sugars and typically impart sulfur-like and roasted aromas to foods (Yin et al., 2021). In this study, one thiazole and one thiophene were detected in each of the five samples, and the concentrations of both showed a decreasing trend with the increasing addition of PSPC. Among them, 5-(2-hydroxyethyl)-4-methylthiazole has been identified as an aroma-active component in chicken breast, providing roasted, nutty, and sulfur aromas (Xiao et al., 2015).

3.7.4. Nonheterocyclic compounds

The nonheterocyclic chemical classes found in the samples were phenols, aldehydes, ketones, alcohols, esters, alkanes, and alkenes. Among them, phenols, aldehydes, alcohols, and esters were the major nonheterocyclic compounds.

Phenols may be produced by the degradation of natural phenolic carboxylic acids present in sesame seeds during the roasting process. Guaiacol and 2-methoxy-4-vinylphenol were found to possess smoky and roasted aromas. They have been reported as aroma actives in roasted sesame seeds and sesame oils (Yin et al., 2021). Among them, 2-methoxy-4-vinylphenol has been identified as a key aroma-active substance in sesame paste, providing roasted nut and toasted sesame flavor (Yang et al., 2024). In this study, the decrease in the total concentration of phenolic compounds may be related to the increase in PSPC, which led to a decrease in the total content of natural phenolic carboxylic acids in the sauces.

Aldehydes are usually described as having greasy, sweet, and green sensory attributes; they have a low olfactory threshold and contribute greatly to the overall flavor of the sauce (Hu et al., 2024). It is produced by beta cleavage of hydroperoxides during heat treatments such as roasting, drying, and frying of foods (Liu et al., 2019). The five sauce samples contained six different aldehydes in total, with phenylaldehyde and phenylacetaldehyde being the main ones. They are Strecker degradation products of aromatic amino acids and provide almond and sweet aromas, respectively (Gao et al., 2023). Phenylaldehyde has been identified as the key aroma-active substance in sesame paste, providing the flavor of roasted nuts and toasted sesame seeds (Yang et al., 2024).

Alcohols are generally produced by secondary hydrogen peroxide degradation of fatty acids or reduction of carbonyl compounds, and they have a weak effect on odor (Wang et al., 2024). The main alcohols in sauces were (*S*, *S*)-2,3-butanediol and 2, 3-butanediol. They were only detected in SP10, SP15, and SP20. Phenylethyl alcohol was found to have a spicy aroma (Liu et al., 2024), and it was detected only in SP20. The alcohol content in the sauce increased with the addition of PSPC, of which SP20 had the highest concentration.

Esters have a low odor threshold and have a great influence on the aroma properties of the sample (Yu et al., 2022). It has been found that the fruity is mainly produced by short-chain free fatty acids interacting with alcohols to produce esters, and the greasy is mainly produced by long-chain fatty acids interacting with alcohols to produce esters (Ai, 1997). The five sauce samples contained ten esters, and the maximum concentration of esters was detected in SP20.

The flavor of a sauce is formed by the composition of flavor substances and their interactions, rather than by the concentration of specific compounds (Gao et al., 2023). Lower concentrations of compounds such as ketones, alkanes, and alkenes also contribute to the overall flavor of a product. Ketones were mostly produced by fat oxidation and had fruity and fermented aromas. Alkanes and alkenes were associated with the off flavors of oxidized oils (Qin et al., 2023).

3.8. E-nose analysis

The sensors in the *E*-nose generate signals for volatile components; foods can be differentiated based on these signals. The E-nose responses are repeatable and more stable than human sensory evaluation. Therefore, this technology has been widely used both in China and abroad, for foods such as alcohol, cereals, beverages, and dairy products (Loutfi et al., 2015). The radargrams of the response values of the sauce samples produced by the 10 sensors of the E-nose are shown in Fig. 6a. The five sauce samples showed the largest and significantly different response values on the W5S and W1W sensors, indicating that nitrogen oxides and sulfur-containing compounds contribute more to the sauces. SP5 and SP10 had the largest response values on the W5S and W1W sensors, which may be explained by the larger concentrations of N-heterocyclic (pyrazines, pyrroles, pyridines, and azoles) and S-heterocyclic (thiazole and thiophene) in the two sauce samples. However, the response values on the remaining eight sensors almost overlapped, indicating that the volatile components detected by these eight sensors were similar in composition.

Principle component analysis (PCA) is a technique that uses orthogonal transformations to convert a set of possibly correlated variables into a set of linearly uncorrelated variables. PC1 and PC2 contributed 87.00 % and 11.20 % (Fig. 6b), respectively, for a total contribution of 98.20 %, demonstrating that the ten sensors of the *E*-nose had significant sensitivity to the volatile components of the samples. Overall, there was a small amount of overlap between SP, SP5, and SP10, suggesting that they have volatile components in common and similar odors. However, they were well distinguished from SP15 and SP20, suggesting that a higher addition of PSPC alters the volatile components and affects the flavor of the sauce. These outcomes indicated that the volatile components of the five sauce samples could be distinguished using PCA. The E-nose results were consistent with the HS-SPME-GC–MS results.

