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Effect of different thermal processing methods on the edible quality and flavor profile of kidney bean and clam soup

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This study investigated how boiling, steaming, and stewing affect the flavor profile of kidney bean and clam soup to enhance its acceptability. We analyzed color, thiobarbituric acid reactive substances (TBARSs), free amino acids, flavor-presenting nucleotides, and volatile compounds using analytical techniques including GC-IMS, electronic nose, and electronic tongue. The boiled soup exhibited the highest levels of total free amino acids (1.3775 mg mL^{-1}) and the flavor-presenting nucleotide (IMP 39.447 ng g^{-1}). GC-IMS identified 3-methylthiopropanal, furfural, ethyl acetate, and 3-methylbutanal as the dominant volatile flavor compounds formed during thermal processing. Electronic nose/tongue data indicated that steaming and stewing generated higher concentrations of these key volatiles and enhanced overall aroma and taste complexity. Boiling preferentially increased umami-related precursors (amino acids/IMP), while steaming and stewing promoted the formation of characteristic aroma volatiles. This demonstrates that the thermal processing method significantly directs the flavor development pathway in kidney bean and clam soup.

Sustainability spotlight

This study identifies optimal thermal processing methods for kidney bean and clam soup that enhance flavor profiles and maintain edible quality. By pinpointing techniques that preserve sensory attributes and extend shelf-life (reducing lipid oxidation), our findings support the development of more energy-efficient food processing and minimizing potential food waste, contributing to more sustainable seafood-legume product systems. Optimizing the thermal processing of nutrient-rich kidney bean and clam soup improves palatability and quality retention. Enhancing the utilization and consumer acceptance of these sustainable protein sources (low-impact bivalves and nitrogen-fixing legumes) through science-driven processing supports diversifying protein supplies with a reduced environmental footprint.

1 Introduction

"No soup, no seat" is a proverb that originated in China. Soup is tasty, simple to digest, and rich in peptides, amino acids, and fatty acids, and it helps improve feelings of fullness—a quality that is highly valued in the traditional Chinese diet.[1] People are increasingly seeking out fast food that is both healthful and nutrient-dense in recent years as consumer awareness of food nutrition has gradually increased.[2] Consumers are favoring and gradually occupying a specific consumer market with an increasing number of portable and nutritious soups (like instant porridge and freeze-dried seaweed egg drop soup). Kidney bean and clam soup is a popular local noodle soup in Dalian that is enjoyed by the locals due to its sweet flavor and rich, mellow scent. The flavor and texture of the entire noodle soup are greatly influenced by the base's taste. The base is made by heating raw ingredients until they dissolve continuously, followed by dissolving substances in the soup through continuous physical and chemical reactions, giving the soup a creamy, fresh flavor.

Clams, with scientific name *Ruditapes Philippinarum*, are also known as miscellaneous clams, flower clams, *etc.* This common beach shellfish can be found all over China's north and south shores, where it has adapted to its natural habitat. It is a common mudflat shellfish that is found throughout China's coastal regions, both north and south, and is quite environment-adaptive. Clams are a consumer-preferred, economical source rich in therapeutic compounds, vitamins, and proteins, while being low in fat and high in unsaturated fatty acids. The meat is also flavorful and easily absorbed by the body. In addition to being highly flavorful, clams are packed with physiologically significant elements (such as free amino acids and nucleotides) that are strongly linked to their physiological functions.[3] Zhang *et al.*[4] discovered that flavorful peptides in the clam enzymatic solution work in concert with

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monosodium glutamate (MSG) to enhance the clams' freshness. *Phaseolus vulgaris L.*, often known as kidney beans, kidney lentils, or four-season beans, is primarily found in Heilongjiang, Jilin, and other northeastern regions. Rich in nutritional fiber, carbs, vitamins, and minerals, fresh kidney beans are known as a typical low-sodium, low-fat, low-calorie vegetable. Their color is tender white, and their pods are fresh fat, are full of seeds, and have a protein content that is much greater than that in ordinary vegetables. Though less research has been done on flavor and taste qualities, current clam research has concentrated on biological activity investigation, processing of seafood flavoring products, and the interaction between nutrients and the farming environment and seasons.[5]

Food that has been cooked has a rich flavor and is more easily digested. Cooking methods for seafood include steaming, boiling, frying, grilling, and smoking.[6] Research on soups, both domestically and internationally, tends to concentrate on the nutritional qualities, flavor quality, and processing conditions of soups, with less attention paid to soups that include vegetables and fish. Zhang *et al.*,[7] for instance, discovered that crucian carp soup cooked at 85 °C had noticeably superior flavor and nutritional value than soup served at five other temperatures. The soup's quality can also be greatly impacted by the processing environment. Thus, boiling soup at a high temperature for an extended period of time might develop dangerous compounds like triglycerides and purines. Research has indicated that there is an increased risk of hyperuricemia in foods containing more than 200 mg of hypoxanthine per 100 g.[8] When compared to regular fish soup, Lv *et al.*[9] discovered that several edible mushroom species significantly increased the concentration of free amino acids, nucleotides, organic acids, and inorganic ions and significantly altered the flavor of the soup. Godoy *et al.*[10] assessed how well-liked various smoked fish soup varieties were by diners.

Though different heating techniques will produce different volatile flavor components in the products, there aren't many research studies on the flavor and taste of soups made using various processing techniques.[11] In order to better understand the variations in kidney bean and clam soups prepared by different heating methods using three types of equipment—a cooking machine, a steamer, and a water bath—this study was conducted to examine the differences in color, thiobarbituric acid value (TBARSs), volatile flavor content, free amino acid and nucleotide content, and electronic nose and tongue levels, in an effort to further realize industrialized production and to promote Dalian's regional traditional foods.

2 Materials and methods

2.1 Sample preparation

At the Qianhe Market in Dalian, Liaoning Province, China, we purchased kidney beans and clams. To make a creamy clam broth stock, kidney beans were chopped into cubes measuring 0.5 ± 0.1 mm and set aside while 3000 g of clams and 3000 mL of drinking water were boiled for 10 minutes at 100 °C. Using a multipurpose food processor (TM6-1), the following ingredients were prepared. 80 g of diced kidney beans, 80 g of edible oil, and 1000 mL of clam juice are boiled for 45 minutes; this group is known as the SZ group. A stainless-steel stewing pot was filled with the contents; the pot was placed into a steamer (SCC WE 101); it was steamed for forty-five minutes. This group is known as the GSZ group. The GSD group included 80 g of chopped kidney beans, 80 g of edible oil, and 1000 mL of clam stock. Each one was placed in an aluminum foil bag and immersed for forty-five minutes in a Diamond S water bath.

2.2 Experimental method

2.2.1 Determination of color. Using the colorimeter's entire transmission mode (Ultra Scan PRO), the L^*, a^*, and b^* values of various thermally processed kidney bean and clam soups were ascertained. A formula was then utilized to quantify each group of soups' whiteness (W):

$$W = 100 - \sqrt{(100 - L^*)^2 + b^{*2} + a^{*2}}$$

where W stands for sample whiteness; L^* stands for sample brightness ($L^* = 0$ for black and $L^* = 100$ for white); b^* stands for sample yellow-blue degree; a^* stands for sample red-green degree.

