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Roasted ground pepper seed press-cake sauce: quality, characteristics and palatability

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RESEARCH

Abstract

Pepper seed press-cake, the by-product of the pepper seed oil pressing process, can be reused to prepare high-quality sauces with significant potential for application and commercial value. In this study, pepper seed press-cakes obtained by roasting at four temperatures (0, 140, 170, and 200°C) were processed with sunflower oil into sauces. The physical properties, rheological characteristics, texture, microstructure, and sensory characteristics of these four sauces were analyzed. The results indicated that sauces made from pepper seed press-cake roasted at 140 and 170°C exhibited better quality. Roasting decreased the oil separation rate (from 10.90 g/100 g to 8.09 g/100 g) and enhanced the storage stability of the sauces. Rheological and textural analyses revealed that roasting reduced both the viscosity and the textural properties of the sauces. The sensory evaluation indicated that sauces prepared from pepper seed press-cake roasted at 170°C exhibited the most intense roasted and nutty aromas, followed by those roasted at 140°C. In a comprehensive assessment, sauces prepared from press-cake roasted at 140–170°C were deemed more suitable for consumer consumption. This study provides strong technical support for the conversion of pepper seed press-cake into a high-value-added commodity.

Keywords: characteristics; palatability; pepper seed press-cake; roasting; sauce processing

Introduction

Pepper (*Capsicum annuum* L.), one of the most consumed horticultural crops, is cultivated in large quantities worldwide. There are various types of peppers, which can be categorized into red, green, and yellow based on color distinctions. Among them, red peppers are commonly consumed as fresh vegetables, dried and ground for use as spices, or processed into sauces or canned foods (Gu *et al*., 2017). During food production, pepper seeds, which account for about 45% of the dry weight of peppers, are separated from the pods and often used as animal feed or discarded, leading to a waste of resources (Liu *et al*., 2020). It has been reported that various pepper seeds contain 6–25% oil, 13–28% protein, and 40–65% total dietary fiber, along with small amounts of capsaicin and other components (Wang *et al*., 2014; Yılmaz *et al*., 2016). Recent research on pepper seeds has mainly focused on their nutritional components, functional characteristics, and applications of pepper seeds, pepper seed oil, and pepper seed flour (Cvetković *et al*., 2020; Cvetkovic *et al*., 2022; Yılmaz *et al*., 2015; Zou *et al*., 2015). Yılmaz *et al*. (2016), ValdezMorales *et al*. (2021), and Cvetković *et al*. (2022) studied the functional characteristics of pepper seed press-cake and found that it possesses good nutritional and functional properties, indicating great potential for use in value-added food formulations. Unfortunately, information on the use of pepper seed press-cake in food applications is still limited.

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Sauces are an integral part of most cuisines, used to enhance the flavor of other food items, and pepper sauce is one of the most popular. Currently, there is a wide variety of pepper sauces with diverse flavors, aromas, and ingredients (Yilmaz, 2020). Roasting is a critical process in the preparation of many processed foods, where complex physicochemical reactions, including the Maillard reaction, lipid oxidation, and Strecker degradation, occur during a short period of high-temperature roasting. These reactions change the colors, odors, and flavors of the foods, imparting distinctive appearances and tastes (Zhang *et al*., 2019). To make good use of roasted pepper seed flour, Bostancı *et al*. (2017) formulated two spreadable products using it as the main ingredient. These new spreads were then sensory analyzed and consumer tested by Yılmaz *et al*. (2018). The data showed that these new pastes were healthy and well appreciated by consumers. These studies provide new insights into the application of pepper seed press-cake.

This study focused on developing novel sauces with a typical pepper flavor using roasted pepper seed press-cakes. The basic constituents and amino acids of pepper seed press-cake were analyzed. Additionally, the particle size distribution, rheological characteristics, texture, microstructure, and four physical properties (color, oil separation rate, and sensory evaluation) of the sauces were comprehensively evaluated. This study is significant for realizing the "waste to treasure" potential of pepper seed press-cake and for enhancing the added value of pepper seed products.

Materials and Methods

Materials and pre-processing

Materials

The variety of pepper used in this study was Xinjiang Sweet Pepper. The peppers were sun-dried, and the seeds were removed. Sweet pepper seeds were purchased from a local market in Hejing, Xinjiang, China. The sunflower oil was obtained from Standard Food Co. (Shanghai, China) and is stored in a UV-resistant plastic bottle with a capacity of 5 liters, produced in September 2023. It contains over 86% unsaturated fatty acids and no trans fatty acids. Amino acid mixtures were sourced from Sigma (St. Louis, MO, USA). Fluorescein isothiocyanate and Nile red stain were purchased from Shanghai Yuanye Biotechnology Co. Ltd. (Shanghai, China). All other reagents were supplied by Macklin Biochemical Co. Ltd. (Shanghai, China) and were of chromatographic or analytical grade.

Preparation of pepper seed press-cake

The preparation of press cake was carried out with partial modifications based on the method of Zhang *et al*. (2019). Pepper seeds were roasted at different temperatures (140, 170, and 200°C) and then pressed using a hydraulic oil press (270B, Luoyang Luofeng Hydraulic Technology Co., China). The remaining press cake after oil extraction was used for this study. The unroasted pepper seeds were pressed directly and served as the control group. The four samples were labeled P-140, P-170, P-200, and UR.

Preparation of sauces

The three roasted and one unroasted pepper seed press-cakes (P-140, P-170, P-200, and UR) were crushed using a crusher (800C, Red Sun Electromechanical Co., China) and passed through a 20-mesh sieve. Sunflower oil, which has a minimal impact on the flavor of pepper seed press-cake and is moderately priced and nutritious (rich in unsaturated fatty acids and vitamin E), was chosen to prepare the novel sauce. Each press-cake was combined with an equal weight of sunflower oil and ground using a grinder (JM-L80, Longxin, China). The four sauce samples produced were labeled RP-140, RP-170, RP-200, and URP, respectively. All samples were analyzed immediately after preparation.