3.9. E-tongue analysis and sensory evaluation

The E-tongue converts chemicals in a liquid matrix into signals; based on the signals, flavors can be identified. The method eliminates the subjectivity of human sensory evaluation to a great extent. Fig. 6c displays the scores for bitterness, aftertaste-B, astringency, aftertaste-A, umami, richness, and saltiness of the five sauce samples. Aftertaste-B indicates a bitter aftertaste; aftertaste-A indicates an astringent aftertaste; richness is the aftertaste of freshness, and it is also referred to as freshness persistence. Sourness was not detected in any of the five sauce samples. According to the E-tongue sensory test findings, adding PSPC gradually increased the flavors of bitterness, aftertaste-B, astringency, aftertaste-A, umami, richness, and saltiness. Umami is a commonly pleasant taste in foods. The increased freshness, richness, and saltiness indicate that the PSPC imparts an additional distinctive taste to the sauces. Furan was found to have caramel, buttery, and popcorn flavors; phenylaldehyde was able to provide an odor similar to that of bitter almonds; the decreased furan content and the increased phenylaldehyde content of sauces may be the cause of its increased bitterness (Zhang et al., 2021). The increased astringency and aftertaste-A appear to be due to specific constituents in the PSPC (Yilmaz, 2020).

E-tongue results were analytically evaluated by PCA. Fig. 6d displays the results of the PCA analysis for the five sauce samples. The contributions of PC1 and PC2 of 89.70 % and 7.30 %, respectively, these two main components can account for the majority of the gustatory information from the sauces. The results of PCA showed that all five samples were partially correlated with each other, with PC1 showing an increasing trend with the increase of PSPC, and PC2 showing an increasing and then decreasing trend. These results indicate that PSPC altered the flavor profile of sesame paste without changing its