2.2.2 Determination of TBARSs. A small adjustment was made to the approach by John *et al.*[12] The procedure involves precisely weighing one gram of the sample, adding five milliliters of thiobarbituric acid (0.375% 2-thiobarbituric acid, 15% trichloroacetic acid, and 0.25 mol L^{-1} hydrochloric acid solution), mixing the mixture thoroughly, heating it in a water bath for twenty minutes, cooling it with running water, centrifuging the sample for fifteen minutes at 4 °C and 8000 rpm (Hi mac CR22N), and measuring the absorbance of the supernatant at 632 nm.

2.2.3 Determination of volatiles. A small adjustment was made to Wang *et al.*'s methodology.[13] Using a Flavour Spec ® GC-IMS (G.A.S., Dortmund, Germany), volatile flavor compounds were examined in kidney bean and clam soups from various thermal processing techniques. The soup samples were autosampled in non-split mode using an 85 °C syringe after being incubated at 60 °C for 15 minutes.

2.2.4 Determination of free amino acids. The approach was somewhat different from that by Zhou *et al.*'s.[14] An automated amino acid analyzer (BaiKang UK) was used to analyze the sample after 5 mL of it was combined with 5 mL of a 5% sulfosalicylic acid solution, centrifuged at 6000 rpm for 10 min at 4 °C, and the entire supernatant was removed and dried in a rotary evaporator. The sample was then dissolved by adding 1 mL of sodium citrate buffer solution and filtered through a 0.45 μm membrane.

2.2.5 Determination of nucleotides by using LC-MS. A slight modification was made to the approach by Cai *et al.*[15] For further processing of the mixtures, 1 mL of each group of samples was placed in a 2 mL centrifuge tube, placed in a freeze-dryer, and vortexed for 1 minute. After the samples were freeze-dried, 0.5 mL of 60% acetonitrile water was added, and centrifugation was performed for 10 minutes at 4 °C and 12 000 rpm (using a TGL-16 Hunan Instrument). The supernatant was then removed and placed aside. Centrifugation at 12 000 rpm for

10 min at 4 °C produced the supernatant (TGL-16 Hunan Xiangyi). Following a 0.22 μm membrane filtering of the supernatant, the filtrate was introduced into an LC-MS for quantitative nucleotide analysis. An AB SCIEX 5500 QQQ-MS, USA, and a Waters Acquity UPLC, Thermo, USA, were the primary instruments used in the data gathering system. A PREMIER BEH Z-HILIC column measuring 100 × 2.1 mm and 1.7 μm in size was used for mass spectrometry.

In the positive ion mode, 0.1% formic acid aqueous solution was used for mobile phase A and 0.1% formic acid acetonitrile was used for mobile phase B. Injection volume was 6 μL, run time was 5 minutes, column temperature was 35 °C, and the flow rate was 0.45 mL min^{-1}. All of the analysis was conducted with the samples in an autosampler at 4 °C. The continuous analysis of the samples was conducted using a random order to prevent the impact of the instrumental detection signal fluctuation.

2.2.6 Analysis of electronic nose. A 20 mL headspace vial containing 5 g of kidney bean and clam soup samples following various heat processing methods was filled and sealed with three layers of a sealing film right away. Two syringe needles, one long and one short, were simultaneously placed into the headspace vials to aspirate the gas after the samples were allowed to remain at room temperature for 30 minutes to allow the gas to equilibrate.

The sample interval time was set to 1 second, the cleaning time was set to 60 seconds, the zero time was set to 10 seconds, the pre-sampling time was set to 5 seconds, the detection time was set to 100 seconds, the carrier gas flow rate was set to 300 mL min^{-1}, the injection volume was set to 300 mL min^{-1}, and the data were analyzed using the Winmuster software that comes with the electronic nose for 80–86 seconds.

2.2.7 Analysis of electronic tongue. A 10 mL of various heat-processed kidney bean and clam soups were centrifuged (Hi mac CR22N) at 8000 rpm for 10 min at 4 °C and filtered, and the supernatant was extracted and diluted five times. A data analysis system included with the electronic tongue was used to examine the data after each sample was measured for 120 seconds (1 second every time) and three times.

2.3 Statistical analysis

Using one-way analysis of variance (ANOVA), which was deemed significant when $P < 0.05$,[16] SPSS 27.0 was utilized to conduct a statistical analysis between the various treatment groups of kidney bean and clam soup. The information was presented as mean ± standard deviation (SD). Using Pearson correlation, the relationship between the data was evaluated. Plotting was done with Prism 10.0.

3 Results and discussion

3.1 Effects of various thermal processing techniques on the color of clam and kidney bean soups

As can be seen from Table 1, there was a significant difference in the color of the kidney bean clam soup treated with these three thermal methods. The color parameters of brightness (L^*), redness (a^*), and yellowness (b^*) of the soup were demonstrated, and each group of parameters was significantly affected by the various heating methods ($p < 0.05$) and Fig. 1A also confirms this. The L^*, b^*, and W values of the GSZ group were considerably greater ($p < 0.05$) than those of the other two groups, and these findings share color features with the study by Wang *et al.*[17] In comparison to alternative thermal processing techniques, the GSZ group generated more water vapor. The increased production of water vapor in the GSZ group kidney bean clam soup may have contributed to the increase in L^* and W values. Additionally, the GSZ group's whiteness (W) was higher than that of the SZ and GSD groups because the fat in their clam broth was emulsified during the preparation process. The clam broth's fat content increased as a result of the cooking machine's rotating blades, which improved the blending of edible oil into the broth during cooking ($p < 0.05$). This could be the reason for the SZ group's significantly lower L^* value compared to the GSD and GSZ groups.

3.2 Effect of different thermal processing methods on TBARS content in kidney bean clam soup

The amount of lipid oxidation in meat can be determined by measuring the amount of TBARSs present because TBARSs can react with malondialdehyde (MDA), which is created when unsaturated fatty acids in meat oxidatively degrade to generate MDA-TBA complexes.[18] Fat hydrolysis and oxidation in aquatic products will have a major impact on the quality of the product changes because they produce low-grade ketones and aldehydes that will alter the taste of the food and cause rancidity and muscle discoloration.[19] As seen in Fig. 1B, the TBARS value of the GSZ group demonstrated the least amount of lipid oxidation. This is likely due to the fact that steaming involves instantaneous heat transfer, which can coagulate proteins and fat in the samples to maximize the amount of fresh juice retained in the food.[20] As a result, steaming aids in maintaining the soup's high quality lipid content; the GSD group had the

Table 1 Effect of different thermal processing methods on the color of kidney bean and clam soup

	L^*	a^*	b^*	W
SZ	83.273 ± 0.258^{c}	-0.257 ± 0.006^{b}	19.563 ± 0.035^{a}	74.259 ± 0.189^{c}
GSZ	89.433 ± 0.359^{a}	-0.213 ± 0.045^{b}	15.160 ± 0.632^{c}	81.519 ± 0.693^{a}
GSD	87.447 ± 0.0451^{b}	-0.133 ± 0.021^{a}	17.077 ± 0.180^{b}	78.805 ± 0.172^{b}

Note: different letters within the same row indicate significant differences (P < 0.05).