Pepper seed press-cake

Proximate analysis

The moisture, ash, crude fat, and protein content were determined with reference to the method of Chang *et al*. (2024). Four samples (P-140, P-170, P-200, and UR) were weighed, dried in an oven at 105°C, and then reweighed to determine moisture content. Ash content was measured by incinerating the press cake in a muffle furnace at 550°C for 8 h. The crude fat content of the pepper seed press-cake was determined using the Soxhlet apparatus. Protein content was measured by the Kjeldahl method.

Amino acids analysis

The composition of amino acids was analyzed following the method proposed by Xu *et al*. (2023). Briefly, 60 mg of samples were accurately weighed and then hydrolyzed with a hydrochloric acid solution at a concentration of 6 mol/L (110°C for 24 h). After hydrolysis, the samples were dried in a tube concentrator at 45°C. The residue was then dissolved in 1 mL of ultrapure water and dried again. Finally, the dried residue was dissolved in 1 mL of citrate buffer (pH 2.2) and passed through a 0.22-μm filter membrane. Amino acid content was determined using an Amino Acid Auto-Analyzer (Biochrom 20, Autosampler version, Amersham Pharmacia Biotech, Sweden).

Pepper seed press-cake grinding sauce

Color analysis

The color of the sauce samples (URP, RP-140, RP-170, and RP-200) was determined using a colorimeter

(CS-821N, Hangzhou Color Spectrum Technology Co., China). Before each measurement, calibration was performed using a standard color palette. The measurements are expressed in terms of L^*, a^*, and b^* values. The L^* value represents brightness, ranging from 0 (black) to 100 (white), the a^* value ranges from green (-100) to red (+100), and the b^* value measures from blue (-100) to yellow (+100). The total color difference (ΔE) of the sauce samples was calculated as follows:

$$\Delta E=[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \quad (1)$$

where the ΔL^*, Δa^*, and Δb^* are the differences between the white ceramic plate and the various sauces.

Particle size distribution

The particle size distribution was assessed using the method of Yang *et al*. (2024) with modifications. One gram of samples (URP, RP-140, RP-170, and RP-200) and 50 mL of water were shaken in a centrifuge tube to uniformly disperse the sauce particles. A laser particle size analyzer (2000ZD, Winner, China) was then used to measure the particle size distribution. In the results, $D(10)$ (μm) represents the size at which 10% of the total particle volume is smaller; $D(50)$ (μm) represents the size at which 50% of particles exceed this value; and $D(90)$ (μm) represents the size at which 90% of the total particle volume is smaller.

Oil separation and storage experiments

Oil separation analyses were conducted with reference to the method of Jin *et al*. (2022a). In brief, 50 mL centrifuge tubes were filled with approximately 30 g of sample (URP, RP-140, RP-170, and RP-200) and centrifuged at 4000 rpm for 10 min (Mod 3-5N, Hunan Hengnuo Instrument Equipment Co., China). Finally, the separated oil was removed using a Pasteur pipette and weighed. The oil separation was calculated by comparing the weight of the separated oil after centrifugation to the total weight of the sample.

Ten grams of sample (URP, RP-140, RP-170, and RP-200) were accurately weighed and placed into a 25 mL glass tube. Three tubes were prepared for each of the four samples. These tubes were stored at 25°C for 0, 10, 20, and 60 days. The samples were periodically photographed, and the height of the separate oil was assessed.

Rheological analysis

A rheometer (MARS40, Thermo Fisher, USA) was used to assess the rheological characteristics of the sauce samples according to Yang *et al*. (2024). All materials were maintained at 25°C. After calibrating the instrument, an appropriate amount of sample was placed on the plate and pressed with a second plate until the distance between the plates was 1 mm. Any material that oozed out at the edges was removed for analysis. The viscosity and oscillation characteristics were evaluated using plate-plate geometry. The flow behavior was described as follows:

$$\tau = K\dot{\gamma}^n \quad (2)$$

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

In terms of dynamic oscillatory rheology, the values of storage modulus (G') and loss modulus (G'') were recorded as the frequency increased from 0.1 to 10 Hz.

Texture

The texture was examined using the TA-XT Plus texture analyzer (Stable Micro System, Godalming, UK) following the method outlined by Jin *et al*. (2022b). The samples (URP, RP-140, RP-170, and RP-200) were transferred to a 50 mL beaker and allowed to stand for 2 h. A trigger force of 10 g was applied to press the P25 probe into the sauce. Throughout the experiment, the pressing distance of the P25 probe was set at 20.00 mm, and the speed was maintained at 1.00 mm/s before, during, and after the test.

Confocal laser scanning microscopy (CLSM) and macro photo

Macromolecules were observed using a Confocal Laser Scanning Microscope (CLSM) (Leica, TCS-SP5, Germany) according to the method of Ningtyas *et al*. (2021) with some modifications. The sauce samples (URP, RP-140, RP-170, and RP-200) were mixed thoroughly, and 1 g of sample was placed in a centrifuge tube. Then, 20 μL of fluorescein isothiocyanate (FITC) and 20 μL of Nile red stain were added to mark proteins and lipids, respectively. After stirring, the mixtures were left overnight. A small quantity of the sample was placed on a slide, covered with a coverslip, and observed using the CLSM. The concentration of Nile red was 0.1% (w/v) and was excited at a wavelength of 488 nm, while the concentration of FITC was 1.0% (w/v) and was excited at a wavelength of 633 nm.

Sensory descriptive analysis

Twelve trained panelists aged between 21 and 26 years, including six females and six males, from Henan University of Technology, evaluated the aroma characteristics of the four sauce samples (URP, RP-140, RP-170, and RP-200). Each panelist had at least two years of experience in sensory evaluation of cooking oil, sesame paste, and other food products. All panelists provided their informed consent before beginning the tests. Each sample was placed in a brown, lidded vial, and sensory evaluations were conducted at room temperature (25°C). Each panelist sniffed the four samples and rated them based on nine attributes to characterize the sensory properties of the sauces. Attributes were rated on a ten-point scale (where 0 = barely detectable and 10 = extremely strong). Each sensory test was conducted in a separate compartment constructed in accordance with ISO 8589:2007 standards. Sensory analysis data were collected using Compusense Cloud (Compusense Inc., Ontario, Canada).