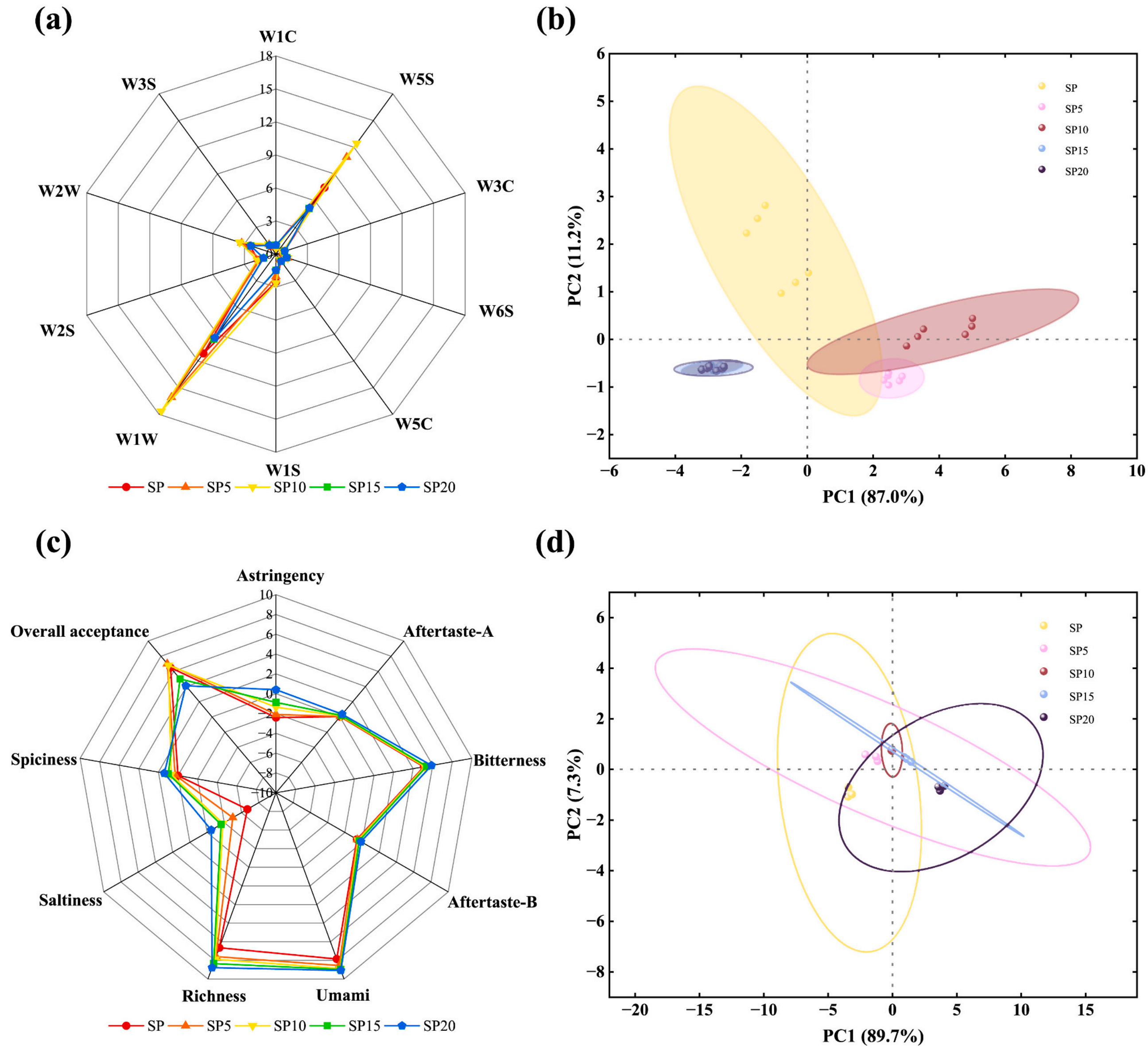

Fig. 6. Radar diagram (a) and PCA analysis (b) for E-nose in samples. Radar diagram (c) and PCA analysis (d) for E-tongue in samples. Sensory evaluation analysis (c) of five sauce samples.

characteristic flavors.

The novel sauce achieved a dual perception of aroma and taste through the synergistic action of the nasal cavity and taste buds during consumption. The release pattern of flavor compounds during consumption is influenced by a variety of factors, including the physical characteristics of the food (particle size, viscosity, textural properties), chemical composition (oils, proteins, sugars, etc.), and physical conditions during consumption (e.g., temperature, chewing intensity, swallowing time, salivary flow rate, etc.) (Guan & Zhang, 2022). In this study, the appropriate addition of PSPC improved the viscosity and textural properties (hardness, adhesiveness, gumminess, and chewiness) of the sesame paste, which may contribute to enhance the perceived intensity and persistence of flavor during consumption (Li & James, 2020).

The sensory quality of food products has a significant impact on consumer satisfaction and purchasing decisions. Statistical analysis revealed that the overall acceptance (texture and aroma) and spiciness of the five sauce samples were significantly different ($P < 0.05$) (Fig. 6c). SP5 had the highest overall acceptance score, followed by SP10. The overall acceptance decreased significantly as the addition of PSPC increased above 10 g/100 g. At those higher proportions, the PSPC created textural and aroma defects which reduced consumer acceptance. Therefore, to cater to the taste of the public, the amount of PSPC added should be controlled within specific limits. The novel sauces received generally low ratings for spiciness, which is largely attributed to the inherently low spiciness of the ingredient (sweet pepper seeds) used. As a result, the sauces are suitable for a wider range of tastes, especially for the public who prefer a milder flavor or are looking for a new experience in their daily diet.

According to a combination of sensory assessment and *E*-tongue data, the texture and flavor of traditional sesame paste might be improved by adding a suitable amount of PSPC. The best flavor of the novel hot pot dipping sauce was prepared when the addition amount was 5–10 g/100 g.

4. Conclusion

In this study, a novel hot pot dipping sauce with added PSPC was produced, and its quality and flavor were comprehensively analyzed and evaluated. Notably, it was observed that PSPC had a significant effect on the physicochemical properties and flavor characteristics of the sauce samples. Specifically, the appropriate addition of PSPC was able to increase the content of palmitic and linoleic acids without significantly decreasing the content of amino acids in the sauce. The accelerated oxidation experiment showed that PSPC could enhance the storage stability of the sauce, providing a strong guarantee for the long-term preservation of the sauce. The appropriate particle size distribution ensured the suspension stability of the sauce and improved the oil-sauce separation problem, further improving the overall quality of the product. Meanwhile, the addition of PSPC improved the rheological behavior and textural properties of the sauce, making it more in line with the taste preferences of consumers. In terms of flavor, the significant increase in the concentration of N-heterocyclic compounds in the SP5 and SP10 samples directly enhanced the roasted and nutty aromas of the sauces. At the same time, the results of the E-nose and E-tongue further proved the excellent performance of PSPC in enhancing the flavor and mouthfeel (umami and saltiness) of the sauces, which resulted in a richer taste and aroma of the novel sauces. In summary, at 5–10 g/100 g of PSPC, the optimum quality, flavor, texture, and overall acceptability of the sauce were achieved. From the economic point of view, this study successfully converted PSPC, a by-product of pepper seeds, into a high-value food ingredient. It not only realized the effective utilization of resources but also promoted the development of the circular economy. In the future, with the continuous progress of technology and the continuous expansion of the market, this new type of sauce with PSPC will be applied and popularized in a wider range of fields, bringing more delicious and healthy choices to consumers.

Compliance with Ethical Standards

Informed consent was obtained for studies in which sensory evaluation involved human participants. All participant rights and privacy are protected.

CRediT authorship contribution statement

Bing-Xin Guo: Writing – original draft, Software, Methodology, Investigation, Data curation. **Cheng-Yuan Chen:** Software, Resources, Investigation. **Rui Wang:** Resources, Investigation. **Yu-Hang Liu:** Resources, Investigation. **Jun-Jie Meng:** Resources, Investigation. **Hua-Min Liu:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Xue-De Wang:** Supervision, Project administration.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fochx.2024.101840.

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