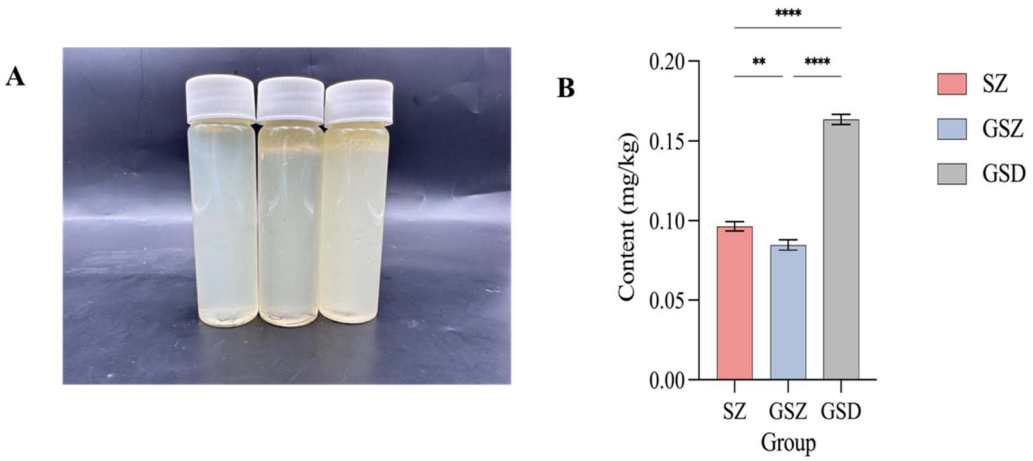

Fig. 1 Different kidney bean and clam soups (A) (from left to right are SZ, GSZ and GSD) and the effect of different thermal processing methods on TBARS values (B) of kidney bean and clam soup.

highest TBARS values, which is likely due to the continuous heat transfer process of stewing and the high temperature environment that encourages fat oxidation. While meat rancidity is a leptokurtic process, oxidative rancidity of muscle fatty acids typically exists in a latent period.

3.3 Effect of different thermal processing methods on the free amino acid content of kidney bean and clam soup

Since fish and fishery products are abundant in high-quality proteins, it's critical to make sure that cooking does not severely alter their amino acid makeup.[21] While natural amino acids typically have a bitter taste connected to their structure,[22] most amino acids have diverse flavors that can be categorized as fresh, sweet, or bitter based on their taste qualities.[23] Aspartic acid (Asp) and glutamic acid (Glu) are two of the flavor-presenting amino acids that are referred to as "fresh-flavor amino acids" due to the fact that their side-chain carboxyl groups exhibit carboxylate anions at low pH, which bind to the T1R1/T1R3 fresh-flavor receptor and generate the characteristic "fresh-flavor" perception. In addition, glycine (Gly), which has

Table 2 Changes in free amino acid content of kidney bean and clam soups by different thermal processing methods (mg mL^{-1})

No.		Flavor characteristics	SZ	GSZ	GSD
1	Asp	Fresh/Sweet (+)	0.155 ± 0.001^{a}	0.146 ± 0.001^{b}	0.149 ± 0.003^{b}
2	Glu	Fresh (+)	0.199 ± 0.001^{a}	0.162 ± 0.004^{a}	0.197 ± 0.001^{b}
	Total fresh amino acids		$0.354 \pm 0.0E0^{a}$	0.308 ± 0.005^{c}	0.345 ± 0.003^{b}
4	Thr	Sweet (+)	0.021 ± 0.001^{a}	0.020 ± 0.001^{a}	0.021 ± 0.001^{a}
5	Ser	Sweet (+)	0.159 ± 0.001^{b}	0.161 ± 0.001^{b}	0.164 ± 0.002^{a}
6	Gly	Sweet (+)	0.330 ± 0.001^{a}	0.317 ± 0.001^{b}	0.311 ± 0.001^{c}
7	Ala	Sweet (+)	0.165 ± 0.002^{b}	0.153 ± 0.006^{c}	0.174 ± 0.002^{a}
8	Pro	Sweet/Bitter (+)	$0.013 \pm 0.0E0^{a}$	$0.015 \pm 0.0E0^{a}$	$0.014 \pm 0.0E0^{a}$
	Total sweet amino acids		0.687 ± 0.002^{a}	0.668 ± 0.003^{c}	0.682 ± 0.001^{b}
9	Val	Bitter (−)	0.028 ± 0.002^{b}	$0.033 \pm 0.0E0^{a}$	0.030 ± 0.001^{b}
10	Ile	Bitter (−)	$0.012 \pm 0.0E0^{ab}$	0.016 ± 0.004^{a}	$0.011 \pm 0.0\ E0^{b}$
11	Leu	Bitter (−)	$0.033 \pm 0.0\ E0^{b}$	0.039 ± 0.001^{a}	0.034 ± 0.001^{a}
12	Lys	Bitter (−)	0.013 ± 0.001^{b}	$0.036 \pm 0.0E0^{a}$	$0.032 \pm 0.0\ E0^{b}$
13	Arg	Bitter (−)	0.110 ± 0.001^{b}	0.112 ± 0.001^{a}	0.112 ± 0.001^{a}
14	His	Bitter (−)	0.016 ± 0.001^{b}	0.018 ± 0.001^{a}	0.016 ± 0.002^{b}
15	Tyr	Bitter (−)	0.015 ± 0.002^{a}	0.017 ± 0.002^{a}	$0.016 \pm 0.0E0^{a}$
16	Met	Bitter (−)	0.017 ± 0.002^{a}	0.019 ± 0.001^{a}	0.017 ± 0.002^{a}
17	Phe	Bitter (−)	0.011 ± 0.001^{b}	0.016 ± 0.001^{a}	$0.010 \pm 0.0\ E0^{b}$
	Total bitter amino acids		0.459 ± 0.198^{a}	0.352 ± 0.019^{a}	0.342 ± 0.003^{a}
	Aromatic amino acids (AAA)		0.026 ± 0.003^{b}	0.033 ± 0.001^{a}	$0.026 \pm 0.0\ E0^{b}$
	Sulfur amino acids (SAA)		0.082 ± 0.002^{a}	0.067 ± 0.015^{a}	0.082 ± 0.001^{a}
	Essential amino acids (EAA)		0.249 ± 0.001^{a}	0.260 ± 0.020^{a}	0.251 ± 0.003^{a}
	Non-essential amino acids (NEAA)		1.129 ± 0.002^{a}	1.096 ± 0.031^{a}	1.118 ± 0.004^{a}
	Total amino acids (TAA)		1.378 ± 0.002^{a}	1.324 ± 0.019^{b}	1.369 ± 0.002^{a}

Note: different letters within the same row indicate significant differences ($P < 0.05$).