Statistical analysis

Three duplicates of each measurement were conducted. Statistical data were analyzed using SPSS version 21.0 (SPSS Inc., Chicago, USA) through variance analysis (ANOVA). The results are presented as mean ± standard deviation (SD). Discrepancies were assessed using Duncan's multiple range test ($p < 0.05$).

Results and Discussion

Proximate analysis of the pepper seed press-cake

The proximate compositions of the roasted pepper seed press-cakes are shown in Table 1. The moisture, fat, ash, and protein contents were in the ranges of 0.03–6.73 g/100 g, 8.13–12.64 g/100 g, 4.20–4.51 g/100 g, and 18.70–19.60 g/100 g, respectively. Roasting increased the fat and ash content while decreasing the moisture and protein content, indicating that roasting temperature had a significant effect on the chemical composition of the press cake. All three roasted pepper seed press-cakes had a moisture level of less than 1 g/100 g. The low moisture content of food samples is desirable and meets national standards for sauce production (Zhang *et al.*, 2019). The fat content of roasted pepper seed press-cake was significantly higher compared to that of unroasted pepper seed press-cake. This may be attributed to the breakdown and denaturation of proteins, which expose hydrophobic groups to the hydrocarbon chains of the oil, thereby increasing the oil absorption capacity in the samples and resulting in less oil being pressed out. Hatamian *et al.* (2020) studied the effect of temperature on the functional properties of chia seed flours, finding that roasting significantly increased the oil absorption capacity of the flours, a result similar to those of the present study. The ash content in the pepper seed press-cake changed after roasting, which may be due to differences in oil yield during the pressing process affecting the proportion of components after pressing (Yılmaz *et al.*, 2016). The decrease in protein content may result from the Maillard reaction occurring during roasting (Tenyang *et al.*, 2017).

Amino acid composition in pepper seed press-cake

Amino acid composition is a critical factor in the quality of any sauce, and it is widely accepted that high concentrations of essential amino acids such as valine, leucine, and phenylalanine can enhance food products (Yang *et al.*, 2021). Table 1 shows the changes in the concentrations of 17 amino acids with roasting temperature. The most abundant amino acids were leucine, arginine, glutamic acid, and asparagine; this aligns with findings from other investigations on the amino acid composition of pepper seeds (Zhang *et al.*, 2019). As shown in the table, the overall number of amino acids in the pepper seed press-cake decreased as the roasting temperature increased. Arginine, lysine, asparagine, and cystine exhibited the greatest declines. After roasting at 200°C, arginine decreased from 1.83 g/100 g to 1.20 g/100 g, lysine from 0.88 g/100 g to 0.34 g/100 g, asparagine from 1.91 g/100 g to 1.58 g/100 g, and cystine from 0.31 g/100 g to 0.02 g/100 g. The reduction in amino acids may be attributed to non-enzymatic browning reactions that occur at high temperatures. During roasting, amino acids undergo Maillard and Strecker degradation reactions with reducing sugars and other substances, resulting in the production of various flavor compounds, such as N-heterocyclic compounds and pigments (Ji *et al.*, 2019). As the reaction proceeds, some amino acids are consumed, leading to a decrease in the amino acid content of the pepper seed press-cake. As the roasting temperature continues to rise, the Maillard reaction accelerates, and the consumption of amino acids becomes more pronounced.

Color of sauce samples

Color is one of the characteristics most closely related to consumer acceptance of food. Figure 1 presents the color properties of the four sauce samples. The L^*, a^*, and b^* values of the sauce samples varied significantly ($p < 0.05$) from one another. As the roasting temperature increased, the L^* values decreased and the ΔE values increased, indicating that the roasting process enhanced the dark components. Non-enzymatic browning, such as the Maillard reaction and caramelization induced by heat treatment, may explain this phenomenon (Elleuch *et al.*, 2007). As the temperature rises, the reactions become more intense, resulting in an increase in the amount of melanoid pigment, which deepens the color (Ji *et al.*, 2019; Sithole *et al.*, 2022).

Particle size distribution in sauce samples

The stability of the sauce is significantly influenced by the particle size distribution. Figure 2 displays the volume proportions among the four sauce samples, with diameters ranging from 0.10 to 756.00 μm. As shown in Figure 2A, the volume curve shifts to the left after roasting, indicating a decrease in the number of large particles

Table 1. Chemical components and amino acid compositions of the pepper seed press-cakes roasted at different temperatures.