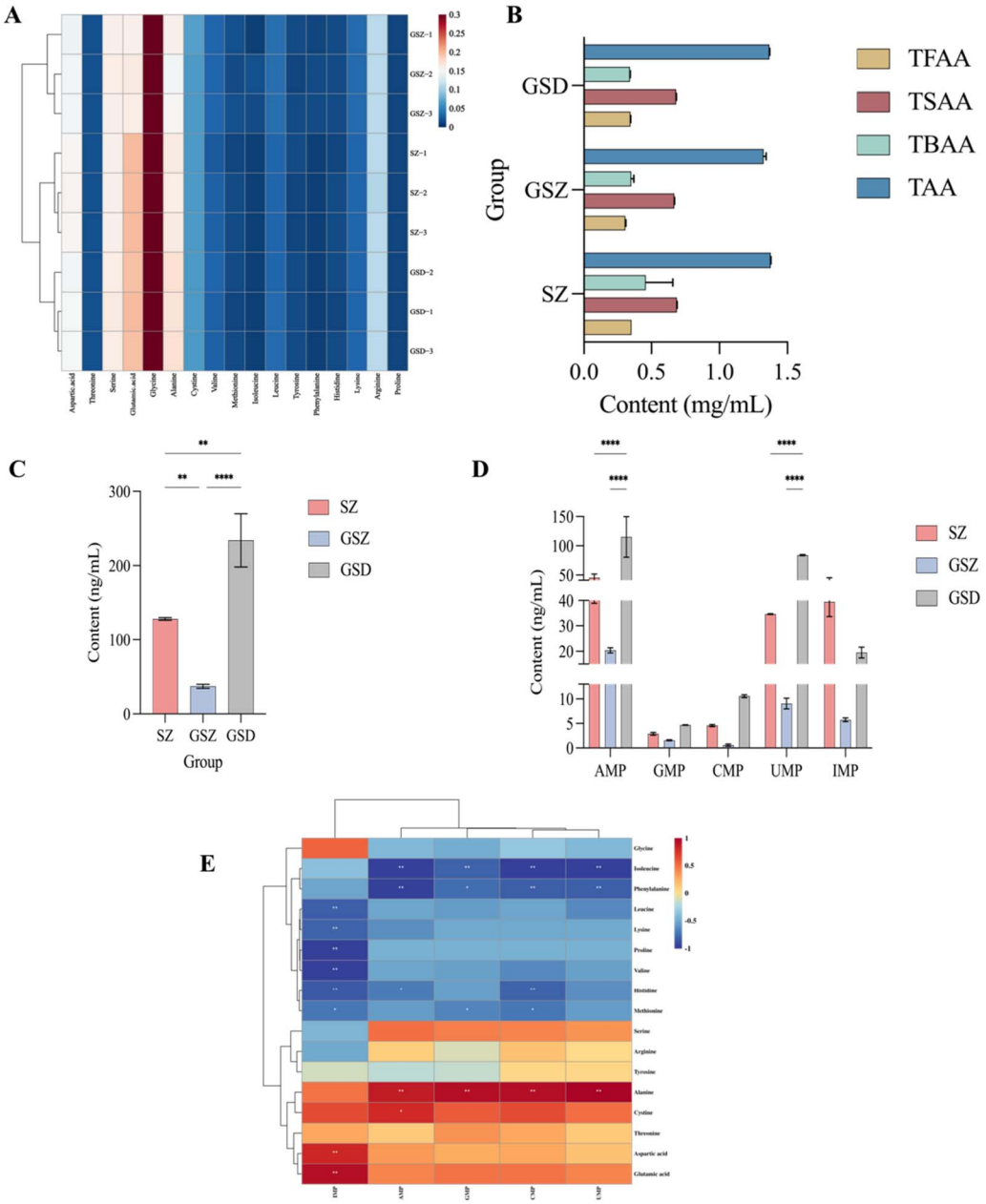

Fig. 2 Differential analysis of the free amino acid clustering heat map in kidney bean and clam soup (A), changes in amino acid content and nucleotide levels of kidney bean and clam soup by different thermal processing methods (B–D) and free amino acid and nucleotide correlations in different heat-processed kidney bean and clam soups (E).

a high threshold of taste presentation on its own and only has hydrogen atoms in its side chain, works in concert with Asp and Glu to considerably increase their freshness intensity. They will work together to enrich the flavor of the kidney bean clam soup. Table 2, Fig. 2A and B demonstrate the impact of various processing techniques on the amount of free amino acids in kidney bean and clam soup. The kidney bean and clam soup was found to have a total of 17 free amino acids, of which 10 were essential amino acids (EAA) and 7 were non-essential amino acids (NEAA). These findings suggest that the soup is high in free amino acids. The amounts of free amino acids in kidney bean and clam soup processed differently showed significant differences ($p < 0.05$).

The kidney bean and clam soup (SZ group) simmered in a multifunctional cooking machine had the greatest total free amino acid (TAA) content of 1.3775 mg mL^{-1}, which was substantially greater than that of the water bath simmering (GSD) and steamer cooking (GSZ) ($p < 0.05$). This was mostly due to the SZ group's sweet amino acid concentration being significantly higher than that of the other two groups ($P < 0.05$). This could be because the automatic stirring of the multipurpose cooker during the simmering period further facilitates the interaction of kidney beans and clam broth, producing more

delicious amino acids. By reducing the freshness threshold of Glu and Asp, they not only directly activate sweetness receptors but also work in concert to enhance freshness.[24] The GSZ group's lowest TAA may have resulted from the free amino acids leaching out during the steaming process along with water vapor.[25] The primary sweet amino acid is glycine, which when combined with ornithine and alanine will work in concert to improve the freshness of foods like fish, meat, and soups. The GSZ group had the lowest amount of fresh flavor amino acids, while the SZ group had the highest concentration, followed by the GSD group. Our results are in line with research that indicates that the Glu content of mutton, hog, and chicken broths was much greater than the Asp concentration.[26] The SZ group had the greatest concentration of glutamic acid, 0.1985 mg mL^{-1}, which was substantially greater than that of the other two groups ($p < 0.05$). Glu is an important flavor amino acid with a strong fresh taste.[27] The GSZ group had a considerably higher concentration of bitter amino acids ($p < 0.05$) compared to the other two groups, which were the GSD and SZ groups. Leucine and lysine were the most abundant amino acid constituents. Research conducted by Lioe *et al.*[28] revealed that bitter amino acid content may considerably improve the freshness and sweetness of other flavored amino acids if it was less than its threshold. The flavor characteristics of fish soup and other broth foods are closely associated with the type of free amino acid present. Following an extended period of high-temperature boiling, the raw material's protein gradually breaks down into polypeptides, which in turn break down into small peptides, free amino acids, and other flavor substances.[29] This thermal processing system causes the following three reactions. The first is the Maillard reaction, which produces an Amadori product by condensing reducing sugars (such as glucose and fructose) with free amino acids (particularly Lys, Arg, Asp, and Glu). This product is then broken down into heterocyclic compounds like furans, pyrazines, pyrroles, and so forth. Strecker degradation follows, where amino acids and α-dicarbonyl intermediates combine to generate Strecker aldehydes (such as 3-methylbutyraldehyde and phenylglyoxal), which give off roasted, nutty scents[30] Lastly, lipid-carotenoid oxidation: high temperatures cause unsaturated fatty acids (C18 : 2, C18 : 3) and β-carotene to cleave, producing compounds with a fruity and floral scent, including (*E*)-2-octenal, β-violet ketone, and flavonoids.[31] These processes not only indirectly aid in the formation of flavor but also break down the precursor substances of aroma and this is how amazing kidney bean and clam soup is made.

Table 3 Changes in nucleotide levels of kidney bean and clam soups by different thermal processing methods (ng g^{-1})

Processing methods	SZ	GSZ	GSD
AMP	45.370 ± 6.470^{b}	20.395 ± 1.035^{b}	115.210 ± 34.580^{a}
GMP	2.890 ± 0.280^{b}	1.567 ± 0.105^{c}	4.680 ± 0.050^{a}
CMP	4.570 ± 0.200^{b}	0.580 ± 0.210^{c}	10.570 ± 0.300^{a}
UMP	34.600 ± 0.150^{b}	9.060 ± 1.100^{c}	84.040 ± 1.000^{a}
IMP	39.447 ± 5.875^{a}	5.740 ± 0.370^{c}	19.537 ± 2.115^{b}

Note: different letters within the same row indicate significant differences (P < 0.05).

3.4 Effect of different thermal processing methods on the nucleotide content of kidney bean and clam soup

The taste of meat products depends on nucleotides; the most widely used ones to enhance freshness are guanine nucleotides (GMP) and hypoxanthine nucleotides (IMP).[21] Free amino acids (Glu and Asp) and inorganic salt ions work in concert with flavor-presenting nucleotides (AMP, IMP, and GMP) to give soups a distinctive freshness that will greatly improve their flavor profile. During the current experiment, the levels of adenosine monophosphate (AMP), guanosine monophosphate (GMP), cytosine monophosphate (CMP), uracil monophosphate (UMP), and inosine 5′-monophosphate (IMP) were measured in each group of kidney bean and clam soup. Table 3 and Fig. 2C and D illustrate the impact of various thermal processing techniques on the nucleotide content of kidney bean and clam soup. Each group showed substantial changes in nucleotide type and content. The GSD group had the greatest GMP content, measuring 4.680 ng mL^{-1}, while the GSZ group had the lowest GMP content, measuring 1.567 ng mL^{-1}. Similarly, the SZ group had the highest IMP content, measuring 39.447 ng mL^{-1}, while the GSZ group had the lowest IMP content, measuring 5.740 ng mL^{-1}. The taste of kidney bean and clam soup can be considerably improved by the use of IMP as a food flavor enhancer. Additionally, the interaction of IMP, AMP, and GMP with free amino acids can further enhance the flavor of the soup.[32] According to Fig. 2E, IMP was significantly ($p < 0.01$) associated with the taste amino acids ASP and Glu and significantly ($p < 0.01$) associated with the sweet amino acid Ala. This demonstrates the incredibly sweet and crisp flavor of kidney bean clam soup. Because of their high threshold levels, CMP and UMP did not significantly enhance the flavor of kidney bean clam soup.

3.5 Effect of different thermal processing methods on volatile flavor substances in kidney bean and clam soup

The volatile components in several thermally processed kidney bean clam soups were examined using GC-IMS. As illustrated in Fig. 3A, the figure's backdrop is blue, the reactive ion peak is represented by the red vertical line on the left, and each point on either side of the line denotes a volatile molecule. The hue then represents the compound's concentration, with blue being a low concentration and red a high one. When the volatile species displayed in the figure difference plots for various heat-processed kidney bean and clam soups are combined for comparison, the background becomes white following deduction; the red color denotes a substance's concentration that is higher than the control's, and the blue color denotes the opposite.[33] The volatile chemicals in the various thermally processed kidney bean and clam soups varied significantly, as shown by a differential analysis of all the spectra performed with the SZ group as a reference. Both the GSZ and GSD groups had higher amounts of volatile compounds than the SZ group, as did the concentrations of the majority of the volatile