Parameter		Sample*			
		UR	P-140	P-170	P-200
Moisture (g/100 g)		6.73±0.03[a]	0.50±0.02[b]	0.03±0.00[c]	0.03±0.00[c]
Fat (g/100 g)		8.13±0.29[b]	11.97±0.88[a]	12.38±0.54[a]	12.64±0.11[a]
Ash (g/100 g)		4.26±0.06[b]	4.20±0.03[b]	4.43±0.01[a]	4.51±0.03[a]
Protein (g/100 g)		19.60±0.37[a]	19.15±0.14[ab]	19.09±0.34[ab]	18.70±0.03[b]
Amino acid (g/100 g)	Asparagine acid	1.91±0.01[a]	1.73±0.01[b]	1.68±0.01[c]	1.58±0.00[d]
	Threonine	0.76±0.01[a]	0.75±0.00[a]	0.70±0.01[b]	0.67±0.01[c]
	Serine	0.91±0.01[a]	0.91±0.01[a]	0.82±0.00[b]	0.76±0.01[c]
	Glutamic acid	4.06±0.01[a]	3.93±0.00[b]	3.71±0.01[c]	3.66±0.00[d]
	Glycine	0.95±0.01[a]	0.90±0.00[b]	0.85±0.00[c]	0.85±0.01[c]
	Alanine	0.91±0.00[a]	0.84±0.01[b]	0.81±0.01[b]	0.82±0.03[b]
	Cystine	0.31±0.01[a]	0.03±0.00[b]	0.03±0.01[b]	0.02±0.00[b]
	Valine	0.86±0.01[a]	0.82±0.01[b]	0.79±0.01[b]	0.81±0.01[b]
	Methionine	0.26±0.00[a]	0.20±0.01[b]	0.17±0.00[c]	0.16±0.01[c]
	Isoleucine	0.75±0.01[a]	0.73±0.01[ab]	0.69±0.02[ab]	0.67±0.04[b]
	Leucine	1.27±0.01[a]	1.24±0.01[ab]	1.16±0.01[ab]	1.18±0.06[b]
	Tyrosine	0.61±0.01[a]	0.49±0.02[b]	0.45±0.01[bc]	0.43±0.00[c]
	Phenylalanine	0.89±0.01[ab]	0.90±0.01[a]	0.88±0.01[ab]	0.87±0.01[b]
	Histidine	0.56±0.00[a]	0.54±0.01[b]	0.53±0.01[b]	0.49±0.01[c]
	Lysine	0.88±0.01[a]	0.78±0.03[b]	0.77±0.04[b]	0.34±0.02[c]
	Arginine	1.83±0.01[a]	1.64±0.01[b]	1.55±0.01[c]	1.20±0.01[d]
	Proline	0.70±0.01[c]	0.76±0.01[b]	0.79±0.01[ab]	0.82±0.01[a]
	Total amino acid	18.37±0.01[a]	17.17±0.05[b]	16.35±0.02[c]	15.28±0.10[d]

*UR represents unroasted pepper seed press-cake; P-140, P-170, and P-200 are press-cakes roasted at 140, 170, and 200°C, respectively. Values of different parameters are expressed as the mean ± standard deviation. Significant differences between means ($p < 0.05$) were determined by Duncan's test.

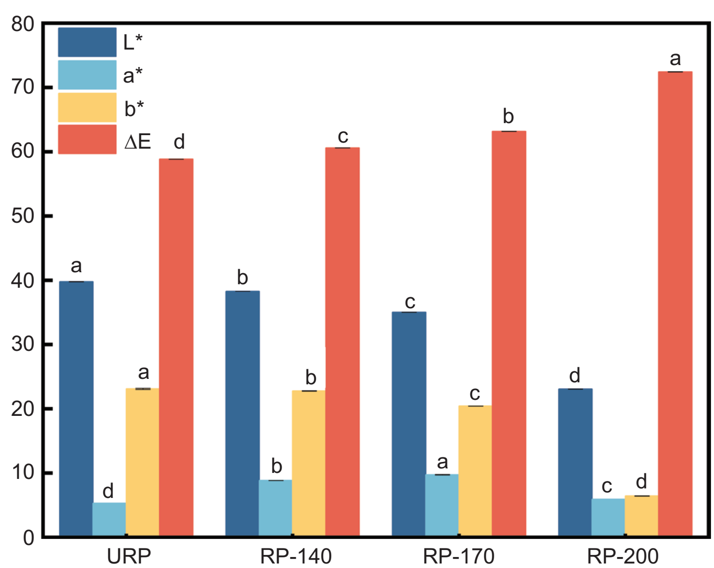

Figure 1. Color properties of the four sauce samples.

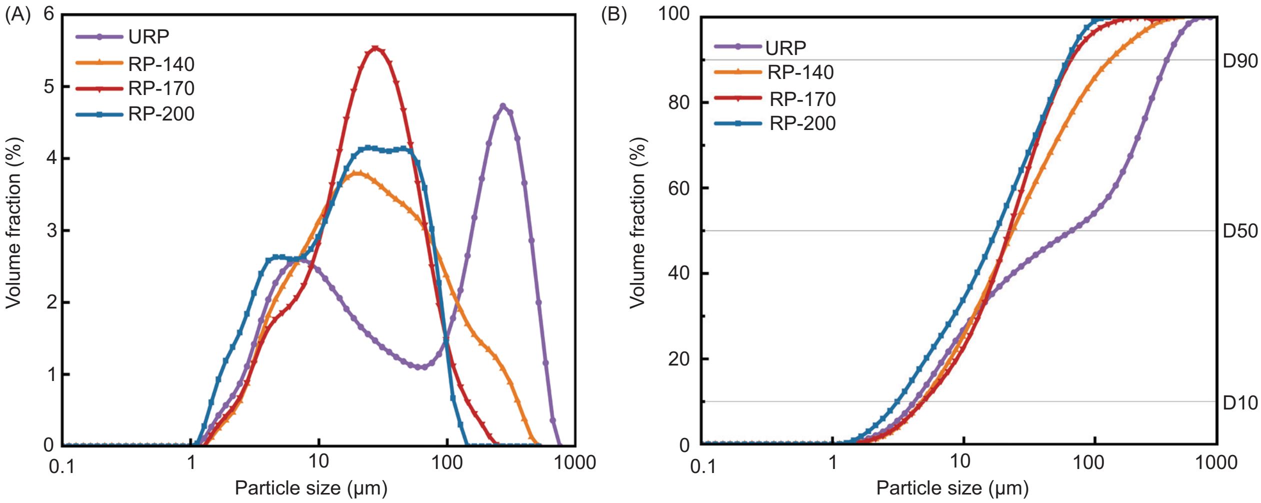

Figure 2. Particle size distribution (A) and cumulative percent particle size distribution (B) of the four sauce samples. *D*(10) (μm) represents the size for which 10% of the total particle volume is smaller; *D*(50) (μm) represents the size for which 50% of the particles exceed this value; and *D*(90) (μm) represents the size for which 90% of the total particle volume is smaller.

in the sauce. Among the four samples, the leftward shift of RP-200 was the most pronounced. Figure 2B indicates that *D*(50) and *D*(90) associated with the sauce samples decreased significantly ($p < 0.05$) as the roasting temperature rose. The *D*(50) of the four sauce samples decreased from 73.75 μm to 20.05 μm, while *D*(90) decreased from 389.00 μm to 69.55 μm. In other words, as the roasting temperature increased, the size of the sauce particles decreased considerably. This is likely because high temperatures denature proteins. Specifically, heat breaks the non-covalent bonds within the protein molecules, reducing the strength of intermolecular interactions and causing the proteins to break down into smaller molecules (Jin *et al*., 2022a). It has been found that breaking down oilseeds into smaller particles may enhance oil release by promoting particle adhesion (Mat Yusoff *et al*., 2015). However, an increase in particle size may result in a shorter shelf life and inferior flavor. Consequently, it is important to consider the impact of particle size when designing processes for making sauces.