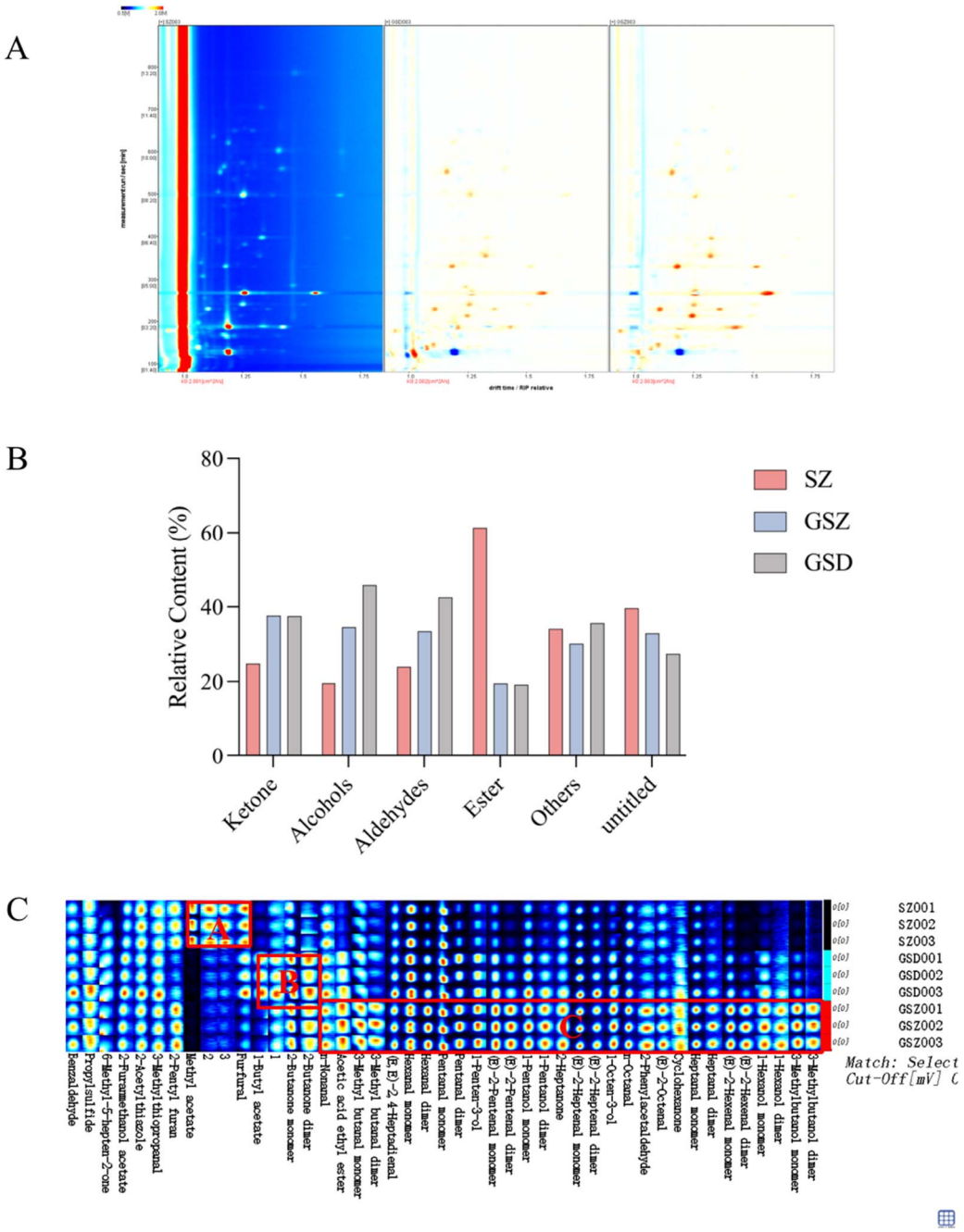

Fig. 3 Two-dimensional spectra of different thermally processed kidney bean and clam soups (A), categorical share of volatile components in different thermally processed kidney bean and clam soups (B) and the gallery plot of volatile compounds in different thermally processed kidney bean and clam soups (C).

compounds. The GSD group showed more noticeable changes than the GSZ group, indicating that simmering is more likely to increase the volatile flavoring substances in the clam and kidney bean soups.

Fig. 3B illustrates the notable variations in volatile taste component composition between several thermally processed kidney bean and clam soups. The SZ group exhibited the highest ester volatile content, making up 61.35% of the total amount, while the GSZ group had a higher ketone volatile content, accounting for over 35% of the total amount. Additionally, the GSD group had a significantly higher content of alcohols, aldehydes, and other volatile substances than the other two groups, accounting for 45.83%, 42.57%, and 35.7% of their total volatile compounds, respectively. Finally, the total content of volatile flavor substances was GSD > GSZ > SZ. Table 4 shows that the compounds analyzed by GC-IMS are primarily esters and alcohols, with the remaining compounds being 22 aldehydes, 8 alcohols, 5 ketones, 4 esters, and 3 others, 3 of

Table 4 Composition of volatiles in different thermally processed kidney bean and clam soups

Compound	Odor type	CAS	Formula	Molecular weight	Retention index	Retention time	Drift time
2-Butanone monomer	Fruity and camphor	C78933	C_4H_8O	72.1	584	137.776	1.06935
2-Butanone dimer	—	C78933	C_4H_8O	72.1	588.2	139.325	1.24463
2-Heptanone	Pear, banana, fruity, and slight medicinal fragrance	C110430	$C_7H_{14}O$	114.2	890.1	381.421	1.26017
6-Methyl-5-hepten-2-one	Citrus, fruity, mouldy, and ketone	C110930	$C_8H_{14}O$	126.2	991	564.788	1.17435
Cyclohexanone	Strong pungent and earthy	C108941	$C_6H_{10}O$	98.1	901.2	398.024	1.15006
1-Penten-3-ol	Ethereal, green, and tropical fruity	C616251	$C_5H_{10}O$	86.1	682.2	178.872	0.944
3-Methylbutanol monomer	Whiskey, banana, and fruity	C123513	$C_5H_{12}O$	88.1	730	213.044	1.24567
3-Methylbutanol dimer	—	C123513	$C_5H_{12}O$	88.1	729.5	212.66	1.49221
1-Pentanol monomer	Balsamic	C71410	$C_5H_{12}O$	88.1	761.5	240.304	1.25087
1-Pentanol dimer	—	C71410	$C_5H_{12}O$	88.1	762	240.688	1.50781
1-Hexanol monomer	Fresh, fruity, winey, sweet, and green	C111273	$C_6H_{14}O$	102.2	869.9	354.985	1.32332
1-Hexanol dimer	—	C111273	$C_6H_{14}O$	102.2	870.8	356.11	1.63746
1-Octen-3-ol	Mushroom, lavender, rose, and hay	C3391864	$C_8H_{16}O$	128.2	985.6	552.976	1.16302
3-Methyl butanal monomer	Chocolate and fat	C590863	$C_5H_{10}O$	86.1	655.4	166.586	1.18221
3-Methyl butanal dimer	—	C590863	$C_5H_{10}O$	86.1	652.8	165.434	1.40899
Pentanal monomer	Green grassy, faint banana, and pungent	C110623	$C_5H_{10}O$	86.1	697.3	188.087	1.19158
Pentanal dimer	—	C110623	$C_5H_{10}O$	86.1	694.1	185.783	1.42355
(*E*)-2-Pentenal monomer	Potato and peas	C1576870	C_5H_8O	84.1	750	229.937	1.10732
(*E*)-2-Pentenal dimer	—	C1576870	C_5H_8O	84.1	748.2	228.401	1.36114
Hexanal monomer	Fresh, green, fat, and fruity	C66251	$C_6H_{12}O$	100.2	792.1	269.484	1.26127
Hexanal dimer	—	C66251	$C_6H_{12}O$	100.2	791.7	269.1	1.56398
(*E*)-2-Hexenal monomer	Green, banana, and fat	C6728263	$C_6H_{12}O$	98.1	850.4	331.3	1.18221
(*E*)-2-Hexenal dimer	—	C6728263	$C_6H_{10}O$	98.1	850	330.798	1.52087
Furfural	Sweet, woody, almond, and bready	C98011	$C_5H_4O_2$	96.1	831.1	309.424	1.08529
Heptanal monomer	Fresh, aldehyde, fatty, green herbs, winey, and fruity	C111717	$C_7H_{14}O$	114.2	901.4	398.295	1.33304
Heptanal dimer	—	C111717	$C_7H_{14}O$	114.2	900.7	397.17	1.69413
3-Methylthiopropanal	Onion, meat, and fruity	C3268493	C_4H_8OS	104.2	907.5	407.857	1.09177
(*E*)-2-Heptenal monomer	Spicy, green vegetables, fresh, and fatty	C18829555	$C_7H_{12}O$	112.2	958.6	497.853	1.26341
(*E*)-2-Heptenal dimer	—	C18829555	$C_7H_{12}O$	112.2	959.5	499.541	1.6666
Benzaldehyde	Bitter almond, cherry, and nutty	C100527	C_7H_6O	106.1	962.7	505.728	1.1533
n-Octanal	Aldehyde, waxy, citrus, orange, fruity, and fatty	C124130	$C_8H_{16}O$	128.2	1011.5	602.354	1.40649
(*E*,*E*)-2,4-heptadienal	Fatty, oily, aldehyde, vegetable, and cinnamon	C4313035	$C_7H_{10}O$	110.2	1022.2	620.929	1.19019
2-Phenylacetaldehyde	Hyacinth, sweet fruity, almond, cherry, clover honey, and cocoa	C122781	C_8H_8O	120.2	1041.4	655.851	1.26171
(*E*)-2-Octenal	Fresh cucumber, fatty, green herbal, banana, and green leaf	C2548870	$C_8H_{14}O$	126.2	1067.4	706.376	1.33148
n-Nonanal	Rose, citrus, and strong oily	C124196	$C_9H_{18}O$	142.2	1105.1	786.622	1.46929
3-Methyl butanal monomer	Chocolate and fat	C590863	$C_5H_{10}O$	86.1	655.4	166.586	1.18221
3-Methyl butanal dimer	—	C590863	$C_5H_{10}O$	86.1	652.8	165.434	1.40899
Pentanal monomer	Green grassy, faint banana, and pungent	C110623	$C_5H_{10}O$	86.1	697.3	188.087	1.19158
Pentanal dimer	—	C110623	$C_5H_{10}O$	86.1	694.1	185.783	1.42355
(*E*)-2-Pentenal monomer	Potato and peas	C1576870	C_5H_8O	84.1	750	229.937	1.10732
(*E*)-2-Pentenal dimer	—	C1576870	C_5H_8O	84.1	748.2	228.401	1.36114
Hexanal monomer	Fresh, green, fat, and fruity	C66251	$C_6H_{12}O$	100.2	792.1	269.484	1.26127
Hexanal dimer	—	C66251	$C_6H_{12}O$	100.2	791.7	269.1	1.56398
(*E*)-2-Hexenal monomer	Green, banana, and fat	C6728263	$C_6H_{10}O$	98.1	850.4	331.3	1.18221

Table 4 (*Contd.*)

Compound	Odor type	CAS	Formula	Molecular weight	Retention index	Retention time	Drift time
(*E*)-2-Hexenal dimer	—	C6728263	$C_6H_{10}O$	98.1	850	330.798	1.52087
Furfural	Sweet, woody, almond, and bready	C98011	$C_5H_4O_2$	96.1	831.1	309.424	1.08529
Heptanal monomer	Fresh, aldehyde, fatty, green herbs, winey, and fruity	C111717	$C_7H_{14}O$	114.2	901.4	398.295	1.33304
Heptanal dimer	—	C111717	$C_7H_{14}O$	114.2	900.7	397.17	1.69413
3-Methylthiopropanal	Onion, meat, and fruity	C3268493	C_4H_8OS	104.2	907.5	407.857	1.09177
(*E*)-2-Heptenal monomer	Spicy, green vegetables, fresh, and fatty	C18829555	$C_7H_{12}O$	112.2	958.6	497.853	1.26341
(*E*)-2-Heptenal dimer	—	C18829555	$C_7H_{12}O$	112.2	959.5	499.541	1.6666
Benzaldehyde	Bitter almond, cherry, and nutty	C100527	C_7H_6O	106.1	962.7	505.728	1.1533
n-Octanal	Aldehyde, waxy, citrus, orange, fruity, and fatty	C124130	$C_8H_{16}O$	128.2	1011.5	602.354	1.40649
(*E*,*E*)-2,4-heptadienal	Fatty, oily, aldehyde, vegetable, and cinnamon	C4313035	$C_7H_{10}O$	110.2	1022.2	620.929	1.19019
2-Phenylacetaldehyde	Hyacinth, sweet fruity, almond, cherry, clover honey, and cocoa	C122781	C_8H_8O	120.2	1041.4	655.851	1.26171
(*E*)-2-Octenal	Fresh cucumber, fatty, green herbal, banana, and green leaf	C2548870	$C_8H_{14}O$	126.2	1067.4	706.376	1.33148
n-Nonanal	Rose, citrus, and strong oily	C124196	$C_9H_{18}O$	142.2	1105.1	786.622	1.46929
Methyl acetate	Ethereal	C79209	$C_3H_6O_2$	74.1	553.5	127.084	1.19162
Acetic acid ethyl ester	Fresh, fruity, sweet, and grassy	C141786	$C_4H_8O_2$	88.1	600.4	143.933	1.10107
1-Butyl acetate	Ftuity	C123864	$C_6H_{12}O_2$	116.2	806.2	283.306	1.24047
2-Furanmethanol acetate	Sweet and banana	C623176	$C_7H_8O_3$	140.1	988.8	560.002	1.41173
2-Pentyl furan	Bean, fruity, earthy, green, and vegetable	C3777693	$C_9H_{14}O$	138.2	995.8	575.475	1.2537
2-Acetylthiazole	Popcorn, stir fried chestnuts, roasted oatmeal, roasted meat, nutty, and bready	C24295032	C_5H_5NOS	127.2	1031.3	637.275	1.13262
Propylsulfide	Pungent, garlic, and onion	C111477	$C_6H_{14}S$	118.2	895	388.479	1.15575
1		Unidentified	*	0	945.9	473.812	1.17623
2		Unidentified	*	0	1039.8	652.879	1.21286
3		Unidentified	*	0	1037.8	649.164	1.29485

which are currently unidentified due to the incompleteness of the GC-IMS database. Fig. 3C displays the volatile taste compound fingerprints for the various kidney bean clam soup heating techniques. By using a gallery plot to compare the differences between the compounds in the three different heat-processed groups of kidney bean clam soup, it can be seen that while the types of volatile compounds in the GSZ and GSD groups are similar, the SZ group has the fewest compounds overall. 3-Methylthiopropanal, 2-pentyl furan, and methyl acetate were the primary constituents of zone A and were detected in higher concentrations in the SZ group. Among these, 3-methylthiopropanal smells like fruit, meat, and onions. In research on the aroma of cooked beef, Mottram *et al.*[34] discovered that 3-methylthiopropanal significantly contributed. Similarly, in research on high-pressure beef and vegetable soup and pork and vegetable soup, Christlbauer *et al.*[35] discovered that 3-methylthiopropanal significantly contributed to the aroma of these types of soups. Furfural, 1-butyl acetate, 2-butanone monomer, and 2-butanone dimer are the principal chemicals in the B zone. These compounds have larger concentrations in the GSD group; furfural has a sweet, almondy, and bready aroma, while 1-butyl acetate has a strong fruity perfume. The majority of esters have a sweet, fruity scent and are typically the result of the esterification reaction between alcohols and carboxylic acids. One reason for the soup's richness in the GSD group is that coexisting esters and ketones may have a coordinating influence on the flavor as a whole. Acetic acid ethyl ester, 3-methyl butanal monomer, 3-methyl butanal dimer, (*E*,*E*)-2,4-heptadienal, hexanal monomer, hexanal dimer, pentanal monomer, and pentanal dimer are among the main compounds in the C zone; these compounds were primarily present in the GSZ group, where the flavor of the kidney bean and clam soup was greatly enhanced by the fresh, fruity, sweet, and grassy flavors of the acetic acid ethyl ester. The process of heating GSZ resulted in a notable increase in the variety of aldehydes found in kidney bean clam soup. These aldehydes can be derived from fatty acids and amino acids. The breakdown of these compounds in the clam soup, which is fueled by high temperature water vapor, produces a wide range of volatile compounds, most of which are aldehydes like 3-methyl butanal, (*E*,*E*)-2,4-heptadienal, hexanal, and so on.[36] The primary process that leads to the production of these compounds is the oxidative deamination-decarboxylation formation of amino acids *via* Strecker degradation in certain heat treatments. The GSZ group had a stronger and more aromatic flavor due to the much higher amount of volatile chemicals (both in terms of type and content) compared to the SZ and GSD groups.