Oil separation and storage experiment

The four sauce samples evaluated in this study are shown in Figure 3A, along with their centrifugal oil-solid separation rates. The ground pepper seed press-cake sauce is a multi-phase dispersed system consisting of pepper seed press-cake and sunflower oil. Due to the influences of gravity and Brownian motion, these components interact and then stratify over time (Jin *et al*., 2022a). It is evident that the separation rate was slower for the roasted samples compared to the unroasted samples. RP-140 had the lowest oil separation rate (8.09 g/100 g), while URP had the highest rate (10.90 g/100 g).

Figure 3B displays the variation in storage stability of the four sauce samples over time. The oil separation height of the sauce samples was measured and recorded (Table 2). The stability of the sauces during storage appeared to be significantly affected by oil release (Saatchi *et al*., 2022). Heavier particles sank as storage time increased, leaving the lighter oil molecules above (Hou *et al*., 2020; Mohd Rozalli *et al*., 2016). The oil separated relatively quickly during the first 20 days of preservation at 25°C, and then more slowly thereafter. The separation heights of the four samples were in ascending order as follows: URP < RP-170 < RP-140 < RP-200. In other words, URP exhibited the lowest level of oil separation, indicating that it was the most stable after 60 days of storage. This sample saw an increase in oil separation level to 4.7 mm, while the oil separation of sample RP-200 increased to 7.3 mm at 60 days. The varying particle sizes, related to the degree of roasting of the samples, may explain this difference. Smaller particles may adhere more readily, reducing the colloidal stability of the sauce. This result aligns with the findings of an earlier study (Mureşan *et al*., 2015).

Rheological tests

Flow behavior

The rheological characteristics of the four samples were determined at 25°C. As shown in Figure 4A, the shear stress increased non-linearly for all samples as the shear rates increased, indicating that all samples behaved as non-Newtonian fluids. These results align with those observed for sesame paste (Jin *et al*., 2022b). Figure 4A also reveals that the shear stress of the sauce samples made from unroasted pepper seed press-cake was higher than that of the samples made from roasted press-cake.

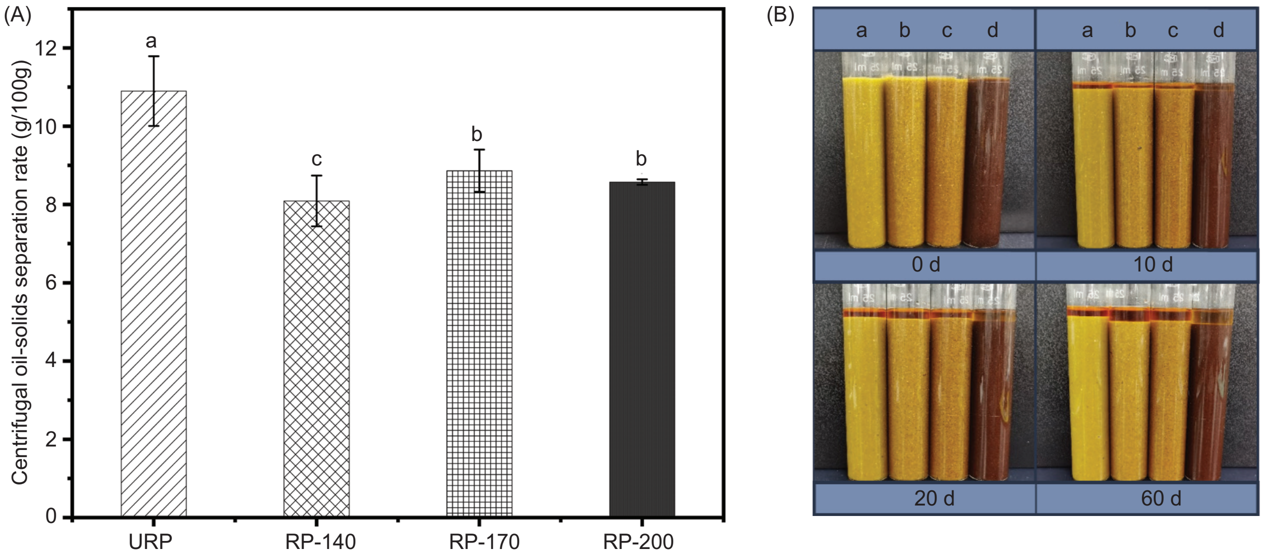

Figure 3. Centrifugal oil-solid separation rates (g/100 g) (A) and storage stability (B) of the four sauce samples. Sample (a) is the sauce made from unroasted pepper seed press-cake, while samples (b), (c), and (d) are sauces made from press-cakes roasted at 140, 170, and 200°C, respectively.

Table 2. Height of oil separated from sauce samples during storage (mm).

Sample*	Storage time(*d*)			
	0	10	20	60
URP	0	3.4	4.5	4.7
RP-140	0	3.2	5.0	7.2
RP-170	0	3.3	4.7	6.0
RP-200	0	3.8	5.4	7.3

*URP is the sauce made from unroasted pepper seed press-cake; RP-140, RP-170, and RP-200 are sauces made from press-cakes roasted at 140, 170, and 200°C, respectively.

At the same shear rate, URP exhibited the highest shear stress. This may be attributed to the fact that the URP samples were unroasted, allowing the molecular structure to remain intact, resulting in stronger intermolecular interactions compared to the other samples. RP-200 had the lowest shear stress, likely because the high roasting temperature weakened its molecular interactions the most (Jin *et al.*, 2022a). The apparent viscosity of the four sauce samples as a function of shear rate is displayed in Figure 4B. The viscosity decreased as the shear rate increased, indicating that shear thinning occurred in all of these sauces. The viscosity of all samples leveled off when the shear rate exceeded 30 s^{-1}. The curves showed that URP exhibited the greatest variation in viscosity, suggesting that roasting stabilized the viscosity of the sauces. This outcome aligns with earlier findings (Taghizadeh and Razavi, 2009). The decrease in viscosity may be attributed to the increase in shear stress, which disrupted the original mesh structure formed by the basic components of the sauce, such as protein, fat, and polysaccharides (Baqeri *et al.*, 2020; He *et al.*, 2021).

A power-law model ($\tau = K\dot{\gamma}^n$) was used to describe the flow behavior of all samples (Figure 4E). The correlation coefficients (R^2) ranged from 0.9930 to 0.9993. An R^2 value higher than 0.90 indicates that the model is highly dependable for explaining the flow behavior of the samples within the examined range. Additionally, K values ranged from 14.47 to 19.80, while n values fluctuated from 0.68 to 0.74. The K value is a crucial measure for assessing the flow behavior of food products. The data shows that the URP sample had the highest K value, or viscosity, whereas the K values of the roasted samples were lower. The reduction in viscosity and consistency of the sauce may be attributed to high temperatures denaturing proteins (He *et al.*, 2021; Huang *et al.*, 2021). This phenomenon aligns with the particle size distribution data.

Dynamic viscoelasticity

Figures 4C and D show the storage modulus (*G*') and loss modulus (*G*") of the four samples, respectively. All *G*' and *G*" values exhibited a linear increase within the studied frequency range. The sauce samples demonstrated larger *G*' and *G*" values after roasting. For the unroasted pepper seed press-cake sauce (URP), *G*" was less than *G*', indicating it behaved as a viscoelastic solid. In contrast, all roasted samples exhibited *G*" values greater than *G*', suggesting they behaved more like liquids. URP had the highest *G*' value, consistent with the flow behavior results, while RP-200 had the lowest *G*' and *G*" values.

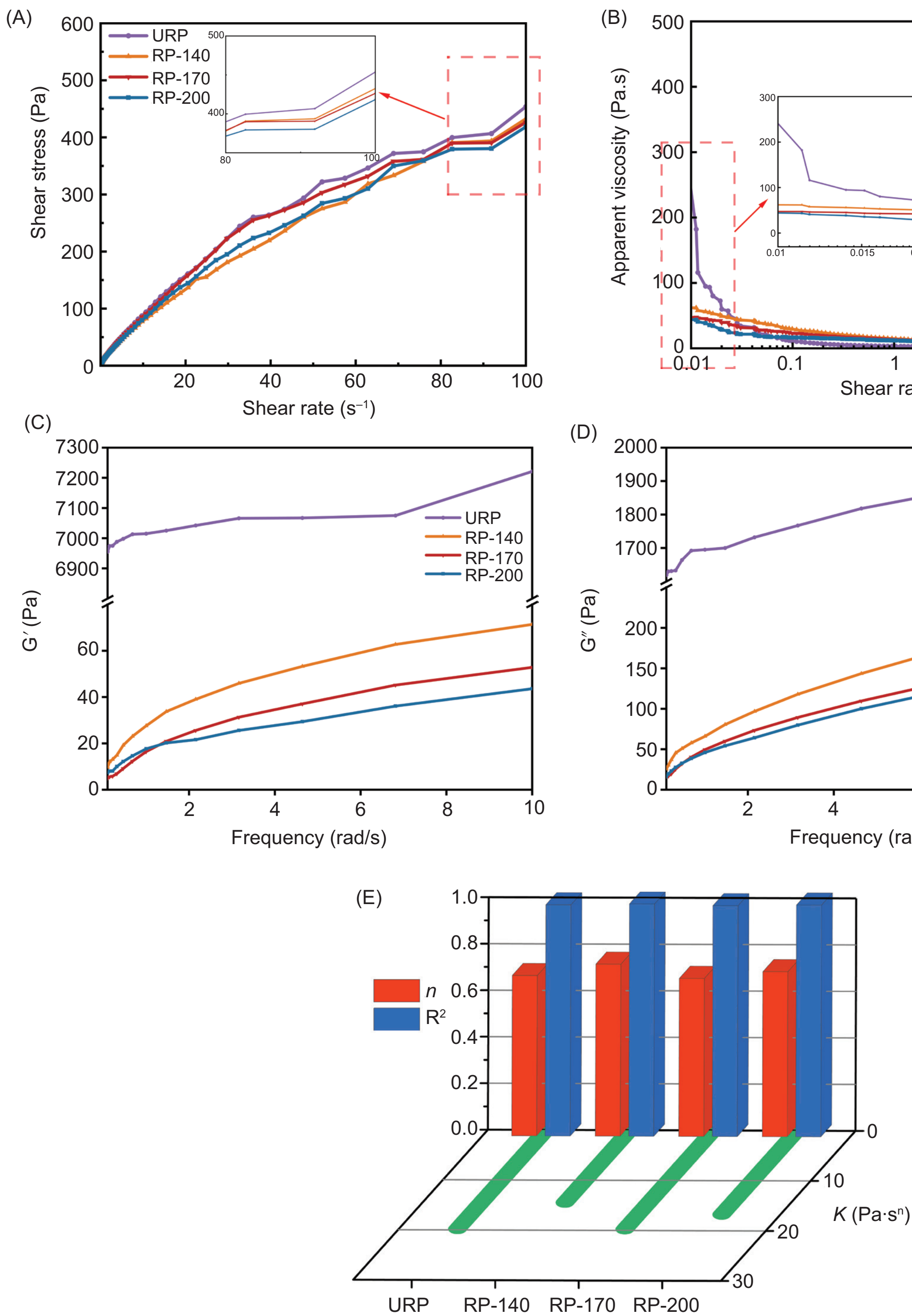

Figure 4. Relationship of shear rate to shear stress (A) and apparent viscosity (B) frequency sweep chart (C) storage modulus; and (D) loss modulus, and flow parameters (E) of the four sauce samples.