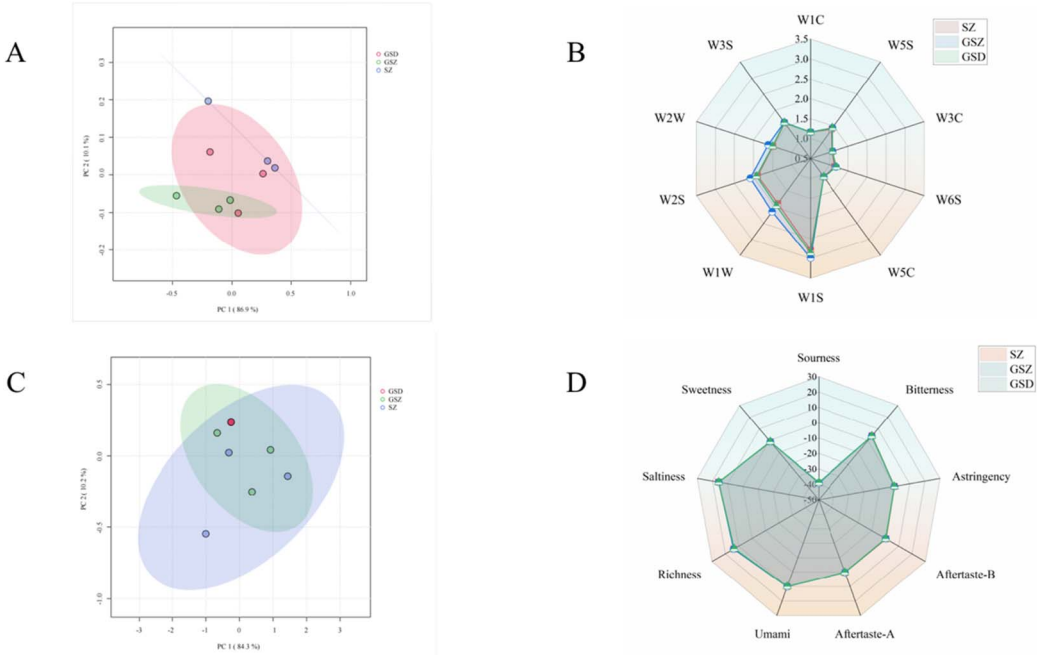

Fig. 4 PCA score plot of e-nose (A), radar plot of e-nose (B), PCA score plot of e-tongue (C) and radar plot of e-tongue (D).

3.6 Effect of different thermal processing methods on e-nose analysis in kidney bean and clam soup

The electronic nose primarily detects and analyzes the gases it detects by using the gas sensor array's sensitivity to certain gases to identify the gas components in the sample. Fig. 4A displays the results of the principal component analysis for the various processing techniques used to produce kidney bean and clam soup. The contribution rates of PC1 and PC2 are 99.67% and 0.23%, respectively, and the total contribution rate is 99.90%. The higher the contribution rate, the more the experiment's raw data can be used to support its validity.[37] The entire overlap of the GSZ and GSD groups suggests that the scents generated by these two groups are similar, implying that the two groups of kidney bean and clam soups have similar aromas. The SZ group does not, however, entirely overlap with these two groups at a certain distance, suggesting that the boiling, steaming, and simmering cooking processes differ in some way. Fig. 4B displays the radar plots of the corresponding values of the electronic nose sensors for the three groups of kidney bean and clam soups. Of the 10 sensors, the W1S sensor has the highest response value, and the response values of W1S, W1W, W2S, and W2W are more prominent. Furthermore, the response values of W1S for various heat-processed clam and kidney bean soups differed significantly, suggesting that the sensor W1S is capable of successfully differentiating between the volatile scents of these three groups.

3.7 Effect of different thermal processing methods on e-tongue analysis in kidney bean and clam soup

The electronic tongue can replicate human taste buds precisely, detect food flavors and intensities, translate flavors into electrical signals, and provide an overall assessment of the food's flavor attributes. The radar chart of the electronic tongue sensor response values of the various heat-processed kidney bean and clam soups is shown in Fig. 4C. The figure suggests that the taste indices of the kidney bean and clam soups boiled in these three ways are somewhat similar, with a high degree of similarity in bitterness, bitterness aftertaste, astringent aftertaste, richness, and saltiness, but differ in the response values of bitterness and fresh taste. As for the SZ group, the values were 3.97 and 10.07 for bitter and fresh taste responses, 3.74 and 10.16 for GSZ, and 3.84 and 10.03 for GSD. The steamed kidney bean and clam soup showed a lower bitter taste compared to the other two groups, but a significantly higher fresh taste value. This difference in taste could be explained by the cooking process, which increased the amount of free amino acids and other flavor-presenting substances in the soup by promoting their breakdown from proteins and other ingredients. The production of bitter heterocyclic amines, furan-2-carboxaldehyde, and peptide bitter fragments is reduced by the mild thermal environment (≈100 °C, saturated steam), which also limits drastic Maillard and Strecker degradation. Additionally, less solubilization from steaming as opposed to boiling results in a significant reduction in the amount of bitter precursors (free Trp, Leu, Arg, *etc.*) entering the broth, which directly lowers the e-lingual bitter response.[38]

4 Conclusion

In this study, three methods of boiling, steaming, and stewing were used to determine the effect of different thermal processing methods on the flavor of kidney bean and clam soup by color, TBARSs, free amino acids, nucleotides, e-nose, e-tongue,

and GC-IMS. The purpose of this investigation was to determine the impact of different thermal processing methods on the quality of kidney bean and clam soup. The findings revealed that the soup in the GSZ group was bright white and had the lowest amount of TBARSs; the soup in the SZ group had slightly higher free amino acid and nucleotide contents than the other two groups, but the differences were not statistically significant; the e-nose and e-tongue revealed that both the GSD group and the GSZ group contained a higher concentration of volatile flavor substances; and the GC-IMS results showed that the GSZ group had a richer variety of flavor substances. Finally, this article can serve as a theoretical guide for consumers selecting the best heat-processing method for kidney bean clam soup. The heat-processed kidney bean clam soup will produce more flavor compounds thanks to the superior heating methods of steaming and stewing. This will enhance the heat processing of pre-prepared dishes and encourage the spread of kidney bean and clam noodle soup, a local specialty in Dalian.

Author contributions

Pengfei Jiang designed and directed the entire experiment and revised the manuscript. Jing Li performed the experiments, analyzed the data and wrote the paper. Xiaoqing Miao and Yan Liu provided assistance with materials and methods. All authors approved the final version of the manuscript.

Conflicts of interest

The authors declare no conflict of interest.

Data availability

Data are provided within the manuscript or SI files.

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