These findings indicate that roasting significantly affects the viscoelastic behavior of the sauce samples, potentially influencing the smoothness of the finished sauce. The high *G*' values of the URP samples suggest a solid network structure with strong particle-particle interactions, likely due to the stability and integrity of the protein structure in the unroasted sample (Saatchi *et al.*, 2022).

Texture

Texture is a crucial parameter in food production, particularly for semi-solid or solid foods. In this study, the hardness, cohesiveness, and adhesiveness of the four sauce samples were assessed, revealing significant differences ($p < 0.05$). As shown in Figure 5, the unroasted pepper seed press-cake sauce (URP) exhibited the highest

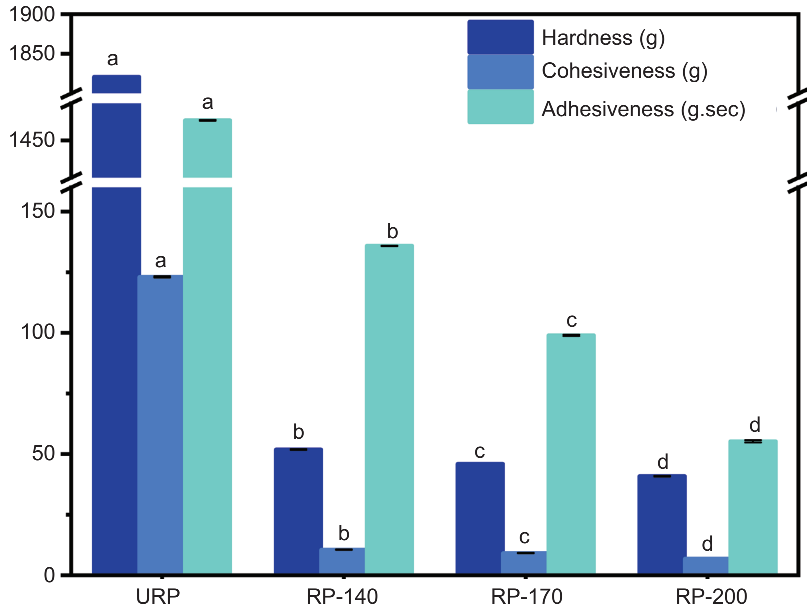

Figure 5. Texture properties of the four sauce samples.

hardness (1820.80 g), cohesiveness (123.10 g), and adhesiveness (1477.00 g·s). This may result from the strong interactions between proteins and oil droplets, forming a three-dimensional structure akin to a solid. Conversely, RP-200 displayed the lowest values for hardness (40.90 g), cohesiveness (6.90 g), and adhesiveness (55.30 g·s), consistent with the rheological analysis results. The texture of the sauces was significantly influenced by the roasting temperature, particularly at lower temperatures; changes in texture became less pronounced as the roasting temperature increased. This observation aligns with findings from Demir and Cronin (2004), which indicated that hardness, adhesiveness, and cohesiveness of the sauces declined as roasting temperatures increased, likely due to heat-induced structural degradation of macromolecules such as fibers and proteins (Baqeri *et al.*, 2020).

Macromolecule imaging

Laser scanning confocal microscopy (CLSM) was employed to investigate the microstructure of four samples to determine the distribution of proteins (solid phase) and lipids (oil phase) in the pepper seed press-cake sauce. Figure 6 illustrates the distribution of fat (red) and protein (green) in the sauces. As shown in Figure 6, an increase in roasting temperature resulted in a more uniform diffusion of oil and protein. This can be attributed to the significant enhancement in the oil absorption capacity of the press cakes due to roasting (Hatamian *et al.*, 2020). Sunflower oil formed a thin layer on the surface of the press-cake particles, providing a lubricating effect that facilitates flow and promotes a more even dispersion of the pepper seed particles in the oil during mixing and grinding (De Graef *et al.*, 2011).

Sensory evaluation

Sensory characteristics are vital aspects of food products and significantly influence consumer purchasing decisions. Figure 7 presents the results of the sensory evaluation of the four sauce samples. Statistical analysis indicated that the sensory characteristics of the samples differed significantly from one another ($p < 0.05$). All samples exhibited a lower level of spiciness, which aligned well with consumer preferences. URP displayed a notably strong green flavor, while RP-200 had a pronounced burnt flavor. In contrast, RP-170 showcased very high roasted and roasted nut aromas, exhibiting positive flavor attributes. RP-170 received the highest acceptability, followed closely by RP-140. These findings lead to two conclusions: first, roasting enhances flavor. Chemically, roasting triggers physicochemical changes (e.g., the Maillard reaction) that affect both aroma and taste. Second, low to medium-high roasting temperatures yield the best quality sauce, whereas high temperatures can compromise flavor (Guo *et al.*, 2023).

Conclusions

In this study, sauces were created by combining pepper seed press-cakes roasted at four different temperatures (0, 140, 170, and 200°C) with sunflower oil. The four sauces were thoroughly characterized and analyzed comparatively. The results demonstrated that roasting had a significant impact on all parameters of the sauce samples. As the roasting temperature increased, the amino acid content decreased, and the color of the sauces changed. Roasting

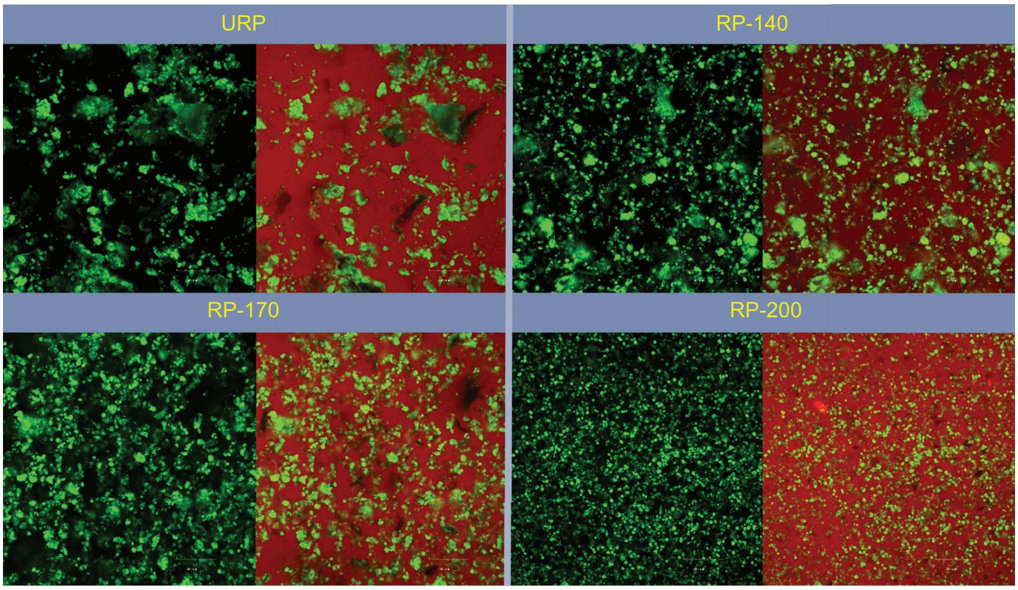

Figure 6. Confocal laser scanning microscopy micrographs of the four sauce samples.

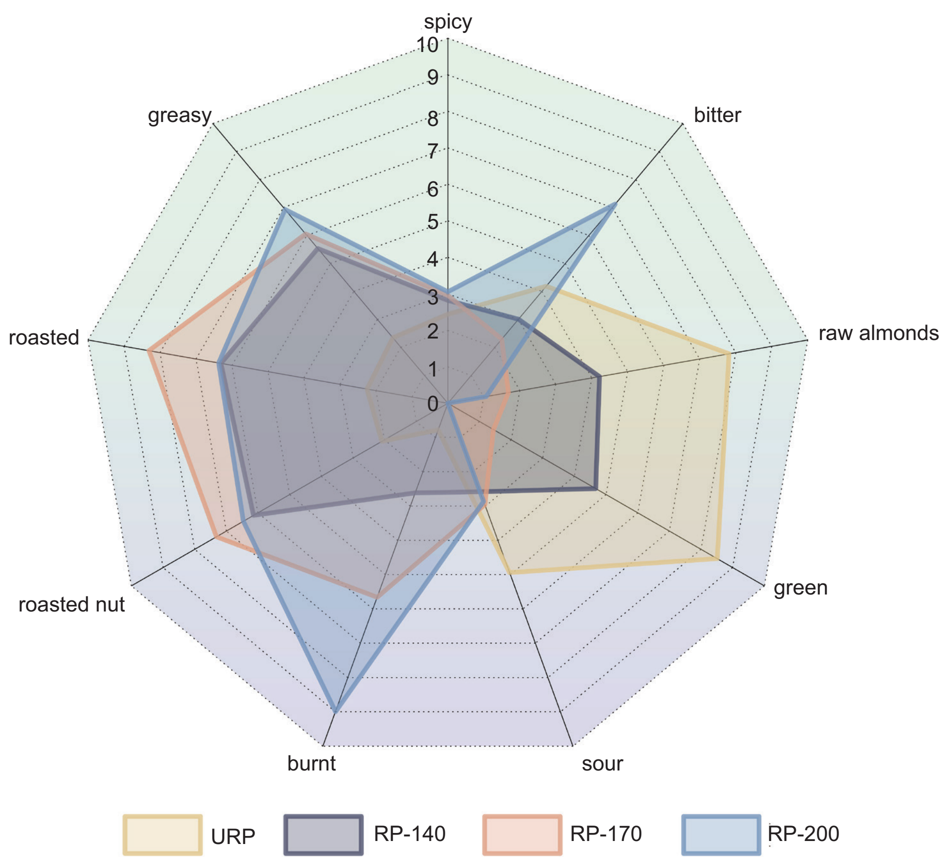

Figure 7. Sensory evaluation of the four sauce samples.

notably reduced the oil separation rate of the sauces (from 10.90 g/100 g to 8.09 g/100 g) and improved their storage stability, which is crucial for extending product shelf life. Additionally, rheological and textural analyses revealed that the roasted sauces exhibited enhanced viscosity, viscoelastic behavior, and textural properties (hardness, cohesiveness, adhesiveness) compared to the unroasted pepper seed press-cake sauces. These changes resulted in a more delicate and softer texture, improving overall quality. In terms of sensory evaluation, RP-170 exhibited strong roasted and nutty aromas, followed by RP-140. In conclusion, sauces made from pepper seed press-cakes roasted at temperatures between 140 and 170°C demonstrated excellent sensory attributes (color, aroma, flavor, and viscosity) and showed strong market potential. This study not only confirmed the viability of using pepper seed press-cake as a raw material for sauce production but also provided a scientific basis for its ability to significantly enhance sauce quality under specific roasting conditions. These findings open up new opportunities for the reutilization of pepper seed press-cake, a food processing byproduct.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

B.-X.G.: data curation, investigation, methodology, software, writing-original draft; R.W.: investigation, resources, software; J.Y.: investigation, resources; X.-P.J.: investigation, resources; L.-Y.Q.: investigation, resources; W.-T.Y.: supervision, validation; H.-M.L.: funding acquisition, project administration, supervision, writing-review and editing; X.-D.W.: Project administration, Supervision.

Statement

The study was reviewed and approved by the Henan University of Technology IRB and informed consent was obtained from each subject prior to their participation in the study.

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